DEVELOPMENT OF A BASIC SAFETY MESSAGE FOR TRACTOR-TRAILERS FOR VEHICLE-TO-VEHICLE COMMUNICATIONS

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ABSTRACT

Currently the Basic Safety Message (BSM) used by heavy truck tractor-trailers was developed for Vehicle-to-Vehicle (V2V) communications in the U.S. DOT Safety Pilot and uses a simplified bounding box algorithm for conveying the position and heading of the tractor-trailer. However, because of the articulated behavior inherent in a tractor-trailer, this approach does not accurately identify the trailer position or vehicle space for V2V safety applications in all situations. Consequently, in certain situations this can lead to an unacceptable number of false and missed warnings to drivers in surrounding connected vehicles. The U.S. DOT, in partnership with the Crash Avoidance Metrics Partnership (CAMP) and Mercedes-Benz Research & Development North America, Inc. (MBRDNA) conducted a project, Tractor-Trailer Basic Safety Message Development (TT-BSM), to develop technical solutions to this location identification problem for heavy truck tractors with one or more articulated trailers. TT-BSM developed several BSM enhancement approaches to more accurately represent tractor-trailer articulation. Furthermore, the team also completed the system and performance requirements and an assessment of the enhanced BSM impact on internal vehicle platform (On-Board Equipment, OBE, necessary vehicle sensors on the tractor and the trailer) and external systems (e.g. communications channel loading, other OBE-equipped vehicles, and backend systems). The enhanced BSM can more accurately transmit position and heading for articulated tractor-trailers and thus allows for better safety warnings and fewer false and missed warnings to drivers.

INTRODUCTION

Over the last several years, the United States Department of Transportation (U.S. DOT) and the Crash Avoidance Metrics Partnership (CAMP) Vehicle Safety Communications 3 (VSC3) Consortium (Ford Motor Company, General Motors Corporation, Honda R&D Americas, Inc., Hyundai-Kia America Technical Center, Inc., Mercedes-Benz Research & Development North America, Inc., Nissan Technical Center North America, Inc., Toyota Motor Engineering & Manufacturing North America, Inc., and Volkswagen Group of America) have collaborated in the area of Vehicle-to-Vehicle (V2V) communications for the Safety Pilot program. [1] V2V safety systems generally rely on Dedicated Short Range Communications (DSRC) transmissions to share position, kinematic, and vehicle information with neighboring vehicles that are similarly equipped and warn their drivers of potential imminent dangers. The Safety Pilot Model Deployment (MD) launched August 21, 2012 running through 2013 provided insight into public perception, acceptance, and effectiveness of active safety systems that could be supported by the use of low-cost technologies, specifically 5.9 GHz DSRC and the Global Positioning System (GPS). This was demonstrated in MD on different prototype vehicles, including tractor-trailers, that hosted multiple DSRC-based safety applications aimed at addressing several crash categories, such as rear-end, lane change, intersecting, or oncoming. [2-3]

Three Class 8 tractor-trailers were equipped with fully integrated on-board equipment (OBE) and used in Driver Clinics held in Ohio and California under the V2V Safety Pilot project. [4] The results of the clinics showed the promise of the technology for heavy vehicles while under controlled conditions on a test track. These trucks were then included in the Model Deployment field test in Ann Arbor, Michigan. [5] For Model Deployment, the position and heading of the tractor-trailer in the Basic Safety Message (BSM) was derived by a simplified bounding box

algorithm which treated the tractor-trailer as a single rigid body. However, because of the articulated behavior inherent in a tractor-trailer, this approach can lead to an unacceptable number of false and missed warnings to drivers in surrounding connected vehicles, especially when the vehicle is in a turn. The U.S. DOT in partnership with CAMP and Mercedes-Benz Research & Development North America, Inc. has developed technical solutions (enhanced BSM) to this issue and established system and performance requirements. Furthermore, the partnership also completed an assessment of the enhanced BSM's impact on the internal vehicle platform (On-Board Equipment, OBE, necessary vehicle sensors on the tractor and the trailer) and external systems (e.g. communications channel loading, other OBE-equipped vehicles, and backend systems). The objective of this paper is to describe these team efforts and results.

Background

V2V communications based on 5.9 GHz DSRC allow vehicles to be aware of other nearby similarly equipped vehicles and assess collision risks by exchanging safety messages describing vehicles' current status. These communications can deliver information beyond on-board sensors' range or field of view and high-quality information such as vehicle weight, size, and brake status. As of now, research has mostly focused on DSRC-based systems aimed at alerting the driver of imminent dangers. A recent NHTSA report shows that just two of many possible V2V safety applications, Intersection Movement Assist (IMA) and Left Turn Assist (LTA), would on an annual basis potentially prevent 25,000 to 592,000 crashes, save 49 to 1,083 lives, avoid 11,000 to 270,000 Maximum Abbreviated Injury Scale 1-5 injuries, and reduce 31,000 to 728,000 property-damage-only crashes by the time V2V technology had spread through the entire fleet. [6]

The first prototype applications developed as part of several CAMP projects sponsored by the U.S. DOT included:

- Emergency Electronic Brake Lights (EEBL)
- Forward Collision Warning (FCW)
- Lane Change Warning (LCW) / Blind Spot Warning (BSW)
- Do Not Pass Warning (DNPW)
- Intersection Movement Assist (IMA)
- Control Loss Warning (CLW)

These V2V applications share a common concept of operations: using BSMs that are periodically broadcast by other similarly-equipped vehicles to track nearby vehicles and assess the risks of collision. BSMs include information on vehicle position, speed, heading, brake status, and size. This small set of information is sufficient to support most V2V safety applications for collision prediction.

Collision prediction algorithms need accurate information on the space occupied by each vehicle over time as well as its movements. This requires a model to represent vehicles and the space they occupy as they travel and execute driving maneuvers on the road. In current V2V systems developed by CAMP, vehicles are modeled as rigid body rectangles with a length and width. The BSM position transmitted over the air corresponds to the vehicle center expressed in terms of latitude, longitude, and elevation. Each vehicle calculates its center as an offset from the physical position of the GPS antenna (typically installed on the roof of the vehicle). V2V applications can tolerate errors in absolute position estimates to a certain degree as long as the relative position estimates meet application accuracy requirements. The V2V positioning system typically supports lane-level (< 1.5m) accuracy.

The recent CAMP projects focused solely on rigid body vehicle representations, as noted above. Unfortunately, the model does not sufficiently describe the space occupied by articulated vehicles during turn maneuvers. This problem can affect any articulated V2V-equipped commercial, transit, or passenger vehicle and will be discussed further in this paper.

V2V with Articulated Vehicles

Understanding how V2V applications generate warnings to the driver provides a foundation for the discussion on articulated vehicles. For example, FCW tracks one or more Remote Vehicles (RVs) ahead of the Host Vehicle (HV) traveling in the same general path and issues a warning to the HV driver if there is an imminent danger of collision

with an RV. FCW compares the HV predicted path (based on its location, speed, heading, and other parameters) with the RV path history. This path history comes from a trail of recent RV positions and is included in its BSM. This vehicle center point is calculated as an offset from the vehicle's GPS antenna (i.e. a constant offset in a rigid body).

When vehicle articulation is considered, additional factors must be included to process V2V applications correctly. In vehicle dynamics terminology, as in Figure 1 below, a vehicle's heading refers to the direction of the forward longitudinal axis of the vehicle's body with respect to a global reference. Its course heading is its instantaneous direction of travel with respect to a global reference. During steering maneuvers, the course heading will always differ from the vehicle heading. This difference is called the side slip angle, or β. When traveling on a straight road, the side slip angle is essentially zero. In addition, the vehicle's articulation angle is defined as the difference between the tractor and trailer headings.

For a light vehicle, reporting the course heading as the vehicle heading is an acceptable approximation. The instantaneous direction of travel (course heading) is far more meaningful to other DSRC-equipped vehicles than the vehicle heading since those vehicles use the direction of travel to predict its future path. This future path helps other vehicles calculate intercepts. This simplification becomes a problem when the broadcasting vehicle has articulation angles between multiple bodies.

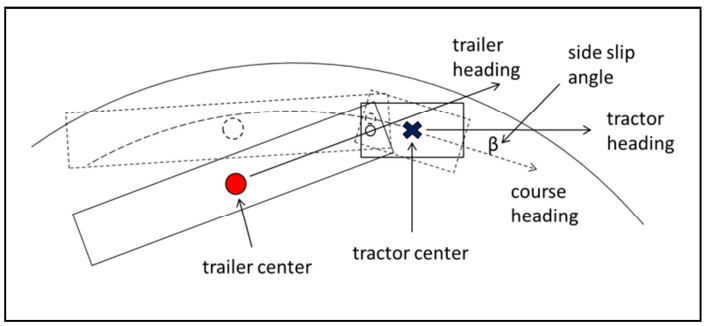


Figure 1. Articulated Vehicle Terminology.

For an articulated vehicle, it became apparent that correcting for articulation angle was not sufficient to accurately represent the location of the trailer. The vehicle is represented as a box, oriented in the direction of its course heading irrespective of the vehicle heading and rotated about its geometric center. Since both the true tractor and trailer poses are rotated about the center of the tractor (since the GPS antenna was mounted on the tractor) by the side slip angle, the DSRC system needed to correct for both the side slip angle and the articulation angle in order to accurately represent the location of the trailer. Without this correction, the error in the trailer orientation would be significant, especially as trailer length or number of trailers increase. Modeling could be further improved with filtering of other error sources (e.g. GPS, yaw rate, etc.), but was not the goal of this project and was omitted.

In the articulated vehicle used for this project, the GPS antenna was mounted on the roof of the tractor so when the vehicle changed direction, this offset remained constant even though the trailer swung in an arc relative to the tractor. As a result, the articulated vehicle path history can be significantly offset from the actual trailer position and orientation. As this erroneous 'ghost' trail was laid behind the vehicle, another approaching vehicle could wrongly trigger or suppress a warning. False warnings might occur when the HV is driving in the neighboring lane and the RV is going into a curve or turn. If the RV trail is in the path ahead of the HV when it is actually to the right of the HV while the road curves to the right, the HV may get a false FCW warning.

V2V safety applications on long, non-articulated vehicles such as city buses may also need to correct for vehicle versus course heading differences. In large steering angle maneuvers, such as pulling out of a bus stop, the vehicle may develop very large side slip angles. These side slip angles could be as much as 60°. It is unclear what impact this problem would have on warning application performance for long vehicles. That question merits further investigation, yet lies outside the scope of this paper.

The TT-BSM project was initiated to address these shortcomings due to misrepresentations of the space occupied by articulated vehicles. The main focus of the project was to derive the position and heading of each part of the articulated vehicle, define over-the-air messages to convey this information to nearby vehicles, and implement and test the solution in an actual vehicle; all with a minimum impact on the existing V2V system and communications standards.

TT-BSM Solution Sets

The TT-BSM project considered three alternative approaches to describe position and heading for each part of an articulated vehicle. The results of these alternatives were compared to the baseline rigid body approach, i.e., the initial rigid body model developed in previous CAMP projects (Figure 2a). This approach was included for comparison and had the advantage of not requiring changes to the V2V safety applications or Standards, but offered a simplistic and inaccurate representation of the trailer position. The second approach (multi-DGPS approach, Figure 2b) used distinct rigid body representations for the tractor and trailer where separate, independent rectangles represented the actual locations of each body of the articulated vehicle. A multi-DGPS receiver system was used to derive these locations. In the third approach (best fit rigid body, Figure 2c), the length and width of the rigid body model was kept the same, but translated its position laterally and longitudinally so that the rectangle is centered in a weighted average of the articulated tractor-trailer's planar area. Even though this solution broadcasts a rigid body model, it still required knowledge of the articulation angle. Finally, the fourth approach (algorithm approach, Figure 2d) used separate rectangles, as in the second approach, but no sensors are used to determine the actual position of the trailer. Rather, this is calculated through a kinematics algorithm. The yaw rate of the tractor is derived from DGPS. This is translated into a lateral velocity at the tractor hitch point (fifth wheel) and, since the trailer hitch point is fixed to the tractor hitch point, this translates into a trailer yaw rate. The trailer yaw angle is then numerically integrated from the trailer yaw rate. The trailer heading and center location are then calculated from the known geometry.

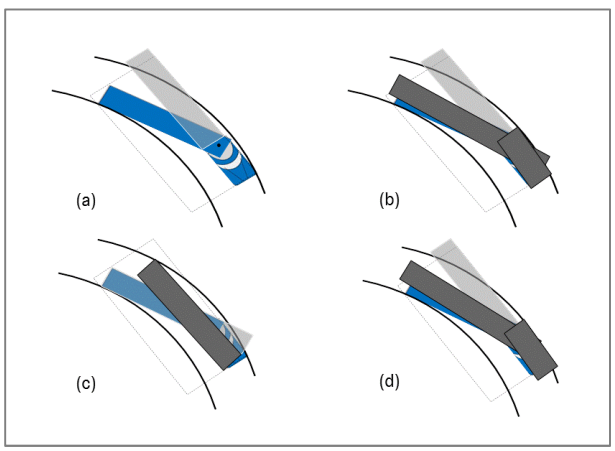


Figure 2. TT-BSM Project Solution Set.

In terms of packaging the trailer description into over-the-air messages, approaches 1 and 3 do not require any changes to the BSM or the safety applications: the baseline is the default light vehicle approach, while the third solution would simply offset the location of the rigid body tractor-trailer representation. Approaches 2 and 4 would require a BSM that could include a separate package of information for trailers in addition to the tractor. In order to select a workable approach for implementation, numerous simulations were developed and run to assess the pros and cons of each.

Simulations

In order to compare the solution approaches, scenarios were first developed to highlight their differences. Since the intention was to address potential problems caused by vehicle articulation, the scenarios incorporated conditions where the tractor-trailer bodies were at different headings, creating a non-zero articulation angle between them.

Furthermore, the vehicle was limited to turning from a thru lane and not a left or right turn pocket. This accentuated the rigid body model misrepresentation of the trailer position and heading by minimizing vehicle offset from the thru lane of travel as close to the intersection as possible.

Once scenarios were defined, tractor and trailer models as well as vehicle motion models simulating vehicle dynamics in the selected scenarios were constructed in the TruckSim simulation tool. At the same time, Matlab and Simulink were used to create models of each approach and V2V safety application functions within the on-board DSRC platform. The result of each simulation was a target classification and threat level for each component of the articulated tractor-trailer relative to the specific approach used. The results for each approach, as applied to a specific scenario, were overlaid and visualized in animations, providing clear comparisons of the various approaches in a simulated environment.

In all, four scenarios were used in the simulations. These included a constant radius of curvature road, two types of right hand turns, and a fast lane change at highway speeds. In all scenarios, the HV is following the tractor-trailer on the same road. The following describes these scenarios and relevant parameters in more detail.

For curved roads, such as a highway cloverleaf exit, the tighter or smaller the curve radius, the more likely the false alert due to misrepresentation of trailer articulation. Conversely, a large radius curve more closely approximates a straight road, reducing articulation angles and the chances for a false alert. In this scenario, a tractor-trailer was driven in a constant radius of curvature turn at steady-state conditions. This modeled pure articulation while removing transient vehicle steering dynamics from consideration. This case was used to determine if using a rigid body model could cause the vehicle to protrude into an adjacent lane virtually and, conversely, if any of the approaches represented the tractor-trailer pose correctly, so as to prevent false warnings.

In the second scenario, multi-lane right hand turns, the tractor-trailer is driven in a typical (for the U.S.) wide intersection turn of 90 degrees. A left hand turn scenario is not used since this is typically done from a left turn pocket or suicide lane and does not fulfill the more stressing condition where the vehicle turns from a thru lane.

For single lane right hand turns, the third scenario, the tractor-trailer makes a 90 degree turn onto a narrow intersecting road. In order to successfully negotiate the tight turn, the tractor-trailer swerves onto the adjacent left lane before turning right. This is more typical in urban settings where narrow roads may be lined with parked cars.

The last scenario involves a fast lane change at highway speeds where the tractor-trailer undergoes high speed negative offtracking. This is a well understood phenomenon for articulated vehicles engaged in evasive lateral maneuvers at highway speeds. This is the only situation in which negative offtracking is anticipated for standard tractor-trailers in typical driving conditions in the U.S.

These scenarios represent the range of kinematics and dynamics of articulation angle in combination tractor-trailers in typical driving conditions. Since tractors and trailers come in many sizes, considerations for their lengths must be made since this directly impacts the BSM information and potential for false alerts. Tractor and trailer sizes considered were limited to those available in the CCV-IT and V2V-MD projects, but represent a large proportion of existing vehicles in U.S. commercial fleets.

For the constant radius of curvature scenario, the likelihood of getting a false warning was maximized when the articulation angle between the two bodies was maximized. In turn, the articulation angle was maximized when the tractor wheelbase was minimized and the trailer wheelbase was maximized. This represented a worst case articulation angle for typical tractor-trailer combinations.

In the right hand turn scenarios, the articulation angle is a dynamic function of position in the turn path. The likelihood of getting a false warning depended on where the tractor was in the turn as well as what the articulation angle was at that point in the turn. The relationship between these two factors and the determination of which of the two factors was dominant depended heavily on the radius of curvature of the turn. In each case, the likelihood of getting a false warning was maximized when the articulation angle was maximized and the total straight-line trailer length was maximized.

For the fast lane change scenario, the likelihood of getting a false warning was maximized when the lane change time and distance were minimized and the articulation angle of the rear-most trailer was maximized. The tractor-trailer essentially acted as a pendulum, with the lateral motion of the tractor acting as an impulse input to the pendulum. A tractor with a shorter wheelbase was able to turn faster and should therefore result in a greater lateral impulse input to the trailer. A trailer with a shorter wheelbase would also result in a greater articulation angle for a given impulse input, but multiple trailers will amplify this effect down the longitudinal axis of the combined tractor trailer system.

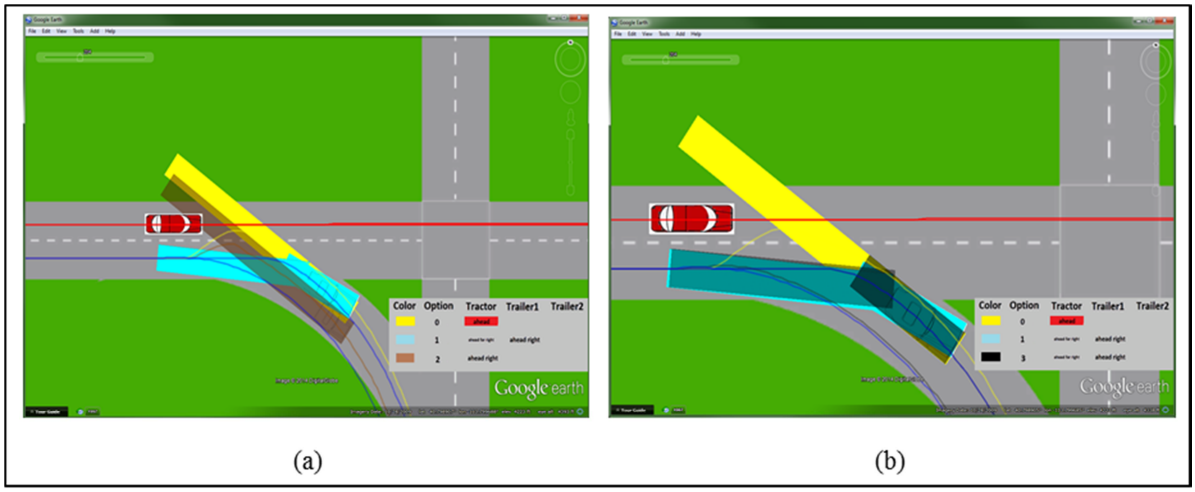
TruckSim was used in a co-simulation environment with Matlab/Simulink, as noted previously. A constant velocity target was sent from Simulink to TruckSim for each vehicle in each scenario. TruckSim then simulated the dynamics of the vehicle in the specific run case of the scenario. In all cases, the tractor-trailer was the remote vehicle, leading the host vehicle on the same road. The analysis required certain conditions, including the presence of vehicle articulation and the potential for collisions. As such, FCW proved most relevant to false alerts since articulation could be produced in turns and curved roads and collisions could be possible from a trailing vehicle. As such, the simulations evaluated the approaches against this specific safety application.

The output that TruckSim sent back to Simulink was a series of reference points that were attached to specific points on the vehicle bodies; most important were the volumetric centers of the vehicle bodies. Simulink/Matlab were then used to compute lateral offsets between HV and RV, RV path history, and lane boundaries so the HV could classify the RV target information. The Simulink/Matlab model was reconfigurable to run the baseline rigid body model or any of the other three approach models. Finally, the data were run through a model of FCW to determine if a warning occurred.

Tractor and trailer models were designed in TruckSim to match up with each of the scenarios and their various run cases. They were also designed to coincide with vehicles that may be available for live testing, where possible, so that TruckSim results could be compared to test results. This resulted in some cases where the tractor-trailer configuration that was optimal for trapping false warnings was not used.

In developing the models, another consideration further constrained the list of scenarios. The purpose of the fast lane change scenario was to trap the effects of high speed negative offtracking since this is the only scenario in which negative offtracking would be expected to occur. A model of a fast lane change was created in TruckSim to analyze this scenario. It was determined from simulations that a lane change would have to occur at an unreasonably fast and dangerous lateral speed in order to induce articulation angle dynamics that could have the potential for false warnings. As a result, the fast lane change at highway speeds was removed from the scenario list and was not considered further in this project.

The simulations showed that some approaches consistently performed better than others. Figure 3 shows examples of simulation results. In all cases, the tractor-trailer was the RV and a light vehicle was the HV. The tractor-trailer color varied by approach: yellow for the baseline rigid body, light blue for multi-DGPS, light brown for the best fit rigid body, and semitransparent black for the algorithm approach. Similarly colored lines were drawn to show the breadcrumb trails of the HV and RV. In all cases, the breadcrumb trails also precede the vehicles due to the limitations of pictures versus animations. Several of the approaches were overlaid in the same graphic in order to show comparisons. A legend was also included to indicate how the HV classified (e.g. ahead, ahead left, ahead right) each target (i.e. tractor, trailer1, and in cases with doubles, trailer2). In the cases where the classification is surrounded by a red border, the HV received an FCW warning for that target. Since both rigid body models (original and best fit) treat the tractor and trailer(s) as a single rigid body, the target classification in the legend is only reflected under the tractor column. It is important to note that the light blue, multi-DGPS approach was considered to be the most accurate method to determine the true pose of the tractor and trailer(s) since this relied on direct DGPS measurements for each. As such, the closer another approach lined up with the multi-DGPS representation and target classification, the more accurate and less likely to generate false alerts that approach was considered.



Source: Google Earth. Used with permission

Figure 3. Sample TT-BSM Simulation Results.

In Figures 3a and 3b, a tractor-trailer is making a right turn and a light vehicle is approaching it from behind in the adjacent lane. This represents the same simulation, but is split into two parts to provide better clarity. The baseline and multi-DGPS solutions remain the same in both, but Figure 3a includes the best fit rigid body approach, whereas Figure 3b shows the algorithm approach. In this case all non-baseline approaches perform better than the baseline since they did not warn inappropriately. From this example and many more similar results, it became clear that the multi-DGPS and algorithm approaches are superior to the baseline and best fit rigid body approaches. They track and classify the tractor and trailer(s) more accurately and do not cause FCW to falsely warn or fail to warn. The best fit rigid body does perform better than the baseline rigid body approach, but not nearly as well as the other two.

Testing

Road tests were designed to verify the accuracy of the proposed solutions to the articulated vehicle BSM problem. The tests enabled comparisons between actual recorded tractor and trailer data and the proposed enhancement to the BSM rigid body model. As part of this project, one of the above approaches was selected for further investigation and implementation. This was the algorithm approach. For comparison purposes, the study team also implemented the baseline rigid body and multi-DGPS approaches. The test system was designed such that multiple approaches could be tested on the road simultaneously. This was the surest way to develop comparable results without having to focus undue energies on precise repetition of test parameters.

Three scenarios were used for testing: constant radius curve, multilane right turn, and single lane right turn. These were based on the simulation scenarios and optimized for a test track environment. The Constant Radius Curve scenario simulated a freeway cloverleaf or other long/wide curve road geometries. This was a steady state scenario in which the truck followed a curved path of constant radius. The centerline of the path driven by the tractor-trailer had a curve radius of 30m. The Multi-lane Right Turn scenario simulated typical wide intersection road geometries in which a truck driver could have multiple lanes available to execute a turn without entering the opposing lanes of travel. A turn radius of 20m was used. This scenario required the use of two, two-lane roads forming a perpendicular intersection. The Single Lane Right Turn scenario simulated the wide-turn strategy truck drivers utilize when turning in very constricted road geometries. In this circumstance it was necessary for the truck to encroach on neighboring lanes, sometimes oncoming, in order to execute a turn such that the trailer does not off-track onto a sidewalk.

Table 1 shows results for tests conducted in this project where a warning was expected. A ‘pass’ meant that a warning was generated when it should have and a ‘fail’ meant that a warning did not occur as it should have. Each cell represents a separate test run. It is clear that the algorithm approach performed best while the rigid body baseline approach fared the worst. This is in line with the simulation results, though the multi-DGPS approach was expected to have better performance. During some of the testing, DGPS readings were inconsistent and may account for the multi-DGPS test failures.

Table 1. Test Results.

	Multi-lane Right Turn					Single Lane Right Turn					Constant Radius Curve				
Rigid	Fail	Fail	Pass	Fail	Pass	Fail	Fail	Pass	Pass	Fail	Pass	Fail	Fail	Fail	Fail
Multi-DGPS	Fail	Pass	Pass	Pass	Pass	Pass	Pass	Fail	Fail	Pass	Pass	Fail	Pass	Pass	Pass
Algorithm	Pass	Pass	Fail	Fail	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

In addition to road testing, a general assessment of the approaches was conducted in order to determine whether other factors may influence the results and either strengthen or undermine the algorithm approach effectiveness. Table 2 contains the summary of this general assessment. Each approach was compared based on various implementation factors. These included potential changes to the BSM structure, the accuracy of tractor and trailer positional representation, additional sensor measurements, changes to computational load, and changes to V2V safety applications. While no approach was perfect in all categories, the algorithm approach performed well and did not impose an insurmountable burden for implementation. Data frames and elements must be defined and added to the BSM Part II structure and some changes are required in supporting V2X software modules, but none of the V2V safety applications required modification for this project. The algorithm approach BSM is backward compatible with existing V2V safety applications, though these will only decipher the tractor information. Vehicles receiving the enhanced BSMs will need to understand the new data frames and elements in order to correctly act on the information they contain.

Table 2. General Assessment of Approaches Relative to Implementation Factors.

		Communication Changes		Representational Accuracy		Required Knowledge		Tractor Calculations	Trailer Calculations	Application Changes
Approach	**Description**	Change to BSM Part I	BSM Part IIs	Tractor Pose	Trailer Pose	Real-Time Hitch Angle	Real-Time Beta Angle	Tractor Pose	Trailer Pose	HV's Target Classifier
Baseline Rigid	Default - single rigid-body, fixed on the tractor	None	0	Good	Poor - no off-tracking	No	No	None	None	None
Multi-DGPS	Two separate bodies, exactly matching tractor and trailer poses	Limited to tractor only	1	Good	Good	Yes	Yes	Heading (beta angle)	Heading (articulation angle)	Must track two bodies
Best Fit Rigid	Single rigid-body, best fit in curve with weighted average of bodies	None	0	Fair - incorrect lateral location	Fair - partial off-tracking	Yes	No	Lateral Location	Lateral location	None
Algorithm	Two separate bodies, estimate tractrix of the curve of trailer	Limited to tractor only	1	Good	Good	No	No	None	Heading (articulation angle)	Must track two bodies

Basic Safety Message Enhancements

The BSM format is specified as part of the SAE J2735 DSRC Message Set standard. [7] A BSM consists of data elements (DEs) and data frames (DFs). A data element is a basic building block and a data frame comprises one or more data elements or other data frames. Data elements and data frames can be used to form BSMs similar to words in a sentence. For this reason, the SAE J2735 standard is often referred to as the data dictionary for V2V communications. Although BSMs are intended for use over the 5.9 GHz DSRC spectrum, their specification is independent of any frequency bands and they can be effectively used in other communication contexts. It is generally accepted that broadcasting BSMs at 10 Hz is sufficient to meet the requirements of the most demanding V2V safety applications.

The BSM format was carefully designed to minimize the message size. Smaller messages can help reduce DSRC channel congestion. To keep BSM sizes small, their content is structured into two parts. Part I – known as Basic Vehicle State – is mandatory and contains those data elements and data frames that must always be included in a BSM. BSM Part I has a fixed size of 39 bytes.

Table 3. BSM Part I Data Elements and Data Frames.

BSM Data Item	Sequence	BSM Part	Type	Bytes
Message ID		I	Data Element	1
Message Count		I	Data Element	1
Temporary ID		I	Data Element	4
Time		I	Data Element	2
Latitude	PositionLocal3D	I	Data Element	4
Longitude		I	Data Element	4
Elevation		I	Data Element	2
Positioning Accuracy		I	Data Frame	4
Transmission & Speed	Motion	I	Data Frame	2
Heading		I	Data Element	2
Steering Wheel Angle		I	Data Element	1
Accelerations		I	Data Frame	7
Brake System Status	Control	I	Data Frame	2
Vehicle Size	VehicleBasics	I	Data Frame	3

Part II, which includes the Vehicle Safety Extensions and Vehicle Status data frames, is optional. Typically, vehicles periodically broadcast BSM Part I only: specific events, such as emergency braking and control loss, can be described by setting the corresponding event flag in BSM Part II.

The Tractor-Trailer Basic Safety Message (TT-BSM) project developed BSM extensions to accurately represent articulated vehicles in V2X communications to reduce the potential for false warnings in the DSRC-based safety applications developed as part of the previous Connected Commercial Vehicle – Integrated Truck (CCV-IT) and

Connected Commercial Vehicle – Retrofit Safety Device (CCV-RSD) projects. When creating extensions to the current BSM format, several design goals were considered. In particular, special efforts were made to:

- accurately represent the position of articulated vehicle bodies in V2X BSMs
- minimize false warnings in nearby V2X-equipped vehicles
- minimize changes to the current SAE J2735 BSM structure
- minimize changes to existing V2X safety applications and equipment

The algorithmic approach from the proposed solutions produced by the TT-BSM project was selected since it met the goals better than the other solutions. In the algorithmic approach, the trailer dynamics during a turn maneuver are calculated in real-time. The trailer hitch point is fixed to the tractor hitch point. The yaw rate of the tractor is derived from GPS; this is translated into a lateral velocity at the hitch point; and this is translated into a yaw rate of the trailer. The trailer yaw angle is then numerically integrated from the trailer yaw rate. The trailer heading and center location are then calculated from the available geometry. A significant advantage of this approach is that no extra sensors are required. In initial testing and simulations, it performed nearly as well as the multi-DGPS solution without the associated long-term costs and complexity of the multi-DGPS solution. It can effectively represent vehicle articulation in multiple tractor-trailer configurations and in several representative scenarios, far better than the existing rigid body approach. Also, it is implementable with reasonable changes to supporting software modules without affecting the function of the safety applications.

With the algorithmic approach, no changes are necessary to BSM Part I, which remains a fixed size of 39 bytes. This ensures a high degree of backward compatibility with existing V2X systems. A new data frame, *DF_TrailerInfo*, is introduced to describe the trailer position and heading. The *DF_TrailerInfo* data frame is optional and is to be included in BSM Part II only when necessary, e.g. when one or more trailers are attached to a tractor. *DF_TrailerInfo* is comprised of a *DE_TrailerCount* data element and one or more *DF_TrailerDetail* data frames, depending on the number of trailers. *DE_TrailerCount* is a new data element that indicates how many *DF_TrailerDetail* data frames follow. *DE_TrailerCount* represents the number of trailers attached to the tractor. Each *DF_TrailerDetail* data frame is formed by elements and frames that are part of the existing BSM specifications.

Table 4. DF_TrailerDetail Items.

DF_TrailerDetail Item	Sequence	Type	Bytes
Latitude	PositionLocal3D	Data Element	4
Longitude		Data Element	4
Elevation		Data Element	2
Positioning Accuracy		Data Frame	4
Transmission & Speed	Motion	Data Frame	2
Heading		Data Element	2
Steering Wheel Angle		Data Element	1
Accelerations		Data Frame	7
Brake System Status	Control	Data Frame	2
Vehicle Size	VehicleBasics	Data Frame	3
Path History		Data Frame	Varies
Path Prediction		Data Frame	Varies
Vehicle Height	VehicleData	Data Element	1
Bumpers Heights		Data Frame	2
Vehicle Mass		Date Element	1
Trailer Weight		Data Element	2
Vehicle Type		Data Element	2

If any trailers exist, then the correspondent *DF_TrailerInfo* data frames shall be included in BSM Part II as necessary. *DF_TrailerInfo* will include as a minimum *DE_TrailerCount* and *DF_TrailerDetailOne*. The size of the *DF_TrailerInfo* data frame varies due to the inclusion of variable size frames such as Path History and Path Prediction and based on the number of articulations. Since the fixed portion of the *DF_TrailerInfo* data frame is 40 bytes, the resulting size roughly compares with the size of BSM Part I for a tractor with a single trailer. In case of multiple trailers, the size of this data frame could reach the double or triple of BSM Part I.

Introducing a new data frame for BSMs may raise concerns about increased over-the-air data traffic and consequent effects on channel load. Even if larger than BSM Part I, this is still a fairly small amount of data and it can be included in a single DSRC packet. It should also be noted that tractor-trailer vehicles represent a very small fraction of overall vehicles on the road.

Additionally, the position of the trailer needs to be described through BSM Part II only during turn maneuvers, which represent a small fraction of the driving time. When an articulated vehicle follows a straight path with small variations of the heading direction, it can describe its dynamics through the long rigid body model, thus broadcasting BSM Part I for a longer body. The onboard V2V system could continuously monitor the trailer articulation angle and adopt the strategy to broadcast BSM Part II only when this angle is larger than a certain threshold.

It should also be observed that the tractor-trailer combination broadcasting BSM Part I (to describe the tractor dynamics) and BSM Part II (to describe the trailer dynamics) contributes to channel load roughly equally to a pair of vehicles closely following each other and occupying the same space on the road. In other words, an articulated vehicle occupies a portion of the road that, in a congested traffic scenario, would be occupied by a pair of light vehicles broadcasting two BSM Part I messages to describe its dynamics. Based on all the above considerations, it can be concluded that introducing the proposed scheme to accurately describe the trailer position and heading does not result in additional over-the-air traffic able to significantly impact DSRC channel load.

CONCLUSIONS

This study investigated solutions to improve the tractor-trailer position algorithm used in the current BSM and proposed an enhanced BSM for articulated vehicles by integrating trailer information into Part II of the BSM. This approach was successful in transmitting this information to surrounding vehicles using V2V communications once trailer parameters were known While only tested with one safety application, the enhancement to the tractor-trailer body model is likely applicable to others as well. Further work on an automated method of obtaining trailer parameters may be necessary to fully implement this solution for articulated commercial vehicles in service.

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Probabilistic Prediction based Automated Driving Control in Urban Traffic Situation

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ABSTRACT
This paper represents an automated driving control algorithm in urban traffic situation. In order to achieve a development of a highly automated driving control algorithm in urban environments, the research issues can be classified into two things. One of the issues is to determine a safe driving envelope with the consideration of probable risks and the other is to achieve robustness of control performance under disturbances and model uncertainties. While human drivers maneuver a vehicle, they determine appropriate steering angle and acceleration based on the predictable trajectories of the surrounding vehicles. Therefore, not only current states of surrounding vehicles but also predictable behaviors of surrounding vehicles and potential obstacles should be considered in designing an automated driving control algorithm. In order to analyze the probabilistic behaviors of surrounding vehicles, we collected driving data on a real road. Then, in order to guarantee safety to the possible change of traffic situation surrounding the subject vehicle during a finite time-horizon, the safe driving envelope which describes the safe driving condition over a finite time horizon is defined in consideration of probabilistic prediction of future positions of surrounding vehicles and potential obstacles. Since an automated driving control algorithm is required to operate in a wide operating region and limit the set of permissible states and inputs, a model predictive control (MPC) approach has been used widely in designing an automated driving control algorithm. MPC approach uses a dynamic model of the vehicle to predict the future states of the system and determines optimal control sequences at each time step to minimize a performance index while satisfying constraints based on the predicted future states. Since the solving nonlinear optimization problem has computational burden, we design an architecture which decides a desired steering angle and longitudinal acceleration parallel to reduce the computational load. For the guarantee of the robustness of control performance, a robust invariant set is used to ensure robust satisfaction of vehicle states and constraints against disturbances and model uncertainties. The effectiveness of the proposed control algorithm is evaluated by comparing between human driver data and proposed algorithm.

I. Introduction

Recently, the interest of automotive industry changes from the passive safety system to the active safety system and, by extension, automated driving system due to advances in sensing technologies. For example, active safety applications, such as vehicle stability control (VSC), adaptive cruise control (ACC), lane keeping assistance (LKA) and lane change assistance (LCA) system, have been extensively researched [1]. In order to enhance safety and achieve zero fatalities, many researches have been undertaken to integrate individual active safety systems for the development of an automated driving system [2].

In developing an automated driving system which is required to operate in a wide operating region and limit the set of permissible states and inputs, MPC approach has been used widely because of its capability to handle system constraints in a systematic way [3], [4]. MPC approach uses a dynamic model of the plant to predict the future states of the system and determines optimal control sequences at each time step to minimize a performance index while satisfying constraints based on the predicted future states [5]. The first term of this optimal control sequences is applied to the system. At next time step, new optimal control sequences is calculated over a shifted prediction horizon. In [6], Falcone et al. present a MPC based active steering controller for tracking the desired trajectory as close as possible while satisfying various constraints. In this research, it is assumed that the desired trajectory over a finite horizon is known. Erlien et al. use a safe driving envelope which means a safe region of states in which the system should be constrained [7]. In this research, the safe driving envelope consists of a stable handling envelope to ensure vehicle stability and an environmental envelope to constrain the position states for the collision avoidance. The environmental envelope is defined based on the current states of surrounding environment of the subject vehicle. In order to compensate the effect on the control performance by model uncertainties and exogenous

disturbances, robust MPC approach which adds a linear feedback control input to the nominal control inputs based on the analysis of robust invariant sets have been introduced and used to design an autonomous control algorithm [8].

In order to develop a highly automated driving system, the research issues can be classified into two things. One of the issues is to enhance safety under the possible change of the behaviors of neighboring vehicles in the future. Human drivers maneuver the vehicle predicting possible surrounding vehicle's trajectories. Therefore, not only current states of surrounding environment of the subject vehicle but also predicted behaviors of surrounding environment should be considered to control the vehicle autonomously [9]. Furthermore, since probable behaviors of surrounding vehicles should be considered to prevent a potential collision accident in the future, a probabilistic prediction is required [10]. The other issue in designing an automated driving system is to achieve robustness of control performance under disturbances and model uncertainties due to inaccurate or time varying parameters [6].

In this research, we focus on designing an automated control algorithm which handles probable risky situations due to the possible change of traffic situation surrounding the subject vehicle while satisfying a robust control performance with respect to model parameter uncertainties and exogenous disturbances. In order to enhance safety with respect to the potential behaviors of surrounding vehicles, a safe driving envelope which describes the safe driving condition over a finite time horizon is defined in consideration of probabilistic prediction of future states of surrounding environment. Then MPC problem is formulated to determine the desired steering angle and desired longitudinal acceleration while maintaining the subject vehicle into the safe driving envelope. A tube-based robust MPC approach is used to guarantee robust performance under model uncertainties and exogenous disturbances.

This paper is structured as follows: The overall architecture of the proposed automated driving control algorithm is described in Section II. In Section III, the lateral dynamics model for the determination of the desired steering angle and longitudinal dynamics model for the determination of the desired longitudinal acceleration are derived briefly. In Section IV, probabilistic prediction of surrounding vehicle behaviors and the description of the safe driving envelope is described briefly. Then the controller is designed based on robust MPC approach in Section V. Section VI shows the vehicle test results for the evaluation of the performance of the proposed algorithm. Then the contribution of this research and introduction of future works are summarized in Section VII.

II. Overall Architecture

The overall architecture of the proposed automated driving control algorithm is shown in Fig. 1. In the integrated perception layer, the information which is required to determine the desired driving mode and safe driving envelope is refined using measurements from various sensors. In order to assess the driving situation precisely, states of the subject vehicle and surrounding vehicles should be estimated from various measurements via exterior sensors, such as vision and radar sensors. Then, the probable behaviors of the surrounding vehicles over a finite prediction horizon are predicted using the information of current states of surrounding vehicles. Using the estimated states of the subject vehicle and the ranges of probable behaviors of the surrounding vehicles over a finite prediction horizon, a desired motion or desired driving mode of the subject vehicle is determined in the risk management layer. Since the goal of the automated driving control algorithm proposed in this paper is to control the vehicle autonomously on the road, the required driving mode is classified into lane keeping and lane change mode. The desired driving mode is determined with the consideration of not only current states of traffic situation surrounding the subject vehicle but also predictable situations among the potential changes of traffic situation surrounding the subject vehicle. Then the safe driving envelope is determined based on the desired driving mode. Then the controller is designed to determine the desired steering angle and the desired longitudinal acceleration separately while satisfying reliability. Using robust MPC approach, the desired control inputs are determined to improve safety and ride comfort while satisfying constraints of states and inputs.

III. Vehicle dynamics model

In order to obtain the desired control inputs separately based on MPC approach, the lateral dynamics model and longitudinal dynamics model should be derived. In this research, the lateral dynamics model is designed by combining the bicycle model and error dynamics with respect to a road. Furthermore, the longitudinal dynamics model is designed by integrating the inter-vehicle dynamics and longitudinal actuator's dynamics.

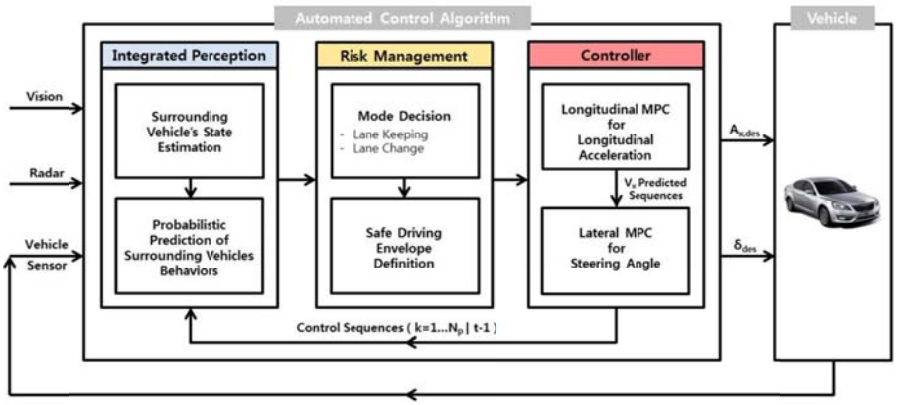


Fig. 1 Overall architecture of the proposed automated driving control algorithm

A. Lateral dynamics model

A classic bicycle model is usually used to design a lateral control law [3]. However, since an automated driving system should operate in a wide operating region, a classic bicycle model which assumes small slip angles of tires could not be suitable as a predictive model. On the other hand, if we use a nonlinear tire model to build a dynamic model, a nonlinear optimization problem should be solved at each time step. However, a computational burden to solve a nonlinear MPC problem is a critical barrier for its implementation [6]. In order to cope with this drawback, we apply a saturated linear tire model to reflect a tire saturation characteristic [11]. Then the bicycle model could be modified as follows:

$$\begin{bmatrix} \dot{\beta} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \delta_f \tag{1}$$

$$\begin{aligned} &a_{11} = -\frac{2k_{\alpha f}C_f + 2k_{\alpha r}C_r}{mv_x}, a_{12} = -1 + \frac{-2k_{\alpha f}C_f l_f + 2k_{\alpha r}C_r l_r}{mv_x^2}, \\ &a_{21} = \frac{-2k_{\alpha f}C_f l_f + 2k_{\alpha r}C_r l_r}{I_z}, a_{22} = -\frac{2k_{\alpha f}C_f l_f^2 + 2k_{\alpha r}C_r l_r^2}{I_z v_x}, \\ &b_1 = \frac{2k_{\alpha f}C_f}{mv_x}, b_2 = \frac{2k_{\alpha f}C_f l_f}{I_z} \end{aligned} \tag{2}$$

where, $k_{\alpha f}$ and $k_{\alpha r}$ are the cornering stiffness adjustment coefficients to reflect a tire saturation characteristic. These adjustment coefficients are assumed to be known exactly in this paper.

In order to control the vehicle in the lateral direction, the modified bicycle model is combined with the error dynamics which describes error with respect to a road. Therefore, the complete model used to design a MPC controller is defined as shown in (3) and a diagram of the vehicle model is depicted in Fig. 2.

$$\dot{x}_{lat} = A_{lat}x_{lat} + B_{lat}u_{lat} + F_{\rho,lat}\rho_{ref} \tag{3}$$

$$A_{lat} = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ v_x & 0 & v_x & 0 \end{bmatrix}, \ B_{lat} = \begin{bmatrix} b_1 \\ b_2 \\ 0 \\ 0 \end{bmatrix}, \ F_{\rho,lat} = \begin{bmatrix} 0 \\ 0 \\ -v_x \\ 0 \end{bmatrix} \tag{4}$$

where, the state vector is $x_{lat} = \begin{bmatrix} \beta & \gamma & e_\psi & e_y \end{bmatrix}^T$, the control input is $u_{lat} = \delta_{f,des}$, e_ψ is the orientation error of the vehicle with respect to the road, e_y denotes the lateral offset with respect to the center line of the lane, and ρ_{ref} is the road curvature.

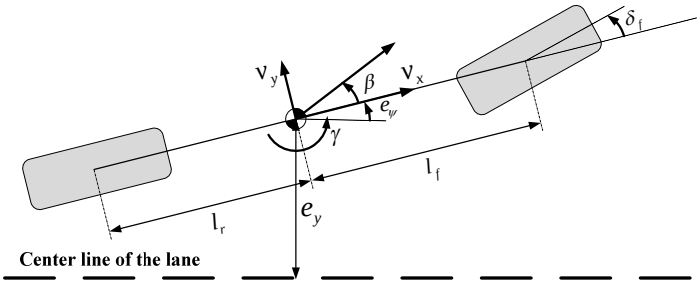


Fig. 2 Diagram of lateral dynamics model

In order to solve a receding horizon optimization problem, the continuous differential equation (3) should be discretized. (1) can be converted as follows:

$$x_{lat}(k+1|t) = A_{lat,d}(k|t)x_{lat}(k|t) + B_{lat,d}(k|t)u(k|t) + F_{\rho,lat,d}(k|t)\rho_{ref}(t) \tag{5}$$

$$A_{lat,d} = e^{A_{lat}T_s},\ B_{lat,d} = \left(\int_0^{T_s} e^{A_{lat}\tau}d\tau\right)B_{lat},\ F_{\rho,lat,d} = \left(\int_0^{T_s} e^{A_{lat}\tau}d\tau\right)F_{\rho,lat} \tag{6}$$

where, T_s is the sampling time. The system matrices of the lateral dynamics model, such as $A_{lat,d}(k|t)$, $B_{lat,d}(k|t)$, and $F_{\rho,lat,d}(k|t)$, are obtained using the predicted sequences of the longitudinal velocity during a finite time-horizon.

B. Longitudinal dynamics model

In designing a longitudinal dynamics model of the subject vehicle, an actuator delay between the desired longitudinal acceleration and the response of the actual longitudinal acceleration is considered as follows [11]:

$$a_x = \frac{1}{\tau_{ax}s+1}a_{x,des} \tag{7}$$

where, τ_{ax} is a time-constant chosen as 0.4 sec based on the analysis of the vehicle test platform.

In this research, two variables, such as distance error Δd and relative speed Δv_x, are used to define the inter-vehicle dynamics.

$$\begin{aligned} &\Delta d = C_x - C_{x,des},\ \ C_{x,des} = \tau_h \cdot v_x + C_{x,safe} \\ &\Delta v_x = v_{x,\text{target}} - v_x \end{aligned} \tag{8}$$

where, C_x and $C_{x,des}$ are the actual clearance and desired clearance between the subject vehicle and the target vehicle respectively, τ_h indicates the time gap, $C_{x,safe}$ is the minimum safety longitudinal clearance and $v_{x,\text{target}}$ is the longitudinal velocity of the target vehicle. In this research, in order to embrace driving characteristics of all of the drivers, the time gap, τ_h, is chosen as 1.36 sec which is the mean value of time gap for collected driving data in steady-state following situation [1]. Furthermore the minimum safety longitudinal clearance, $C_{x,safe}$, is chosen as 2 meters which is identical with the mean value of the clearance at the zero speed for all of the drivers [1]. The method how to select the target vehicle among the surrounding vehicle would be described in Section IV.

The derivative of the equation (8) could be derived as shown in (9)

$$\begin{aligned} &\Delta\dot{d} = \Delta v_x - \tau_h \cdot a_x \\ &\Delta\dot{v}_x = a_{x,\text{target}} - a_x \end{aligned} \tag{9}$$

Combining equation (7) and equation (9), the longitudinal dynamics model could be described as follows:

$$\dot{x}_{long} = A_{long}x_{long} + B_{long}u_{long} + F_{long}a_{x,\text{target}} \tag{10}$$

$$A_{long} = \begin{bmatrix} 0 & 1 & -\tau_h \\ 0 & 0 & -1 \\ 0 & 0 & -1/\tau_{ax} \end{bmatrix}, B_{long} = \begin{bmatrix} 0 \\ 0 \\ 1/\tau_{ax} \end{bmatrix}, F_{long} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{11}$$

where, the state vector is $x_{long} = \begin{bmatrix}\Delta d & \Delta v_x & a_x\end{bmatrix}^T$ and the control input is $u_{long} = a_{x,des}$.

As similar as the lateral dynamics model, the discretization of the continuous state equation (10) is conducted through the ZOH method as follows:

$$x_{long}(k+1) = A_{long,d}\, x_{long}(k) + B_{long,d}\, u_{long}(k) + F_{long,d}\, a_{x,\text{target}}(k) \tag{12}$$

$$A_{long,d} = e^{A_{long} T_s},\ B_{long,d} = \left(\int_0^{T_s} e^{A_{long}\tau} d\tau\right) B_{long},\ F_{\rho,long,d} = \left(\int_0^{T_s} e^{A_{long}\tau} d\tau\right) F_{\rho,long} \tag{13}$$

IV. Safe driving Envelope

Generally, human drivers monitor surrounding environment and predict the future states of surrounding environment based on the current states of that. Then drivers estimate the threat level of possible actions and decide the maneuver of the subject vehicle in consideration of the predicted states of surrounding vehicles during a finite time-horizon. Therefore, in order to develop a highly automated driving system, a safe driving envelope which indicates the drivable boundaries for safe driving over a finite prediction horizon should be determined with the consideration of not only current states of traffic situation surrounding the subject vehicle but also probable future states of that simultaneously [9]. Considering probable future states of surrounding vehicles, it could be expected that the automated driving control algorithm could handle probable risky situation during a finite time-horizon and enhance safety. Furthermore, if we define the safe driving envelope based on the probabilistic prediction, it is expected that an automated driving control algorithm which reflects human driver's driving characteristics with an acceptable ride comfort could be developed. Firstly, the method of the probabilistic prediction method is presented in Section III-A. Then the determination of the desired driving mode and the safe driving envelope is represented in Section III-B.

A. Probabilistic prediction of surrounding vehicle's behavior

One of common approach to predict the future states of traffic situation surrounding the subject vehicles is a deterministic prediction which assumes that the surrounding vehicles maintain its current movement during a finite time horizon. Since this approach ignores the probability of all possible movements of surrounding vehicles, this could cause incorrect interpretation of the current driving situation.

In order to compensate the shortcomings of the deterministic prediction of the behaviors of surrounding vehicles, the possible behaviors of surrounding vehicles are predicted and the risky behaviors among the possible behaviors of other vehicles surrounding the subject vehicle are considered in determining the safe driving envelope.

For the prediction of the reasonable and realistic behaviors of surrounding vehicles, the interaction between vehicles and the restriction on surrounding vehicle's maneuver due to the road geometry should be considered [12]. Moreover, it is assumed that drivers of the surrounding vehicles obey general traffic rules [13]. It means that the surrounding vehicle's behavior is assumed to keep the lane or change one lane at a time, not two or more lanes at a time. If one of surrounding vehicles changes the lane, then that vehicle is assumed to keep the relevant lane in the far-off future. Furthermore the violation of the centerline of surrounding vehicles is prohibited.

In predicting reasonable ranges of the future states of surrounding vehicles, driving data are collected on test track and real road to analyze the probabilistic movement characteristics of the vehicle [14]. For the implementation of these assumptions, a path-following model is designed while interacting with a vehicle state predictor during one cycle of the prediction process. In the vehicle state predictor, the vehicle's probable position and its error covariance over a finite time horizon are predicted by *Extended Kalman Filter* using the desired yaw rate obtained by the path-following model as the virtual measurement.

Fig. 3 depicts the overall architecture of probabilistic prediction of surrounding vehicles. Using measurements from the various sensors, such as vehicle sensor, radar and vision sensor, the range of the predicted states with corresponding uncertainty is determined as shown in Fig. 3. p_x is the longitudinal position of the vehicle, p_y is the lateral position of the vehicle, N_p denotes the prediction horizon, and subscript '*j*' means the *j*-th objects. In predicting the position of the surrounding vehicle, it is assumed that the size of the object is equivalent to the subject vehicle. The ellipse in Fig. 3 indicates the predicted probable range of the center gravity of the vehicle at the prediction time. A detailed description on the computational procedures to predict the probabilistic range of future states during a finite time horizon is described concretely in [10], [15].

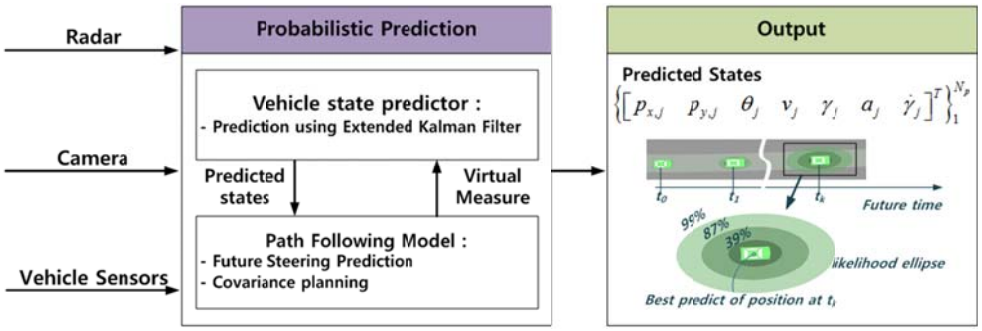


Fig. 3 Overall architecture of probabilistic prediction of surrounding vehicle's behavior

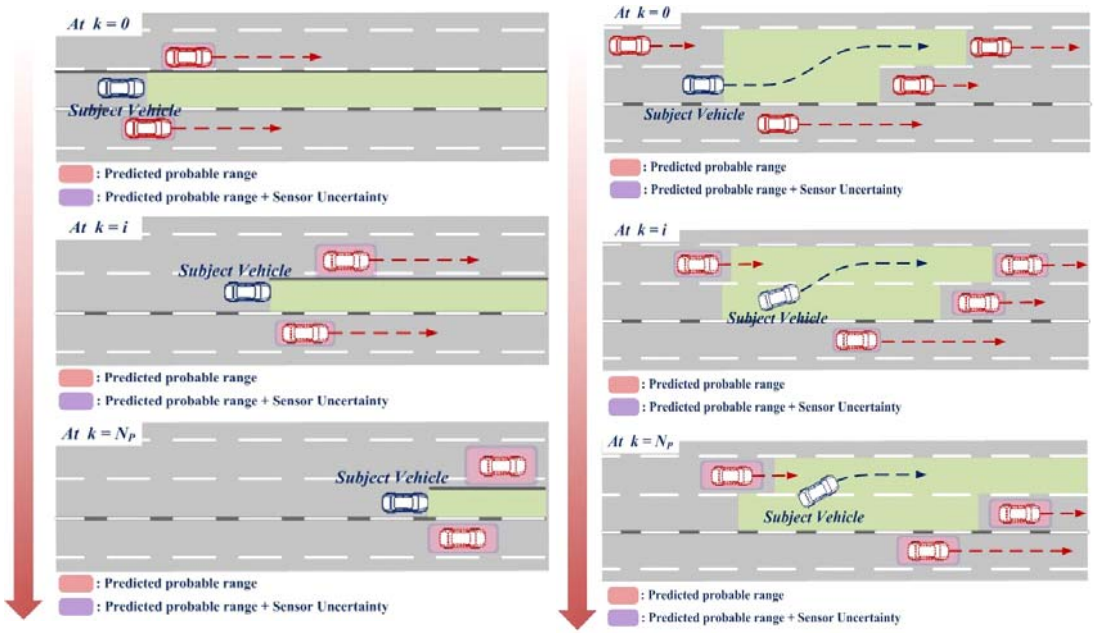
B. Driving mode and Environmental envelope decision

For the determination of the environmental envelope to improve safety, first of all, a potential risky situation should be considered. The risky situation among the probable behaviors of the surrounding vehicles could be classified roughly into three types. Firstly, if the preceding vehicle in the originating lane of the subject vehicle decelerates abruptly, then the potential risk of collision between the preceding vehicle and the subject vehicle would increase. Secondly, if the approaching vehicle in the adjacent lane accelerates during a lane change maneuver of the subject vehicle, then the collision between the approaching vehicle in the adjacent lane and the subject vehicle could be expected. Thirdly, there could be a potential risk of collision due to a sudden cut-in vehicle. Therefore, for the enhancement of safety, not only current states of surrounding environment of the subject vehicle but also these risky behaviors of the surrounding vehicles over a finite prediction horizon should be considered in determining the environmental envelope to improve safety.

Since the environmental envelope should be defined based on the desired motion, we should determine the desired motion or desired driving mode of the subject vehicle before the decision of the environmental envelope. The required driving mode could be approximately classified into lane keeping and lane change mode on an auto road. If there is no preceding vehicle in the originating lane which has a potential risk of collision during a finite prediction horizon, the desired driving mode could be determined as a lane keeping mode. In this case, the environmental envelope is determined to keep the originating lane while maintaining safety with respect to the surrounding vehicle. If the longitudinal or lateral clearances expected at the prediction time step k between the subject vehicle and surrounding vehicle are larger than predefined threshold value, then the collision risk is low and the environmental envelope for e_y is determined to prevent a lane departure. On the other hand, if the longitudinal or lateral clearances at the prediction time step k are expected to be smaller than thresholds, then the collision risk is high. Therefore the environmental envelope for e_y is determined to keep the originating lane while evading the approaching vehicle in the adjacent lane. The decision process of the environmental envelope for a lane keeping mode and the environmental envelope to keep the originating lane while maintaining safety with respect to the surrounding vehicles are described in Fig. 4-(a). In Fig. 4-(a), the pink rectangle indicates the region of the possible behavior of surrounding vehicles and the violet rectangle indicates the region of the possible behavior of surrounding vehicles with the consideration of sensor uncertainty.

On the other hand, there could be a preceding vehicle in the originating lane which has a collision risk during a finite prediction horizon or one of the surrounding vehicles in the adjacent lane is expected to change the lane into the originating lane of the subject vehicle during the prediction time horizon. In this case, the lane change of the subject vehicle from the originating lane to the adjacent lane might be required. Then the feasibility of the lane change and safety after the lane change should be considered. If there is no vehicle is in the adjacent lane when the lane change of the subject vehicle is required, then the lane change could be permitted. Otherwise, we should investigate the minimum longitudinal clearance between the subject vehicle and the vehicle in the adjacent lane to which the subject vehicle change the lane from the originating lane over a finite prediction horizon. If the minimum longitudinal clearance between the subject vehicle and the vehicle in the adjacent lane is larger than the minimum safety longitudinal clearance over a finite prediction horizon, then the collision between the subject vehicle and the vehicle in the adjacent lane would be avoided over a finite prediction horizon. Therefore, the lane change of the subject vehicle could be permitted and the desired driving mode could be determined as a lane change mode. On the

contrary, if the minimum longitudinal clearance between the subject vehicle and the vehicle in the adjacent lane is smaller than the minimum safety longitudinal clearance over a finite prediction horizon, there could be a collision between the subject vehicle and the vehicle in the adjacent lane during a finite time-horizon and the lane change of the subject vehicle should not be permitted. The decision process of the environmental envelope for a lane change mode is described in Fig. 4-(b).



(a) Lane keeping mode ***(b) Lane Chang mode***

Fig. 4 Decision process of the environmental envelope

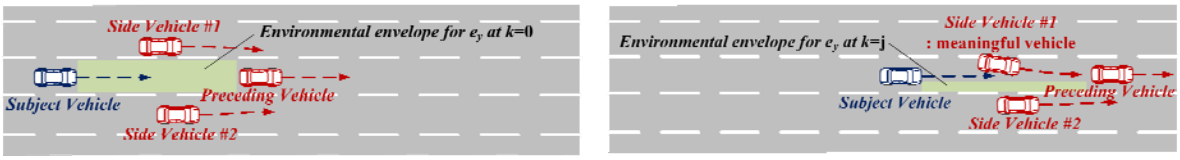
Consequently, the condition of limitation of the lateral deviation, e_y, to satisfying the environmental envelope can be written as follows:

$$\begin{aligned} &H_{env} \cdot x(k) \le G_{env,upper,bound}(k), \quad k = 1,\ldots,N_p \\ &G_{env,lower,bound}(k) \le H_{env} \cdot x(k), \quad k = 1,\ldots,N_p \\ &\textit{where,} \\ &\quad H_{env} = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{14}$$

Before the determination of the environmental envelope to guarantee the longitudinal safety, we need to define the state of the target vehicle for the control of the longitudinal acceleration. In the case of a lane keeping mode, if the width of the environmental envelope for e_y over a finite prediction horizon is large enough, it means that possible behaviors of surrounding vehicles in the adjacent lane are predicted to keep their lane. Then the preceding vehicle in the originating lane is chosen as the target vehicle for the control of the longitudinal acceleration. If there is no preceding vehicle in the originating lane or the clearance between the subject vehicle and the preceding vehicle is too far, then the virtual vehicle to follow the desired velocity is chosen as the target vehicle for the control of the longitudinal acceleration.

On the other hand, one of adjacent vehicles could be expected to approach to the originating lane of the subject vehicle or change the lane into the originating lane of the subject vehicle. In this case, the width of the environmental envelope for e_y could be smaller than minimum safety width. It means that the subject vehicle could not keep the lane only with the steering maneuver. Generally, when drivers recognize that the neighboring vehicle in the adjacent lane is entering into the lane of the subject vehicle, drivers generally tend to release the throttle pedal or apply the brakes to decelerate [16]. According to the previous research [16], the target vehicle is generated by combining the preceding vehicle in the originating lane and the meaningful vehicle in the adjacent lane. Based on this research, the clearance and relative speed between the subject vehicle and the meaningful vehicle in the adjacent lane are integrated with those between the subject vehicle and the preceding vehicle in the originating lane for the generation of the target vehicle's information. For instance, if the width of the environmental envelope for

e_y at the prediction time step j is expected to be smaller than minimum safety width as shown in Fig. 8, then the weighting factor, ω_{LK}, to determine the target vehicle's state for the longitudinal acceleration control is determined as shown in (15).



(a) Environmental envelope at the prediction time step k = 0 ***(b) Environmental envelope at the prediction time step k = j***

Fig. 5 Determination of the target vehicle for the longitudinal acceleration control in a lane keeping mode

$$\begin{aligned}\omega_{LK} &= f(n,\mathbf{Risk}), \qquad (0<\omega_{LK}\le 1)\\ &= \max\left(\max\left(\left.\frac{\min\left(TTC^{-1},TTC^{-1}{}_{th}\right)}{TTC^{-1}{}_{th}}\right|_n, 1-\left.\frac{\min\left(\mathbf{x},\mathbf{x}_{th}\right)}{\mathbf{x}_{th}}\right|_n\right)\right)\end{aligned} \tag{15}$$

where, TTC means the time to collision and $\mathbf{x}$ indicates the non-dimensional warning index [1]. n in (15) indicates the prediction time step at which the width of the environmental envelope for e_y is smaller than minimum safety width.

Consequently, the integration between the preceding vehicle in the originating lane and meaningful vehicle in the adjacent lane is defined as shown in (16).

$$\begin{bmatrix} C_x(t) \\ v_{x,\mathbf{target}}(t) \\ a_{x,\mathbf{target}}(t) \end{bmatrix} = \omega_{LK}\cdot\begin{bmatrix} C_{x,\text{meaningful}}(j|t) \\ v_{x,\text{meaningful}}(j|t) \\ a_{x,\text{meaningful}}(j|t) \end{bmatrix} + (1-\omega_{LK})\cdot\begin{bmatrix} C_{x,inlane}(t) \\ v_{x,inlane}(t) \\ a_{x,inlane}(t) \end{bmatrix} \tag{16}$$

In the case of a lane change mode, the target vehicle's states are determined by the integration between the preceding vehicle and the surrounding vehicle in the adjacent lane of the lane change direction. For instance, if the lane change direction is left, then the target vehicle's states are determined by the integration between the preceding vehicle in the originating lane and the surrounding vehicle in the left lane. The weighting factor for the integration in a lane change mode, ω_{LC}, is defined as shown in (17). Then the integration for the determination of the target vehicle's states to control a longitudinal acceleration during a lane change mode is defined as shown in (18).

$$\omega_{LC} = \frac{|e_y|}{2/3\cdot W_{road}}, \qquad (0<\omega_{LC}\le 1) \tag{17}$$

$$\begin{bmatrix} C_x(t) \\ v_{x,\mathbf{target}}(t) \\ a_{x,\mathbf{target}}(t) \end{bmatrix} = \omega_{LC}\cdot\begin{bmatrix} C_{x,sidelane,LC} \\ v_{x,sidelane,LC} \\ a_{x,sidelane,LC} \end{bmatrix} + (1-\omega_{LC})\cdot\begin{bmatrix} C_{x,inlane}(t) \\ v_{x,inlane}(t) \\ a_{x,inlane}(t) \end{bmatrix} \tag{18}$$

where, the subscript 'side-lane' means the vehicle in the adjacent lane to which the subject vehicle changes the lane from the originating lane and W_{road} is the road width which could be known from the vision sensor.

After the determination of the state of the target vehicle for the control of the longitudinal acceleration, then we could define the environmental envelope to guarantee the longitudinal safety. In order to avoid the collision over a finite prediction horizon, the clearance between the subject vehicle and the target vehicle should be larger than minimum safety longitudinal clearance, $C_{x,safe}$, as shown in (19).

$$C_x(k|t) \ge C_{x,safe}, \quad k=1,\ldots,N_p \tag{19}$$

To satisfy the condition described in (19), the constraint of the distance error between the actual clearance and desired clearance could be defined as follows:

$$\Delta d(k|t) \ge C_{x,safe} - C_{x,des}(k|t) = -\tau_h\cdot v_x, \quad k=1,\ldots,N_p \tag{20}$$

Moreover, for the improvement of the longitudinal safety, the relative speed between the subject vehicle and the

target vehicle should be larger than the threshold of the relative speed, $\Delta v_{x,\min}$, as shown in (21).

$$\Delta v_x(k|t) \geq \Delta v_{x,\min}, \quad k = 1,\ldots,N_p \tag{21}$$

Consequently, the environmental envelope to guarantee the longitudinal safety could be represented as the linear inequality as shown in (22).

$$H_{long} \cdot x_{long,d}(k|t) \geq G_{long,\min}, \quad k = 1,\ldots,N_p \quad where,\ H_{long} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix},\ G_{long,\min} = \begin{bmatrix} -\tau_h \cdot v_x \\ \Delta v_{x,\min} \end{bmatrix} \tag{22}$$

V. Robust MPC based Controller design

As mentioned in Section I, distributed control architecture which is composed of the lateral control law based on robust MPC approach and the longitudinal control law based on robust MPC approach is adopted. In this research, the sampling time, T_s, is chosen as 0.1 second and the length of the prediction horizon, N_p, is chosen as 20. These receding horizon optimization problems are solved at each time step and the first terms of the optimal control sequences are applied to the system. Then receding horizon optimization problems for a shifted prediction horizon are solved to obtain new optimal control inputs at next time step. To solve MPC problem in MATLAB, CVXGEN which is designed to be utilizable in MATLAB is used as solver [17]. The MPC problem is defined using CVXGEN syntax, and the CVXGEN returns convex optimization solver for the defined optimization solver for the defined optimization problem.

A. Background on Robust Model Predictive Control

In this section, we present the background on robust MPC which is used to decide the desired control inputs for the robust control performance. The control problem based on robust MPC is classified into a feedforward control input for the nominal system and a linear feedback control input to reduce the error between the actual state and the nominal state predicted by model of the plant.

Then the control law can be written as follows:

$$u(k) = \bar{u}(k) + K(x(k) - \bar{x}(k)) = \bar{u}(k) + Ke \tag{23}$$

where, $K \in \mathbf{R}^{m \times n}$ is the linear state feedback gain and $e := (x(k) - \bar{x}(k))$ is the error between the actual state and the predicted nominal state. In this paper, the control law of the state feedback gain is LQR.

B. Desired Steering Angle Decision

As mentioned above, in order to obtain the desired steering angle to keep the vehicle in the safe driving envelope while satisfying the robustness of the control performance under model uncertainties and exogenous disturbances, a feedforward steering input for the nominal lateral dynamics model and a feedback steering input for the compensation of the error between the actual states and the predicted nominal states should be integrated. For the determination of a feedforward steering input, we design the cost function as follows:

$$J = \sum_{k=1}^{N_p-1} \bar{x}_{lat}(k|t)^T W_{\text{cost},lat}\, \bar{x}_{lat}(k|t) + R_{lat,\Delta u} \sum_{k=0}^{N_p-2} \left\| \bar{u}_{lat}(k+1|t) - \bar{u}_{lat}(k|t) \right\|_2 + \left(H\, \bar{x}_{lat}(N_p|t) - y_{des} \right)^T W_{N_p} \left(H\, \bar{x}_{lat}(N_p|t) - y_{des} \right) + R_{lat} \sum_{k=0}^{N_p-1} \left\| \bar{u}_{lat}(k|t) \right\|_2$$

$$where, \quad H = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{24}$$

where, $W_{\text{cost},lat}$ is predefined weighting matrix, which penalize the differences between states and zero, W_{N_p} is predefined weighting matrix to reduce the differences between the final position of the vehicle over a finite prediction horizon and the desired position, R_{lat} and $R_{lat,\Delta u}$ are predefined weighting matrices for the reduction of magnitudes of steering angle control sequences and the rate of change in steering angle control sequences respectively. These matrices are positive-definite symmetric. W_{N_p} is defined as shown in (25).

$$\begin{aligned} y_{des} &= \begin{bmatrix} 0 & W_{road} \end{bmatrix}^T : \ Left\ \ Lane\ \ Change \\ y_{des} &= \begin{bmatrix} 0 & -W_{road} \end{bmatrix}^T : \ Right\ \ Lane\ \ Change \end{aligned} \tag{25}$$

Since the actuator has a limitation to operate, the control input and there derivatives need to be constrained. These constraints are given as follows:

$$\begin{aligned} &\left|u_{lat}(k|t)\right| \le u_{lat,\max}, && k=0\ldots N_p-1 \\ &\left\|u_{lat}(k+1|t)-u_{lat}(k|t)\right\|_\infty \le S_{lat}, && k=0\ldots N_p-2 \end{aligned} \tag{26}$$

where, $u_{lat,\max}$ is the maximum magnitude of the steering control input and S_{lat} is the maximum magnitude of the rate of change of the steering control input.

In order to ensure the stability of the vehicle, the side slip angle and lateral acceleration should be restricted for the stability of the vehicle. Therefore the condition for the stability of the vehicle can be written as follows:

$$\left|\beta(k|t)\right| \le \beta_{\max} = \tan^{-1}\left(0.02\mu g\right), \quad k=1,\ldots,N_p \tag{27}$$

$$\left|\gamma(k|t)\right| \le \gamma_{\max} = \frac{A_{y,\max}}{v_x}, \quad k=1,\ldots,N_p \tag{28}$$

where, μ denotes tire-road friction coefficient and $A_{y,\max}$ is the threshold of the lateral acceleration, which is chosen as 8m/s^2.

The constraints for the stability of the vehicle which are defined in (27) and (28) can be represented as the linear inequality as shown in (29).

$$\left|H_{veh}\cdot x_{lat}(k|t)\right| \le G_{veh,\max}, \quad k=1,\ldots,N_p \quad where,\ H_{veh}=\begin{bmatrix}1&0&0&0\\0&1&0&0\end{bmatrix},\ G_{veh,\max}=\begin{bmatrix}\beta_{\max}\\ \gamma_{\max}\end{bmatrix} \tag{29}$$

Then MPC problem for the determination of the feedforward steering input could be defined by combining (5), (14), (24), (26) and (29) as follows:

$$\begin{aligned} &\min\ (24) \\ &s.t.\ (5),(14),(26),(29) \end{aligned} \tag{30}$$

In order to design the robust MPC while reducing complexity, the effect of model parameter uncertainties and exogenous disturbances on the linear dynamics model in (5) is represented as an additive equivalent disturbance. Then the lateral dynamics model including the additional disturbance term is written as follows:

$$x_{lat}(k+1) = A_{lat,d}\,x(k) + B_{lat,d}\,u(k) + F_{\rho,lat,d}\,\rho_{ref}(k) + w_{lat,eq} \tag{31}$$

where, $w_{lat,eq} \in \mathbf{R}^{4\times 1}$ is the additive equivalent disturbance on the lateral dynamics model. The equivalent disturbance $w_{lat,eq}$ is unknown but assumed to be bounded as shown in (32).

$$w_{lat,eq} \in W_{lat},\ \left|w_{lat,eq}\right| \le \left[0.05, 0.05, 0.5\cdot\frac{\pi}{180}, 0.1\right]^T \tag{32}$$

C. Desired Longitudinal Acceleration Decision

Similar to the lateral control law, the longitudinal control law should be designed to obtain the desired longitudinal acceleration to keep the vehicle in the safe driving envelope while ensuring the robust control performance. Therefore the desired longitudinal acceleration is determined by combining a feedforward input for the nominal longitudinal dynamics model and a feedback input to attenuate the effect on the system by model parameter uncertainties or external disturbances.

In order to determine the feedforward control input for the longitudinal control of the vehicle, we design the cost function as shown in (33).

$$J_{long} = \sum_{k=1}^{N_p} \bar{x}_{long}(k|t)^T W_{\text{cost},long}\,\bar{x}_{long}(k|t) + R_{long}\sum_{k=0}^{N_p-1}\left\|\bar{u}_{long}(k|t)\right\|_2 + \left|\bar{u}_{long}(0|t)-a_x\right| + R_{long,\Delta u}\sum_{k=0}^{N_p-2}\left\|\bar{u}_{long}(k+1|t)-\bar{u}_{long}(k|t)\right\|_2 \tag{33}$$

where, $W_{\text{cost},long}$ is predefined weighting matrix for the minimization of the differences between states and zero, R_{long} is predefined weighting matrix to reduce the magnitudes of longitudinal acceleration sequences and $R_{long,\Delta u}$ is predefined weighting matrix to prevent abrupt change of longitudinal acceleration in sequences. These weighting matrices are positive-definite symmetric.

The constraints on the range of the longitudinal acceleration control input and change rate during a finite prediction horizon are written as follows:

$$\begin{aligned} &\bar{u}_{long,\min} \le \bar{u}_{long}(k|t) \le \bar{u}_{long,\max}, && k=0\ldots N_p-1 \\ &\left\|\bar{u}_{long}(k+1)-\bar{u}_{long}(k)\right\|_\infty \le \bar{S}_{long}, && k=0\ldots N_p-2 \end{aligned} \tag{34}$$

where, $\bar{u}_{long,\min}$ and $\bar{u}_{long,\max}$ are the minimum and maximum magnitude of the longitudinal acceleration control

input respectively. $\overline{S}_{long}$ is the maximum magnitude of the rate of change of the longitudinal acceleration control input.

Then MPC problem for the determination of the feedforward longitudinal acceleration input could be formulated by combining (10), (22), (33) and (34) as follows:

$$\begin{aligned} &\min\ (33) \\ &s.t.\ (10),(22),(34) \end{aligned} \tag{35}$$

In order to determine a feedback control input for the longitudinal control of the vehicle, an additive equivalent disturbance is included in (10) to represent the effect on the system by model parameter uncertainties or external disturbances.

$$x_{long}(k+1) = A_{long,d}x_{long}(k) + B_{long,d}u_{long}(k) + F_{long,d}a_{x,\text{target}}(k) + w_{long,eq} \tag{36}$$

where, $w_{long,eq} \in \mathbf{R}^{3\times1}$ is the additive equivalent disturbance on the longitudinal dynamics model. Similar to the equivalent disturbance on the lateral dynamics model, it is assumed that the equivalent disturbance on the longitudinal dynamics model, $w_{long,eq}$, is unknown but bounded as shown in (37).

$$w_{long,eq} \in W_{long},\ \left|w_{long,eq}\right| \le [0.05, 0.1, 0.05]^T \tag{37}$$

VI. Vehicle test results

The proposed automated driving control algorithm is evaluated through computer vehicle tests. In order to evaluate the proposed algorithm on a real test vehicle, Hyundai-Kia Motors K7 is used as a test vehicle platform. Figure 6 shows the test vehicle configuration. In order to measure DLC, heading angle and road curvature, a Mobileye camera system is equipped on the test vehicle. The proposed algorithm has been implemented on "dSPACE Autobox", which is used for the real-time application and equipped with a DS1005 processor board. Delphi radars are equipped on the test vehicle to perceive surrounding environments. The hardware components mentioned above communicate through a CAN bus.

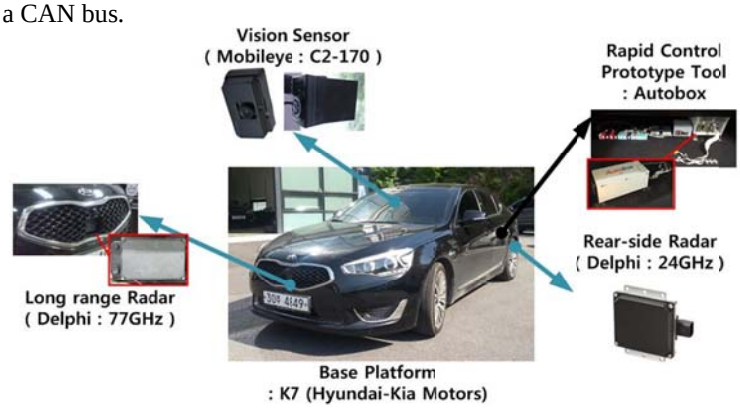


Fig. 6 Test vehicle configuration

The test track is a straight road. The road-tire friction coefficient is assumed to be 0.85, since the road of the test track is a dry asphalt road. Two cases of experiments have been conducted. In order to evaluate the performance of the proposed algorithm under lane change situation, the scenario of experiment is designed to evaluate the performance of the proposed algorithm under overtaking situation as shown in Figure 7.

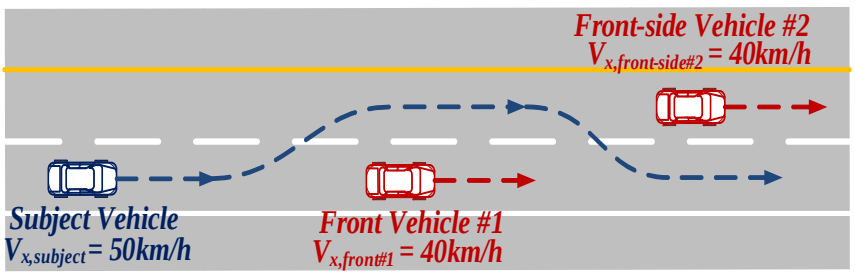
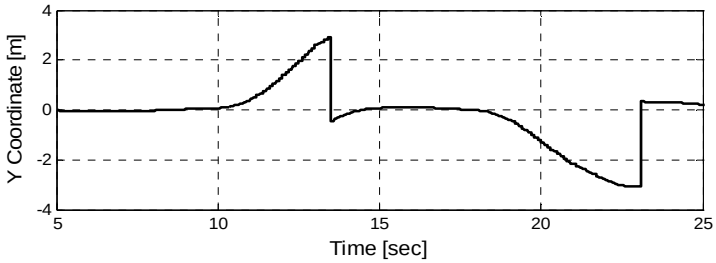
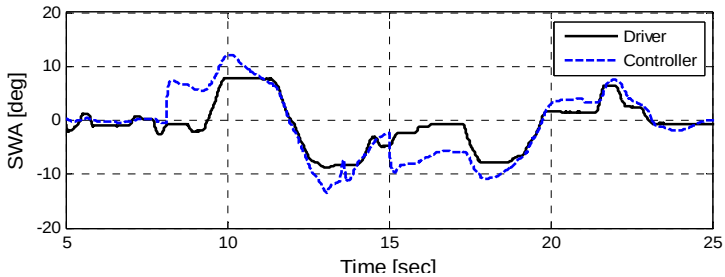


Fig. 7 Experiment scenario for overtaking

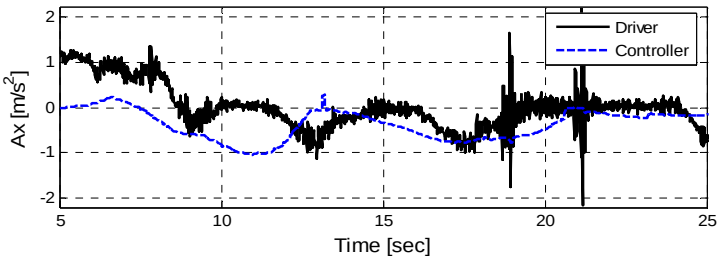
The simulation results are presented in Figure 8. As shown in Figure 8, it can be known that the controller shows quite similar performances to the human driver while changing lane. Based on these results, it has been shown that the proposed algorithm could reflect human driver's driving characteristics. It means that the proposed algorithm could provide acceptable ride comfort in general driving situations. Since lateral offset is measured by camera sensors, lateral offset is plotted as discontinuous as shown in Figure 8-(a). Figure 8-(b) and (c) depict steering angle and longitudinal acceleration comparing results between the human driver and the controller. Lateral acceleration has reasonable magnitude as shown in Figure 8-(d).



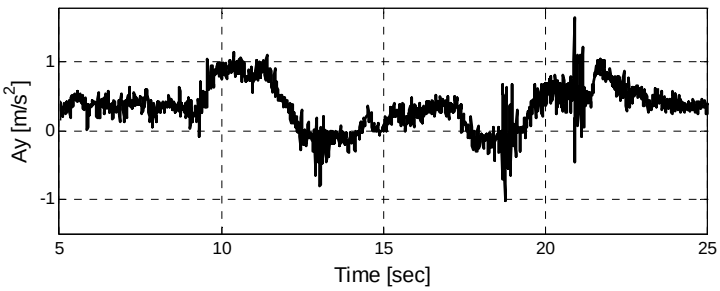
(a) Lateral offset



(b) Comparison of the steering angle between the driver and the controller



(c) Comparison of the longitudinal acceleration between the driver and the controller



(d) Lateral acceleration

Fig. 8 Comparison between the driver and the proposed algorithm under overtaking situation

VII. Conclusion

A robust MPC based vehicle speed and steering control algorithm has been developed to enhance safety and ensure constraint satisfaction under model uncertainties and external disturbances. In order to cope with potential risky situation, not only current states of surrounding environment but also potential risky behaviors of that during a finite time horizon are considered simultaneously in determining the desired driving mode and the safe driving envelope. Then distributed control architecture based on robust MPC approach is used to determine the desired steering angle and desired longitudinal acceleration separately while satisfying reliability and reducing a computational burden.

In order to verify the effectiveness of the proposed control algorithm, computer simulations have been conducted. The simulation results show that the proposed control algorithm enhances safety with respect to the potential risk and provides permissible ride comfort. Furthermore it has been shown that robust vehicle control performance can be obtained in the presence of additional disturbances by using the proposed algorithm.

In the future, we should verify the performance of the proposed algorithm via vehicle tests.

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INTELLIGENT VEHICLES + INFRASTRUCTURE TO ADDRESS TRANSPORTATION PROBLEMS – A STRATEGIC APPROACH

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ABSTRACT

Transportation systems around the world are showing signs of strain, and safety, congestion, and energy usage are significant societal problems. In the past, transportation professionals have attempted to solve these problems through largely "siloed" approaches focused on vehicle crashworthiness, infrastructure design, or energy efficiency. These separate approaches have had success, however transportation problems continue to grow.

The University of Michigan has formed the Mobility Transformation Center (MTC) to create a consortium of industrial, government, and academic partners who comprise an ecosystem for enabling a future transportation system that leverages connected and automated technologies. This group has convened to define a potential ecosystem, identify and prioritize key research needs for enabling a holistic approach, identify key technology and policy hurdles with paths forward, identify business drivers and opportunities, as well as identify gaps in standards, testing, facilities, and risk management schemes. A key goal is to lay a foundation for, and demonstrate, a commercially viable connected and automated transportation system in Ann Arbor by 2021.

To achieve these goals, MTC is designing, building, and deploying significant test beds, facilities, and deployments so that real-world results can be incorporated into this process in a rapid fashion.

This paper presents a summary of current status and early results of this effort, to the extent that they are ready for dissemination. This includes a description of the role various industrial sectors may play in a future transportation system, as well as identified first-level research gaps.

Included is a high-level description of strengths and weaknesses of various technologies (vehicle sensors and communication, infrastructure sensors and communication, infrastructure operating systems, data systems, etc.) and their ability to address key transportation problems and opportunities.

Lastly, a summary of the current status of the physical test beds and deployments will be included.

The authors seek to further the discussion of the potential roles various transportation system components and industrial sectors, as well as the roles for government and academia. Additionally, the authors hope to generate meaningful discussion on the importance of a systems approach to solving key transportation problems, including proper technology planning, evaluation and deployment to ensure that results address the widest range of societal needs as possible.

INTRODUCTION

Transportation systems around the world are showing signs of strain, and safety, congestion, and energy usage are significant societal problems. In the United States 32,719 people were killed in motor vehicle crashes in 2013, and 2,313,000 were injured [1]. While these were decreased from 2012, motor vehicle crashes remain as a significant and persistent societal problem.

Similarly, traffic congestion is a well-known persistent problem in many U.S., and international cities, with significant impact on national economy and quality of life. It is estimated that congestion costs the U.S. over $120B annually, and causes 2.9B gallons of wasted fuel [2]. Unless unchecked, there are expectations that these costs and negative effects will increase as the population rises in the next 50 years.

In the past, transportation professionals have attempted to solve these problems through largely "siloed" approaches focused either on vehicle crashworthiness, infrastructure design, or energy efficiency. These separate approaches have had success, however transportation problems continue to grow.

New technologies including communication systems, automation, and "big" transportation data systems are being developed to address various problems. For the high-level strategic purposes of this paper, the following definitions are employed:

Connected – technologies that enable direct or indirect communication to and between transportation agents including vehicles, infrastructure, pedestrians, operation centers, and other entities. These include DSRC, cellular, Wi-Fi, satellite, and other media, and enable many applications and functions including navigation, driving information, infotainment, V2V, V2I, I2I, V2P (pedestrian), mapping, amongst others.

Automated Vehicles – technologies that enable automatic operation of some or all safety-critical control functions, including steering, throttle, braking, and motive power selection (forward, reverse, and other), and at various levels of occupant involvement or monitoring. Generally, the NHTSA-defined levels of automation will be used [3].

"Big" Transportation Data – data systems and technologies that gather, amalgamate, analyze, and report on numerous significant transportation and related data streams, such as vehicle-based data, telemetric data, fleet data, location data (to the extent that privacy is appropriately protected), operations data, maps, video data, weather, crash data, fuel usage data, amongst others. These systems must also address key components of cybersecurity and privacy.

The overarching premise is that a systems approach, encompassing all three technologies listed above, must be employed to ensure that society receives the maximum benefit from these technologies. Each of these are extremely complicated technologies, especially when applied to the very large scale of a national transportation system. If any of these are developed in isolation, we will not fully address the key needs of a future transportation system: safety, mobility, and energy efficiency.

As an example of this systems approach philosophy, MTC embraces the idea that these Connected and Automated vehicle technologies will not only function well together, but will developed simultaneously and be very complementary to maximize the functionality and benefit of each. MTC has subjectively considered the relative pros and cons of various applications of these technologies, and the results are shown in Table 1. Generally connected technology is relatively inexpensive, provides otherwise unavailable information on road partners and conditions, and provides a longer range "sensor" data compared to typical radar, camera, and lidar sensors. On the other hand, connected technology requires a

significant concentration of equipped vehicles/infrastructure, still relies ultimately on actions of human drivers, and can be perceived as a relinquishment of privacy.

Generally, automated technology can reduce dependencies on human action (and presumably error), doesn't rely on equipage of other vehicles, and has a high consumer interest. On the other hand for the highest levels of automation, the cost of sensors and onboard computing is quite high (which may limit broad adoption), the technology is not easily retrofitable and is not proven, and requires significant policy decisions and potentially changes for licensing, insurance, enforcement, etc.

	pros	cons
Connected		
V2V	proven effective for safety - avoiding collisions	relies on driver reaction
	inexpensive - can be applied on many vehicles	relies on other vehicles (critical mass)
	retrofittable	requires security system
	sees around corners	perception of privacy loss
	sees through fog/rain/snow	
	sees at longest sensor range	
	sees multiple vehicles ahead	
	knows much more about road partners	
+ V2I	enhances mobility thru adpative signal control	requires infrastructure investment
	enhances energy-use through eco routing/timing	requires added security system
	enables weather apps	further perception of privacy loss
	enables 0/1st level eco-driving	
	enables pedestrian detection in crosswalk	
	enables smart parking	
Automated		
AV	relies less on human intervention	expensive - can't be applied on many vehicles
	doesn't rely on other vehicles	technology not fully ready
	added driver convenience	not yet proven reliability
	high customer interest	not retrofitatable
	potential for improved safety, unproven	requires security system
	potential for improved eco-driving	requires policy decisions/changes
		unclear if all veh data can remain private/anonymous
		may add VMT due to convenience
Automated + Connected		
AV + V2V + V2I	all advantages above	most disadvantages above
	adds reliability to sensing & decision making	added cost
	enables platooning at close following distance	added proveout requirements
	enables safer lane changing and passing	requires comprehensive security system
	communicates locations of map changes/updates	
	communicates road construction / maintainence	
	enables 2/3/4th level eco-driving	
	enables L4 driverless (on most roads)	
all + V2P	enables safe urban operation around pedestrians	requires smart phone/device solution
	enables rapid retrofit system	

Table1.
Comparison of relative pros and cons of various applications of technologies.

MTC has also considered, albeit subjectively, the relative future potential capabilities for these technologies to deliver key benefits in the form of core transportation metrics, namely safety, mobility, environment, and convenience, shown in Table 2. Generally, both technologies provide some potential benefit in all of these categories, though primarily to lower costs and greater penetration, connected technology provides a greater portion of safety and mobility benefits. While automation, primarily due to

the ability to relieve the driver provides significant convenience, especially at the highest levels of automation. Both technologies may play an equal role in delivering environmental benefits, and future research programs should strongly consider inclusion of a focus on environmental and energy saving opportunities for these technologies.

Because of these significant benefits, and in spite of the challenges, MTC has concluded that it is very likely, perhaps necessary that both technologies continue to be developed and deployed, along with accompanying data systems. This dual development will take advantage of significant synergies between the technologies and provide significant opportunities for benefit in key transportation metrics. Ultimately the expectation is that the benefit will outweigh the investment costs in both vehicles and infrastructure.

		Safety	Mobility	Environment	Convenience
Connected					
V2V		5	2	2	1
V2I		1	5	3	2
Automated					
L2		2	1	2	1
L3		0	0	1	2
L4		2	2	2	4
Con+Auto		10	10	10	10

Table 2.
Relative benefit levels for Connected and Automated technologies.
(Higher number indicates increased benefit)

ESTABLISHING an ECO-SYSTEM

The University of Michigan has formed the Mobility Transformation Center (MTC) to create a consortium of industrial, government, and academic partners who represent a potential ecosystem for enabling a future transportation system. This group has convened to define a potential ecosystem, identify and prioritize key research needs for enabling a holistic approach, identify key technology and policy hurdles with ways forward, identify business drivers and opportunities, as well as identify gaps in standards, testing, facilities, and risk management schemes, all with the goal of fielding a significant demonstration of a working system in the next 6 years.

After surveying the current state of development of the above technologies, the following industries were identified as critical to a future transportation system:

- Auto and truck manufacturers
- Auto components and systems
- Telecommunications & communication services
- Consumer electronic devices

- Big data management and mapping
- Freight movement and logistics
- Traffic control systems
- Insurance
- Public transportation
- Payment systems
- Parking operations and systems

In parallel with industrial efforts, governmental bodies that have operational and jurisdictional roles at the national, state, city, and local levels are critical stakeholders. Lastly, academia must play a critical role in identifying, developing, and evaluating key technologies and as agents of change. Together, by including stakeholders from all of these realms, MTC has formed a true public-private partnership to further the technology, identify policy issues, and where needed, changes, spur innovation, provide living laboratories to test and evaluate technologies, and prototype an entire working system to identify at least one path forward to large-scale deployment.

KEY RESEARCH NEEDS

The MTC has undertaken an extensive effort to identify, understand, categorize, and prioritize the state of art of the three key technologies from the viewpoint of members and stakeholders. Based on this effort and the resulting state-of-art assessment, a number of research thrusts were identifed in two different categories:

Technology

- Connectivity (V2X)
- Automation
- Cybersecurity
- ITS Interoperability
- Data Analytics
- Human Factors
- Energy Use & Emissions
- Standards
- Regulatory Issues
- Compliance

Policy

- Congestion Management
- Consumer Acceptance
- Public Policy
- Urban Planning
- Infrastructure Design
- Social Implications
- Legal Issues
- Business Models
- Payment Methods

Based on the above research thrusts, MTC has collected, brainstormed, and refined a number of research questions that need to be addressed to enable an accelerated and meaningful step towards significant demonstration. This full list of research questions is too long to reproduce fully in this report. And of course not all of these research topics can be addressed at one time, or in the context of pre-competitive research. Therefore MTC, along with its Leadership Circle Members, has undertaken a prioritization effort to identify the first and most critcal research thrusts and research questions. These are shown below, in appropriate categories.

Connected Technologies

- What applications, beyond safety, bring day-one value to the users and stakeholders?
- How are safety benefits extended to all road users including pedestrians?
- What is the business model of connected infrastructure deployment?
- How will a full-scale Security Credential Management System (SCMS) function?

Vehicle Automation

- How can automated vehicle technology be tested and validated to determine readiness for deployment?
- What role does the built roadside infrastructure play in a connected + automated environment and specifically what upgrades or updates, if any, would be required?
- What role does the data and mapping infrastructure play in a connected + automated environment and specifically what upgrades or updates would be required?
- What is the process to achieve broad accepatnce and engagement with the community?

"Big" Transportation Data

- What are the key cybersecurity risks and needs for automated vehicles?
- What data sets are required for connected + automated vehicles and what will be the tools and analytical approach?
- What data should be collected, and how are they useful for different purposes?
- How can the data drive entrepreneurship and new business models?
- How can the data support product development?

Policy

- What any changes if any are required to our legal system to maximize the value to connected + automated? State vs. Federal, Shared liability regimes, etc.
- How will fault be assessed in Automated Vehicle (AV) crashes?
- What are the key privacy impacts of automated vehicles?
- Do we need an ethics decision-making model for vehicle automation?

Customer Acceptance

- How do you define and measure value & customer acceptance?
- How do you define and measure value for all stakeholders (municipalities, etc)?

Standards

- What are the gaps in standards gaps for CAVs? which are a priority?
- Are existing regulations impediments to testing of connected and automated vehicles?
- What is the role of simulation in the prove-out of automated vehicle standards?
- Is a new testing methodology required to test the safety of connected and automated vehicles (confirmation of good events)?

Societal Impacts

- What is the implication of AVs on traffic congestion and VMT?
- How does a fully evolved connected and automated environment impact congestion, mobility, energy, public health, etc?
- What is the behavioral and economic impact of automated transportation?
- How will AVs impact urban transportation and design?
- What are implications for AVs on the aging population?

MTC has begun conducting internally-funded research projects on some of these, and other, questions and topics. The first round of research results and tools will be available in the August 2015 timeframe, and the second round was kicked off in April 2015. Results will discussed at MTC Annual Congress, currently being scheduled for September 2015 in Michigan.

DEVELOPMENT and DEMONSTRATION PLANS

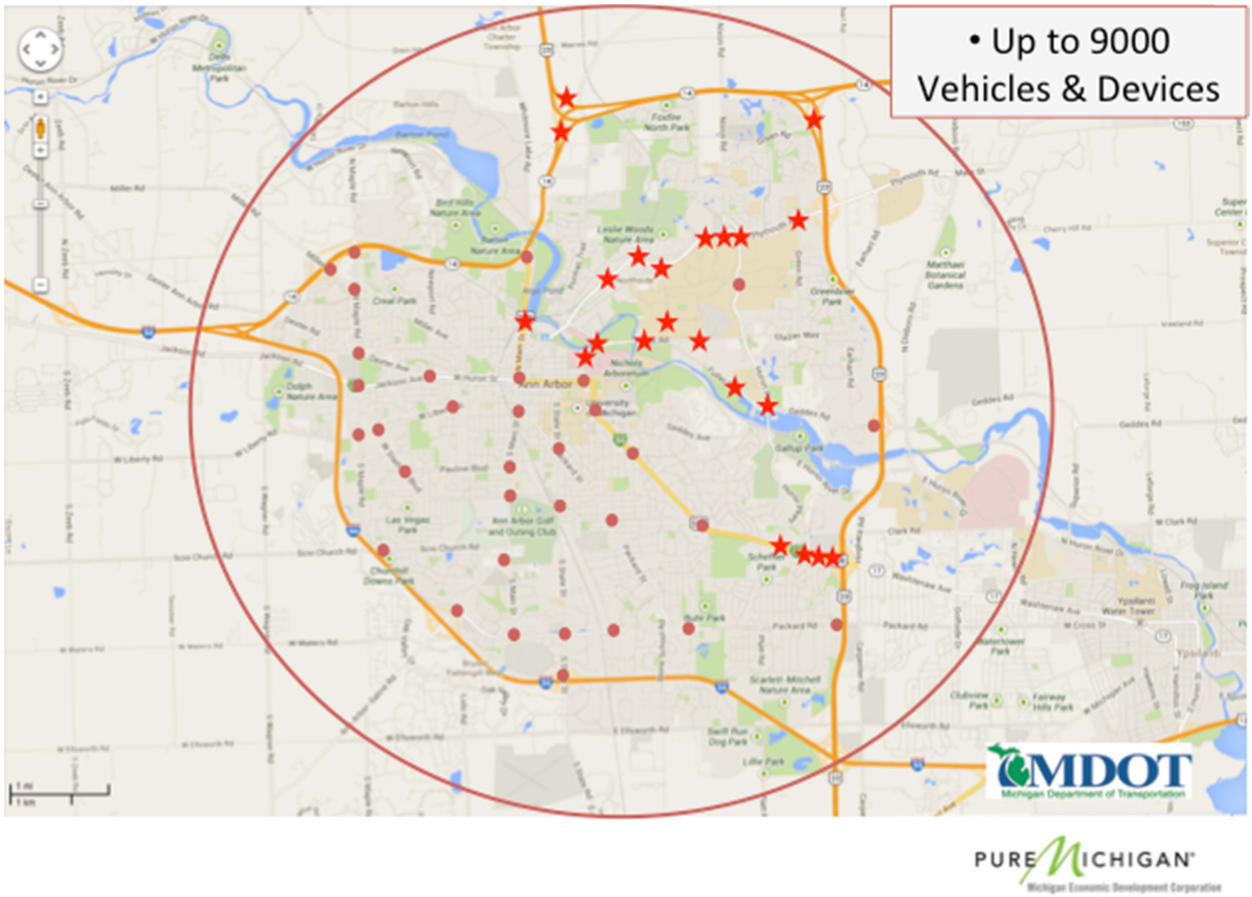
MTC believes that there are a number of significant, complex, and often intertwined questions and unknowns that need to be addressed to develop and deploy these technologies. These questions include those listed above, as well as many others. If left to standard, and individual, product research and development processes, these questions would likely require a decades-long product rollout. But given the significant potential benefits for transportation, MTC believes that these processes should be accelerated. MTC is promoting acceleration through collaborative efforts, and by fielding meaningful and ambitious model deployments to provide "living laboratories" and by creating unique purpose-built test facilities. MTC has undertaken work to build three "pillar" model deployments and one test facility.

Pillar 1: Connected Ann Arbor

MTC, with the collaboration of the City of Ann Arbor, will build on the success of the USDOT-funded Connected Vehicle Safety Pilot Model Deployment and expand that deployment up to 9,000 connected vehicles, and over 65 infrastructure nodes. This deployment will shift focus towards V2I applications, specifically those that can provide "day-one" benefits to drivers, road operators, cities, and importantly, vulnerable road users including motorcyclists, pedestrians and bicyclists. Figure 1 shows the geographic layout of this concept.

Pillar 2: Connected Southeast Michigan Initial Deployment

MTC, in a partnership with Michigan Department of Transportation (MDOT), member companies, and others, taking advantage of the region's uniquely large number of V2X activities and stakeholders, will create the first large scale connected transportation deployment in the United States. This deployment will leverage the MDOT Connected Corridor Program, as well as encompass the four existing test beds in the region, including Ann Arbor, Novi/Farmington, Telegraph Road, and City of Detroit. This deployment will focus also on V2I applications, especially to quantify benefit for road operators and municipalities for future investment decisions. Additionally, this deployment will support the auto industry by provding a dense connected environment to finalize development of V2V technology ahead of a NHTSA mandate. This deployment will also provide a unique opportunity to prototype and test a fully functional SCMS that can be scaled nationally. Lastly, this deployment will support early research and product development of AVs. Figure 2 shows the geographic layout of this concept.



- 60 Intersections • 3 Curve-related sites • 12 Freeway sites
- Over-the-air security • All DSRC communications logged
- Backhaul communication network • Back-end data

Figure 1.
Pillar 1: Connected Ann Arbor, MI

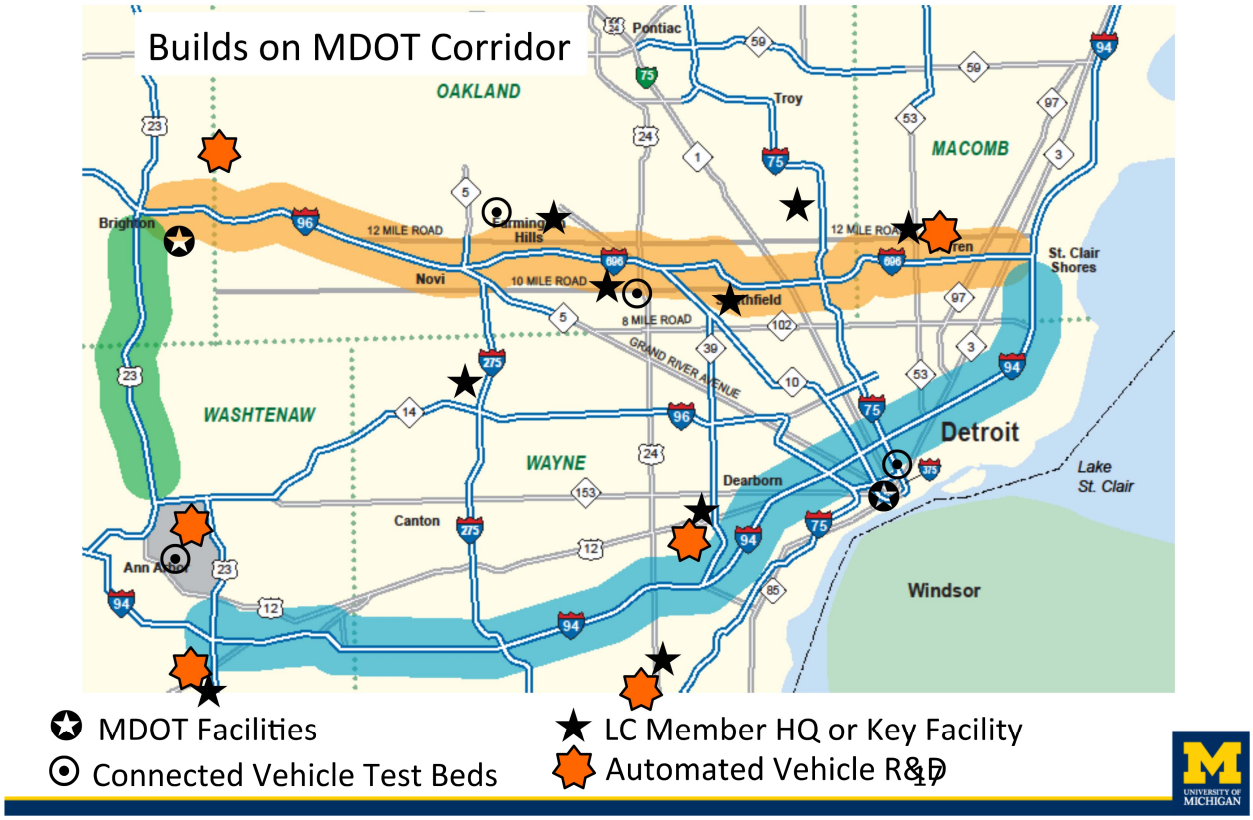


Figure 2.
Pillar 2: Connected Southeast Michigan Initial Deployment

<u>Pillar 3: Automated Ann Arbor</u>

MTC, in collaboration with the Leadership Circle of Companies, MDOT, and with the City of Ann Arbor, will utilize the dense connected Ann Arbor deployment to deploy an on-demand transportation service including 2,000 automated vehicles (AVs), including some number of levels 2, 3, and 4 vehicles. This transportation service will include the movement of people and goods, and will serve as a prototype for a future transportation system that will provide significant transportation benefits to the city and community. This deployment will include a fully-developed simulation platform (sensor, vehicle, driver, communications, infrastructure, environment) to complement the on-road environment. This deployment will leverage a to-be-developed "smart city" data and digital infrastructure, including backhaul and functions. It is expected that this deployment will also provide

an incredibly rich environment for product research and development, as well as addressing both technical and policy issues and questions.

Purpose-Built Test Facility: M City

MTC believes that a combination of both test track and on-road testing will be required for full development of high level AVs. Test tracks can provide a safe, controlled, and repeatable environment for early development without putting an unknowing public, especially pedestrians, at risk. And on-road testing is required because no track or simulation can anticipate the full plethora of conditions and scenarios that human drivers negotiate in the real world.

Therefore, MTC has designed and constructed a new, one-of-a-kind purpose built test facility for connected + and automated vehicles, named M City. This facility is designed to be a condensed, built to standard, simulation of a US city that will appear as a real environment to AV sensors. It is located directly adjacent to the Pillar 1 Connected Ann Arbor environment. Figure 3 shows the concept model of M City.

Figure 3. Conceptual model of M City.

M City includes an urban area with 13 intersection of various geometric designs, various road surfaces, curves of varying radii and elevation, round-about, traffic circle, building facades of varying geometry and materials, various traffic control devices and signage, pedestrian crossings and

bike lanes, street lighting, and mechanized pedestrians and bicyclists, amongst other features. It also includes a simulated highway stretch with on and off-ramps, multiple surface materials and markings, overhead and post-mounted signage, etc. Additionally, like the Automated Ann Arbor deployment, a full complement of simulations and tools will accompany the physical test facility.

Civil works and construction for this facility were completed in November 2014, with equipage of traffic control devices, lighting, and building facades scheduled at the time of this writing. The facility is expected to be fully operational by July 2015. Figure 4 shows an aerial photograph and layout of M City.

Figure 4. Aerial photograph of M City.

MTC and its private and public partners intend to utilize these deployments and this facility, and any others like it around the world, to conduct research and aid development of harmonized testing regimes, criteria, standards, and even future regulations that can speed the deployment of AV technology. MTC welcomes collaborations with other research and development stakeholders to achieve this goal.

CONCLUSIONS

MTC has been formed to accelerate the development and deployment of connected and automated vehicle technologies, and believes both will be needed, and are largely complementary, to achieve significant improvements in our future transportation system. Many significant technical and policy questions remain to be answered, and model deployments will be a powerful, and likely necessary, tool to address these questions and find a way forward.

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A MULTIPLE TARGET TRACKING STRATEGY USING MOVING HORIZON ESTIMATION APPROACH

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ABSTRACT

Tracking multiple road users is playing a significant role in autonomous vehicles and advanced driver assistance systems. Different from Multiple Target Tracking (MTT) in aerospace, the motion of the ground vehicles is likely constrained by their operational environment such as road and terrain. This information could be taken as additional domain knowledge and exploited in the development of tracking algorithms so as to enhance tracking quality and continuity.This paper proposes a new MTT strategy, Multiple Hypothesis Tracking using Moving Horizon Estimation approach (MHE-MHT), for tracking ground vehicles aided by road width constraints. In this strategy, tracking association ambiguity is handled by MHT algorithms which are proved as a preferred data association method for solving the data association problem arising in MTT. Unlike most of the MTT strategies, which solve target state estimation using Kalman filter (and its derivations), we propose a new solution using the moving horizon estimation (MHE) concept. By applying optimization based MHE, not only nonlinear dynamic systems but additional state constraints in target tracking problems such as road width can be naturally handled. The proposed MHE-MHT algorithm is demonstrated by a ground vehicle tracking scenario with an unknown and time varying number of targets observed in clutter environments. Using the optimal subpattern assignment metric, numerical results are presented to show the advantages of the constrained MHE-MHT structure by comparing it with the Kalman filter based MHT.

Keywords: Multiple target tracking, Multiple hypothesis tracking, Moving horizon estimation, Inequality constraints, Autonomous vehicles

INTRODUCTION

Multiple target tracking (MTT) is an important research topic in automated vehicle field. Although a number of MTT algorithms have been developed, e.g. [1], it is still a quite challenging task to implement MTT in realistic situations, especially when suffering from low visibility of sensors, high clutter and high target density. One promising approach that has drawn a great deal of attention recently is to improve the performance of tracking algorithms by utilizing trajectory and other constraints/knowledge imposed from environments including available road maps. It has become a consensus that prior nonstandard information such as target speed constraints, road network and terrain information can be exploited in the tracker to reduce estimaiton error and provide better tracking accuracy [2]. For instance, a vehicle travelling on a road is expected to move within the road boundaries and follow its speed limitation. In other words, the performance of tracking systems is often limited if ignoring or not taking use of this additional source of informaiton. Even for the cases of low signal quality with high clutter density, the incorporation fo such constaint information is sufficient enough to get a relatively good tracking performance [11].

A. Constrained state estimation

One effective approach of solving the road constrained MTT is to incorporate the constraint-related information into a standard filter algorithm (state estimation process) as state constraints. For most MTT structures, Kalman filtering and its variations are commonly used to estimate the state of a target based on its state process and measurement models. However, when the road state constraints cannot fit easily into the structure of a Kalman filter, they are often ignored or dealt with heuristically [3Although constrained Kalman filter methods are relatively easy in implementation, these methods have several disadvantages even for basic linear and equality constraints [3]. Recently, some other methods, for example, see [7], [8], [9], [10], are also developed based on optimization and truncation approaches. The majority of filters proposed to solve the constrained estimation problems focus on linear (in)equality or nonlinear equality constraints. A little research has been conducted on nonlinear inequality

constraints so far. However, (non)linear inequality constraints have played an important role for most tracking scenarios in ground vehicle tracking problems,, e.g. roundabout boundary.
More specifically, Rao et al. [10] have proposed a constrained state estimation for nonlinear discrete-time systems. It is based on a moving horizon concept based state estimation known as moving horizon estimation (MHE). The basic strategy of MHE in determining the optimal state estimation is to reformulate the estimation problem as an optimisation problem using a fixed-size estimation window. This method has been widely used in chemical engineering. Other applications include hybrid system, distributed, network system, large-scale system and so on. However, the implementation of moving horizon approach based estimation method in target tracking is still relatively an uncharted area. Advantages for using MHE to solve target tracking state estimation could be significant. Since the method is optimization based, road constraints or similar in target tracking problems can be naturally handled by MHE as additional (non)linear and/or (in)equality constraints on linear or nonlinear systems under consideration. In addition to state constraints, MHE is also able to incorporate constraints on the state process and/or observation noises. In vehicle tracking, such constraints are typically used to model bounded disturbance or truncated distribution/density representing the influence of the operation environment on vehicle movement such as vehicle acceleration and deceleration.
Another advantage of using MHE as a state estimation method in target tracking is that it always considers a window of N latest measurements. Such feature is very meaningful in target tracking problems especially when targets are occluded by each other/static obstacles which leads to no reliable measurement at specific time step/steps. MHE utilizes the measurements in a receding horizon window could reduce the effect of unreliable measurements such as in the above situation in state estimation. Simulation results in [4] show that MHE achieves the smallest estimation error for nonlinear systems and nonlinear constraints. Theoretically, for a linear system without constraints and with a quadratic cost, MHE reduces to Kalman filtering algorithms when an infinite horizon window is considered.

B. Multiple target tracking problem

The problem of estimating the position of moving targets, also known as MTT, has become an important part in autonomous vehicles and advanced driver assistance systems. Knowledge about the state of moving objects can be taken as powerful information to improve the level of autonomy for vehicles. MTT techniques are required in a number of automotive applications including Advanced Driver Assistance Systems (ADAS), Collision Avoidance Systems, and Vehicle-automation Systems. Such systems can incorporate functions such as adaptive cruise control, lane keeping, precise manoeuvring, pedestrian detection and so on [12] aiming for achieving an improved collision avoidance behaviour and safe road driving even in populated environments. By using state-of-the-art on-board sensors such like radar, lidar, GPS and camera vision systems together with accurate global and local maps, different levels of automation could be achieved in automotive applications, from individual autonomous functionalities to fully automated vehicles.
Several approaches for MTT have been developed over the last decades, overviews can be found in Pulford [13] and Christophe [14]. Basically, these methods can be divided into two categories – the data association based 'classic' methods and the more recent finite set statistics (FISST) based approaches. The data association based methods are largely based on probability, stochastic processes and estimation theory. Existing methods include Nearest Neighbour Standard Filter (NNSF) [15], Global Nearest Neighbour (GNN) approach [16], Joint Probabilistic Data Association (JPDA) [17] and Multiple Hypothesis tracking (MHT) algorithm [18]. Among them, MHE is a more complex approach that considers data association across multiple scans and multiple hypotheses. In other words, MHT algorithm attempts to keep all possible association hypotheses over multiple frames of data. This results in an exponentially growing number of hypotheses and thus a NP-hard problem. Cox [19] in 1997 developed an efficient implementation by using polynomial time optimization algorithm to find the k-best solutions to an assignment problem along with pruning and merging techniques to reduce the number of low probability hypotheses. MHT essentially keeps a set of multiple hypotheses and thus the assignment ambiguity will be resolved in future when subsequent new observations are arrived. In this case, hard decisions are not made until they need to be with the fact of using more information, rather than just the current data frame, thus possible error association could be corrected when more evidences are updated. Such features along with the dramatic increases in computational capabilities have made MHT a preferred data association method for modern systems [20].
Until very recent, a new concept has been introduced in MTT area - the random finite set statistics (FISST) [27]. While the conventional MTT methods try to solve the problem explicitly by expending single target tracking with data association capabilities, the number of targets is also considered as a random variable (random set) and explicit data association are avoided in FISST. The innovation of FISST is to model both the system and measurement as

random finite sets (RFSs) and directly apply the Bayes recursion to these set-valued random variables and thus solving the data association problem implicitly. In contrast to explicit data association methods, conventional probability-mass functions are replaced by belief-mass functions. Probability hypothesis density filter (PHD) [28] and multi-target multi-Bernoulli (MeMBer) [29] filter proposed by Mahler have successfully implemented the FISST concept into MTT.

The objective of this paper is to derive an efficient strategy for road-constrained MTT. The main contribution of this work is twofold: 1) a constrained MHE algorithm is proposed to solve the state estimation problem arising in road maps assisted target tracking. Since MHE is an optimization based method, it provides a natural way to handle nonlinear systems and incorporate various inequality constraints that may be difficult to be dealt with in other state estimation algorithms. 2) The work is further extended from single target tracking into MTT. A new MTT strategy for tracking multiple ground vehicles, namely MHE-MHT, is proposed, where moving horizon concept is combined with MHT to incorporate various road and other environment information. In this combined strategy, tracking association ambiguity is handled by MHT algorithms that have been proved as a preferred data association method while constrained state estimation is solved by MHE.

The paper is organized as follows. After presenting the introduction in road map constrained MTT, MHE based single target tracking is proposed for incorporating the road and other possible constraints. This work is further extended to MTT by combing with MHT in the following section In order to verify the efficiency of the proposed algorithms, simulation results of multiple target tracking with inequality road width constraints are presented . Finally, this paper ends with conclusions.

MHE BASED TARGET TRACKING WITH ROAD CONSTRAINT

In the operation of automated vehicles, it is necessary to track all the nearby road users to make sure the safety of the vehicles and other road users. Tracking road users is in fact a constrained estimation problem as the objects of interest must be on the road. In this section, both the road constrained state estimation problem and MHE based target tracking are described.

A. System specification

Consider the movement of objects of interest described by the discrete system:

$$x_{k+1} = f(x_k) + \omega_k \qquad (1)$$

and the observation equation:

$$y_k = h(x_k) + v_k \qquad (2)$$

where the time point k takes integer values, $f: \mathbb{R}^n \to \mathbb{R}^n$ is the nonlinear system function and $h: \mathbb{R}^n \to \mathbb{R}^m$ is the nonlinear measurement model. $x_k \in \mathbb{R}^n$ is the state vector, $y_k \in \mathbb{R}^m$ is the vector of available measurements. The vectors $\omega_k \in \mathbb{R}^n$ and $v_k \in \mathbb{R}^m$ are Gaussian noises of the process and the measurement described by independent pdfs $p(\omega_k) = N(0, Q)$ and $p(v_k) = N(0, R)$, respectively, where Q and R are covariance matrices. It is commonly assumed that the initial pdf of the state vector is known as a Gaussian pdf $p(x_0) = N(\tilde{x}_0, \tilde{P}_0)$. Let F_k, G_k and H_k be the Jacobian matrices with respect to x_k, ω_k and measurement states, respectively.. Then the system described in (1) and (2) is now equivalent to a linear system.

B. Target tracking road width constraints

As discussed in Introduction, ground targets are constrained when moving along a road network. Thus the knowledge of terrain database and road maps can be used as constraints and incorporated into the tracking algorithm. In most existing techniques, the road map constraints target motion in a one-dimensional physical space [30] (by ignoring the road width) and incorporate them as equality constraints. This is fairly good approach when an observer is far away from the moving objects such as in the scenario of unmanned aircraft tracking a ground vehicle. However in automated vehicles, only objects in proximity are of interests. The road width is comparable to the measurement accuracy (high accuracy sensors such as lidar). In this paper, road network information is considered as road width inequality constraints and the target motion is restricted by these physical constraints in both straight and curved segments.

<u>Linear state inequality constraints</u> Suppose that at each time step k, x_k is subject to the following linear inequality constraint:

$$a_k \leq C_k(x_k) \leq b_k \qquad (3)$$

where $C_k: \mathbb{R}^n \rightarrow \mathbb{R}^c$, a_k, $b_k \in \mathbb{R}^c$, and the inequality $\leq$ holds for all elements of the vectors and $a_k \neq b_k$, $\forall k$. C_k is a known $c \times n$ matrix, a_k and b_k are the known vectors each with a dimension of $c \times 1$ representing the lower and upper road boundary individually, c is the number of constraints, n is the number of states, and $c \leq n$. C_k is supposed to be of full rank. For target tracking with straight (linear) road width constraint shown in Figure 1, Eq (3) is expressed as:

$$\begin{bmatrix} -I \\ I \end{bmatrix} * T_{g,l}(x_k) \leq \begin{bmatrix} -ub \\ lb \end{bmatrix} \qquad (4)$$

where $T_{g,l}$ is known as the transformation matrix representing the rotation from the global coordinate to the road network local coordinate (with orientation along and orthogonal to the road) by rotation angle θ.

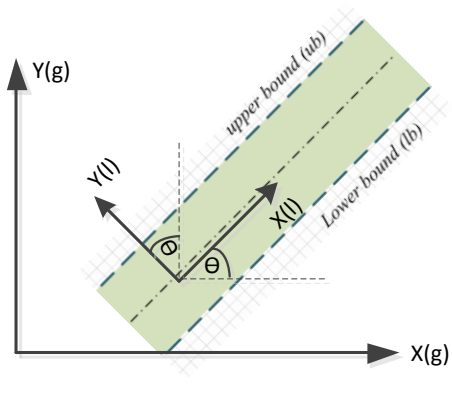

Figure 1. Straight road width linear constraint

<u>Nonlinear state inequality constraints</u> In the same fashion as the linear road width constraint shown in (3), a circular or curved road segment shown in Figure 2 can be represented as a nonlinear inequality constraint as

$$r_1 \leq \sqrt{{x_{1,k}}^2 + {x_{2,k}}^2} \leq r_2 \qquad (5)$$

The road is defined by two arcs with radii r_1 and r_2 representing the lower/upper road boundary, with the center at the origin of the Cartesian coordinate system. At each time step k, target position state $x_{1,k}$ and $x_{2,k}$ are subject to the following nonlinear inequality constraint

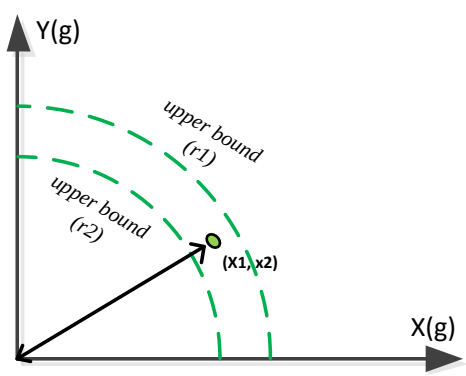

Figure 2. Curved road width nonlinear constraint

C. Moving horizon estimation with constraints

MHE is an optimization approach based state estimation method that can take into account the constraint during estimation process and provide a constrained estimate directly. Essentially, MHE follows Bayes rule which maximizes the probability density function of the past states given the measurements in a fixed length of horizon . Considering a horizon length of N past time steps, the joint conditional density is then given by:

$$p(X_N|Y_N) \propto p(Y_N|X_N)\, p(X_N|Y_{0:k-N-1}) \,, \qquad (6)$$

where $p(X_N|Y_{0:k-N-1}) = p(x_{k-N}, \dots, x_{k-1}|y_0, \dots, y_{k-N-1})$, is the *a priori* state density given the measurements before the horizon; $p(Y_N|X_N) = p(y_{k-N}, \dots, y_{k-1}|x_{k-N}, \dots, x_{k-1})$ is the joint measurement likelihood function. Assuming that X_N is a first order Markovian chain, the *a posteriori* joint conditional density of (6) is:

$$p(X_N|Y_N) = c \prod_{j=k-N}^{k-1} p\left(y_j\middle|x_j\right) \prod_{j=k-N}^{k-1} p\left(x_{j+1}\middle|x_j\right) p(x_{k-N}|Y_{0:k-N-1}) \,, \qquad (7)$$

where c is the constant and $p\left(y_j\middle|x_j\right)$ is the likelihood function for each measurement within the horizon. $p\left(x_{j+1}\middle|x_j\right)$ is the state transition probability density function and $p(x_{k-N}|Y_{0:k-N-1})$ is the *a priori* density of the initial state of the horizon. For system (1) and (2), the state transition pdf is defined as $p(x_{k+1} - f(x_k))$:

$$p(x_{k+1}|x_k) = p(\omega_k) = p(\mathrm{x}_{\mathrm{k}+1} - \hat{x}_{k+1}) = p(x_{k+1} - f(x_k)) \,, \qquad (8)$$

where ω_k is the system process noise defined by $N(0, Q)$, and the likelihood function is defined by $p(y_k - h(x_k))$

$$p(y_k|x_k) = p(v_k) = p(y_k - \hat{y}_k) = p(y_k - h(x_k)) \,, \qquad (9)$$

where v_k is the measurement noise of $N(0, R)$. Now by applying negative logarithm to joint density (7), we obtain the MHE cost function for system (1)-(2) which is a quadratic programming (optimization) problem:

$$\phi_T^* = \min_{x_0, \{\omega_k\}_{k=0}^{T-1}} \phi_T(x_0, \{\omega_k\}) = \arg \min_{z(,\{\omega_k\}_{k=T-N}^{T-1}} \sum_{k=T-N}^{T-1} \|\omega_k\|_{Q^{-1}}^2 + \|v_k\|_{R^{-1}}^2 + \Gamma_{T-N}(z) \,, \qquad (10)$$

where $\|\alpha\|_A^2 = \alpha^T A \alpha$ for quadratic form. $x_k \coloneqq x(k; z, \{\omega_j\}_{j=T-N}^{k-1})$ denotes the solution of (10) for system (1),(2) at time k with initial state z and process noise $\{\omega_j\}_{j=T-N}^{k-1}$ in horizon length. $\Gamma_{T-N}(z)$ is referred to as arrival cost which plays an important role in summarizing the effect of the past measurements $\{y_k\}_{k=0}^{T-N-1}$ as *a priori* information on the state x_{T-N} ($\Gamma_{\mathrm{T-N}}(\mathrm{z}) = -\log\left(\mathrm{p}(x_{k-N}|Y_{0:k-N-1})\right)$). However, the initialization of MHE with the best choice of the arrival cost term is an open issue. In this paper, the arrival cost is approximated using the EKF with the following form:

$$\Gamma_{\mathrm{T-N}}(\mathrm{z}) \approx (z - \bar{x}_{T-N}^{mh})' \, P_{T-N}{}^{-1} (z - \bar{x}_{T-N}^{mh}), \qquad (11)$$

where $\bar{x}_{T-N}^{mh}$ is the optimal estimate at time *T-N* generated in (10) given measurements from time 0 to *T-N-1*, the covariance matrix P_{T-N} is an estimate of the covariance of $\bar{x}_{T-N}^{mh}$ calculated by EKF. Typically any nonlinear filter capable of propagating the conditional mean and covariance could be used to compute the arrival cost in MHE such as unscented Kalmen filters, particle filters and cell filters.
Since MHE is an optimization framework based state estimation algorithm, the physical road width constraints discussed above could be easily imposed on the MHE state variables.

MHE BASED MULTIPLE HYPOTHESIS TRACKING (MHE-MHT)

In this section, we first review the original MHT algorithm described by Reid [18] and Cox [19]. Then the formation of MHE-MHT structure is set forth explicitly.

A. Multiple hypothesis tracking structure

The original MHT algorithm is a deferred decision logic which forms alternative association hypotheses in order to deal with observation to track assignment uncertainties. According to Reid's paper, the hypothesis based MHT keeps the past hypotheses in the memory between consecutive time steps. MHT has the advantage of being able to deal with track creation, confirmation, occlusion and deletion in a probabilistically consistent way. The original MHT framework contains three main processes: hypothesis generation, probability calculation and hypothesis reduction. When a new measurement is received, observations that fall within the gate region set a possible measurement to track assignment thus an existing hypothesis is extended to a set of new hypotheses by considering all possible tracks to measurements assignments. Several assumptions are made when generating hypothesis:

Assumption 1

(i) Each hypothesis contains a set of compatible observation to track assignments,
(ii) Assignments are defined as 'compatible' if they have no measurements in common which means in each Hypothesis, each measurement can only update with one of the existing tracks.

B. MHE-MHT framework

In Figure 3, we present the flow diagram of MHE-MHT algorithm. Let $Y_k = \{y_i^k\}_{i=1}^{m_k}$ denote the set of m_k measurements received at time k. Each of the measurement has three possible hypotheses:

- The measurement starts a new target
- The measurement is a false alarm
- The measurement belongs to an existing target

1) Gate Check: First the distance between the predicted priori target and the current measurements is calculated known as measurement prediction error/innovation. The prediction of target position is done by KF prediction update and the distance is defined as the Mahalanobis distance:

$$\left(y_m^k - \hat{y}_{k/k-1}\right)^T S_{k/k-1}\left(y_m^k - \hat{y}_{k/k-1}\right) \leq Gating, \qquad (12)$$

where y_m^k is the measurement *m* at time *k*, $\hat{y}_{k/k-1}$ is the predicted target position and $S_{k/k-1}$ is the covariance of innovation vector , ${S^{-1}}_{k/k-1} = H\, P_{(k)} H + R$ both are calculated by KF. $Gating$ is a matrix of binary values which indicates maximum possible distance between measurement and targets. Only the measurements inside the gate are considered for assignment. Later, these statistical differences are used in data association.

2) Data association: MHE-MHT implements the same data association process as the Reids algorithm[18] which has been explained above. The assignment matrix is generated to represent all possible target-to-measurement associations. Then each new hypothesis contains a set of potential target-to-measurement assignments, leading to an exhaustive approach of enumerating all the possible assignment combinations. To solve this problem, the Murty's algorithm [19] is used to find the *k*-best assignment/new hypotheses generated from each parent hypothesis. To further reduce the computational cost, a merging algorithm is also implemented in to prevent hypotheses from being considered if the ratio of their probability to the best hypothesis becomes too small.

3) Target Maintenance: For ground target tracking scenarios, vehicles may enter or leave the surveillance field of view during the tracking process. Moreover, occlusion or miss detection is also possible when a vehicle is hidden behind another one. In order to achieve a fully functional tracking algorithm, we implement target maintenance logic in MHE-MHT structure. Basically, there are three possible status for a set of targets in this logic: target initiation, confirmation/deletion and maintenance. The implementation is based on track-oriented approach. The targets present at a time step are a combination of existing targets from the parent tracks and any new targets resulting from the set of measurement associations. For any targets in existence at time *k*-1, the possible associations at time *k*:

- Target initiation: If the measurement is associated with a new target and the new target hypothesis appears in the current *k*-best hypotheses. Add a target *lifetime* index to the target with value 1.
- Target confirmation/deletion: The new target is confirmed only if the detected target appears along the same track over a consecutive iterations of *Ct* times. The *lifetime* index is accumulated by 1whenever the tentative target is detected and will become *Ct* (confirmation threshold) when confirmed. On the contrary, the *lifetime* index for any existing target is reduced by 1 whenever the target is not associated with the current measurement and will be permanently deleted from target list when the *lifetime* is 0.
- Target maintenance: The confirmed target may be temporally occluded or undetected by the sensor.

For this situation, the track measurement for unassociated targets is updated according to the predicted position of the target last associated states.

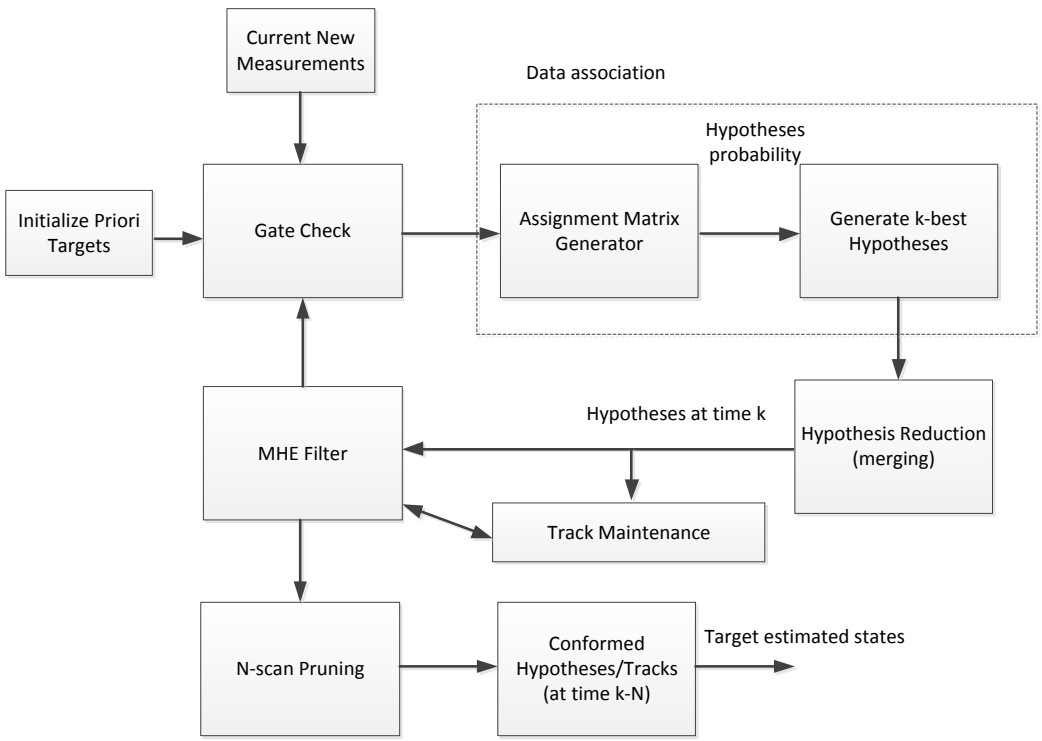

Figure 3. Flow diagram of MHE-MHT algorithm

4) MHE filter: The details about implementing MHE for constrained target tracking have been discussed in previous section in this paper. In this part, the main work will focus on comparing the difference between MHE and KF under the MHT structure. In the original MHT, the 'Filter' process is based on Kalman state estimation including two individual steps: prediction update and measurement update. However, the two steps are combined in MHE and solved directly by optimization solver. In MHE, the state estimation is determined online by solving a finite horizon state estimation problem. To determine new estimate of the target state, the finite horizon of latest measurements are resolved while the problem is solved recursively with only the current step measurement being considered in KF. Assuming that at time k, $x_k \coloneqq x(k; z, \{\omega_j\}_{j=T-N}^{k-1})$ denotes the solution of MHE optimization function (10) for a linear, time-invariant discrete-time system with initial state z and process noise $\{\omega_j\}_{j=T-N}^{k-1}$ in horizon length N. Then the estimation result is:

$$x(k; z, \{\omega_j\}_{j=T-N}^{k-1}) = F^k z + \sum_{j=0}^{k-1} F^{k-j-1} G \omega_j \quad , \qquad (13)$$

and if considering the road linear inequality constraint in (3), an additional MHE state constraint is consideredas

$$a_k \leq H_{C_k} F^k z + H_{C_k} \sum_{j=0}^{k-1} F^{k-j-1} G w_j + \sum_{j=0}^{k-1} v_j \leq b_k, \qquad (14)$$

where F is the linear state transition matrix, and H_{C_k} is the linear constraint matrix. $\{v_j\}_{j=T-N}^{k-1}$ is the estimated measurement noise for N horizon length.

The filtering process would be similar to KF if measurements are always detected and updated with the target, However, a problem arises when miss detection happens among a horizon of measurements, since there is no individual predict update process in MHE and the estimation problem is solved by an optimization solver. In the MHE-MHT algorithm, the missing target measurement is presumed as one step predicted state calculated by KF: $x_k = F x_{k-1}$ and thus the estimated process noise ω_j and measurement noise v_j for time k is taken as null. This

assumption is equivalent the one used in KF-MHT for missed detection which treats the non-available posterior measurement updated estimate as the prior predicted state. The proof is shown below:

- For Kalman filter at time k
  Prediction Update: $\hat{x}_{k|k-1} = F\hat{x}_{k-1|k-1}$
  Measurement Update: $\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(y_k - \hat{y}_{k|k-1})$
- If at time k, measurement y_k is missing, then the predicted state $\hat{x}_{k|k-1}$ is taken as estimated state $\hat{x}_{k|k}$, In other words, the measurement update step is rejected
- So $K_k(y_k - \hat{y}_{k|k-1}) = 0$, and thus $y_k = \hat{y}_{k|k-1}$, where $\hat{y}_{k|k-1}$ is predicted target $\hat{y}_{k|k-1} = HF\hat{x}_{k-1|k-1}$
- In this case, for system :
  $x_{k+1} = Fx_k + \omega_k$
  $y_k = Hx_k + v_k$
- So $y_k = \hat{y}_{k|k-1} = HFx_k$ and thus ω_k *and* v_k are null

Correspondingly, the high level logic for MHE-MHT target maintenance is shown below in Table 1:

Table 1.

High level logic for MHE-MHT target maintenance

```
 -- At time k, for nExistedTarg number of existing target in a hypothesis
For k=1: nExistedTarg
    (Case one: permanent deleted targets)
    If LifePoint == 0
       Continue; (the target is permanently deleted/already disappeared)
    End
    (Case two: target maintenance—target updating with measurement or temporally miss detection)
    If Targ≠asso (Target not associated with current measurement)
       LifePoint=LifePoint-1;
         If LifePoint>0
           Implement KF prediction for MHE estimation
         End
    Else (Target associated with current measurement)
       Implement MHE update;
         If LifePoint<MaxLifePoint
           LifePoint= LifePoint+1;
         End
    End
    (Case three: target initialization)
For k=1: nNewTarg (measurement is associated to a new target)
    Use current measurement as initial position;
    LifePoint=0;
End
```

5) N-scan pruning: The key principle of the MHT method is that difficult data association decisions are deferred until more data are received, which could be achieved by using N-scan pruning. The structure provides a convenient mechanism for implementing deferred decision logic and for presenting a coherent output from the MHT. The continued growth of the tracks is also controlled by N-scan pruning technique by keeping only the N previous scans in the trees. The hypotheses with low probability are deleted after N-scan pruning. The survive target after pruning process are predicted using the new measurements obtained and reformed into new hypotheses. In MHE-MHT the number of N scans is chosen as the same value for horizon length in MHE. As a result, the association uncertainty at time k-N is resolved by the hypotheses given at time k and meanwhile the estimation process considers all measurements within the last N scans.

SIMULATION and RESULTS

In this section, the proposed algorithm is evaluated by means of two examples. The first example is aimed at illustration of handling nonlinear inequality road constraint using a MHE based approach, using a single target circular road tracking scenario. The second one which is inspired by [28] is a complex multiple target tracking scenario incorporating road inequality constraints for an intersection scenario.

A. Target tracking with nonlinear road inequality constraints

In the first example, we follow the previous study of [8] in 2012 to set up the test scenario. A moving vehicle on a circular road section is considered as shown in Figure 4. The road is defined by two boundaries with two arcs of *r1*=96m and *r2*=100m, respectively, centered at the origin of a Cartesian coordinate system. The vehicle dynamics is described by a white noise acceleration motion model.

$$x_{k+1} = \begin{bmatrix} 1 & T & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T \\ 0 & 0 & 0 & 1 \end{bmatrix} x_k + \begin{bmatrix} T^2/2 & 0 \\ 0 & T^2/2 \\ T & 0 \\ 0 & T \end{bmatrix} \omega_k \tag{15}$$

where the state vector $x_k = [x_{1,k}, x_{2,k}, \dot{x}_{1,k}, \dot{x}_{1,k}]^T$ consists of the vehicle position and velocity in x and y directions, $T = 1$ is the sampling interval, and ω_k is a two-dimensional Gaussian process noise with zero mean and covariance matrix $Q = eye(2)$. The initial state of the vehicle is $x_0 = [98,0,0,10]^T$. The vehicle is supposed to move for $k = 1, \dots, K$ with $K = 20$.
The vehicle is tracked by range and bearing sensors modelled as:

$$z_k = \begin{bmatrix} \sqrt{x_{1,k}^2 + x_{2,k}^2} \\ arctan\left(\frac{x_{2,k}}{x_{1,k}}\right) \end{bmatrix} + v_k \tag{16}$$

where v_k is a two-dimensional Gaussian zero-mean measurement noise with a diagonal covariance matrix $R = diag\{8, 10^{-3}\}$. Given the road boundaries, the state inequality constraint is shown in (5): $r_1 \leq \sqrt{{x_{1,k}}^2 + {x_{2,k}}^2} \leq r_2$.

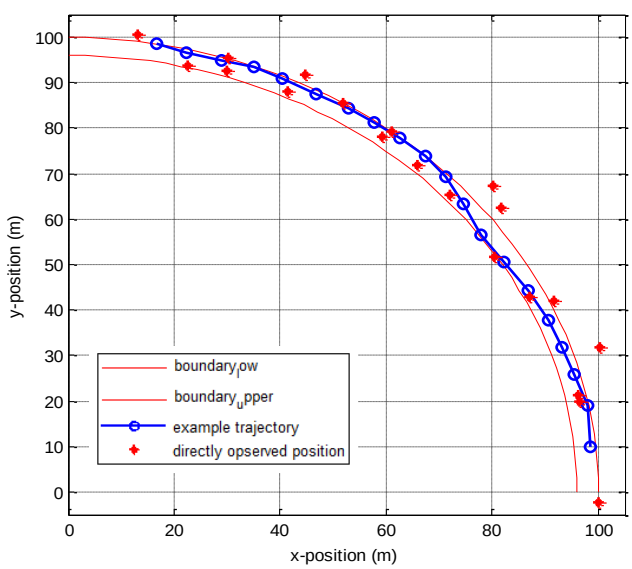

Figure 4. Tracking scenario for example 1

The performance of constrained MHE filter was measured using the mean-square error (MSE):

$$MSE = \left(2(K+1)\right)^{-1} \sum_{k=0}^{K} \sum_{i=1}^{2} (x_{1,k} - \hat{x}_{\mathrm{i,k}})^2 \tag{17}$$

We compare the performance of constrained MHE (cMHE) with different horizon length (N=2 and 8) with some other conventional filters. In [8], Straka compared several conventional filters including the unscented Kalman filter (UKF), divided difference filter (DFF), the Gaussian mixture filter (GMF), constrained particle filter (cPF) and the truncated versions tUKF, tDDF, and tGMF. The results are shown in table.2:

Table 2.

Estimation performance of filters for example 1

	UKF	DDF	GMF	tUKF	tDDF	tGMF	cPF(10^3samples)	cMHE (N=2)	cMHE(N=8)
MSE	7.79	20.27	6.31	4.23	4.90	3.63	4.29	4.46	3.98
Time (s)	0.019	0.027	0.042	3.280	3.458	6.612	9.28	1.09	2.97

It can be seen from Table 2 that the tUKF, tDDF, tGMF outperform their unconstrained conventional filters UKF, DDF and GMF. The cPF provides high quality estimates however at an expense of high computational cost. The proposed constrained MHE in this paper provides reasonable good performance especially when increasing the horizon length. When N=8 the cMHE provides the second best MSE=3.98 among all filters in Table.2 which is slightly worse than tGMF with MSE=3.63 however cMHE provides a much better the computational cost with only half time taken for tGMF by using *fmincon* server in MATLAB.

B. Multiple target tracking for intersecting road scenario

In the second example, we set up a multiple target tracking simulation for interacting scenario. As illustrated in Figure5, the region of interest is [-1000m,1000m] x [-1000m,1000m] with an unknown and time varying number of targets observed in a clutter environment. The vehicle dynamics is described the same as (15) and the state vector $x_k = [x_{1,k}, x_{2,k}, \dot{x}_{1,k}, \dot{x}_{1,k}]^T$ consists of the vehicle position and velocity while the measurement model is defined as a noisy position in x and y directions. $T = 1$ is the sampling interval and the two-dimensional Gaussian process noise has covariance matrix Q of 5 m/s^2 standard deviation. Initially, two targets start moving in the environment with initial state $x_{1,0} = [250,250,0,0]^T$ and $x_{2,0} = [-250,-250,0,0]^T$. The target initial covariance is defined as $P_0 = diag[100,100,25,25]^T$for both two targets. Each target is detected with a probability of $P_d = 0.98$, and the Gaussian noise based position measurement has a standard deviation of 10m in both directions. The detected measurements are immersed in clutter that can be modeled as a Poisson distribution with clutter density of β_{FA}=$12.5 * 10^{-6}$ over the $4 * 10^6 m^2$ region (i.e., 50 clutter returns over the region of interest). As shown in Figure 5, Target 1 and 2 appear at the same time in different locations, traveling along straight lines and cross each other at K=53s. A new target spawns from Target 1's trajectory at time K=66s. The total simulation time is K=100s.
The target trajectories are supposed to be constrained by road boundaries, each with a width of 6 meters using the road inequality constraint in (4). The position estimates are shown in Figure 6, it can be seen that the constrained MHE-MHT algorithm provides accurate tracking performance. Moreover, the algorithm not only tracks Target 1 and 2 but also able to detect and track the spawned Target 3. The lifetime threshold is defined as 4, which means any new target can only be confirmed if successfully detected in 4 sequential time steps. The horizon length used in MHE in chosen as 4 and so as for N-scan pruning. At each time 3-best hypothesis are generated from each parent hypothesis.

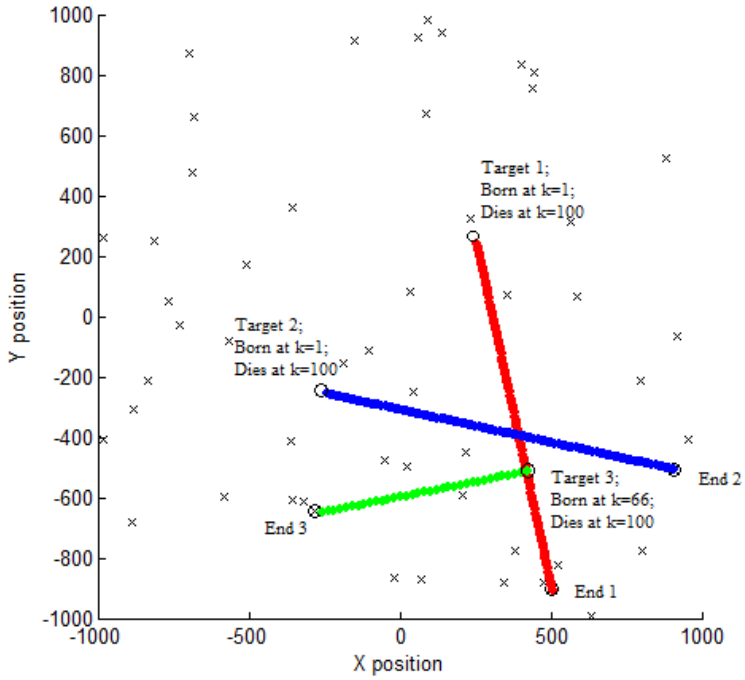

Figure 5. Target trajectories for scenario 2

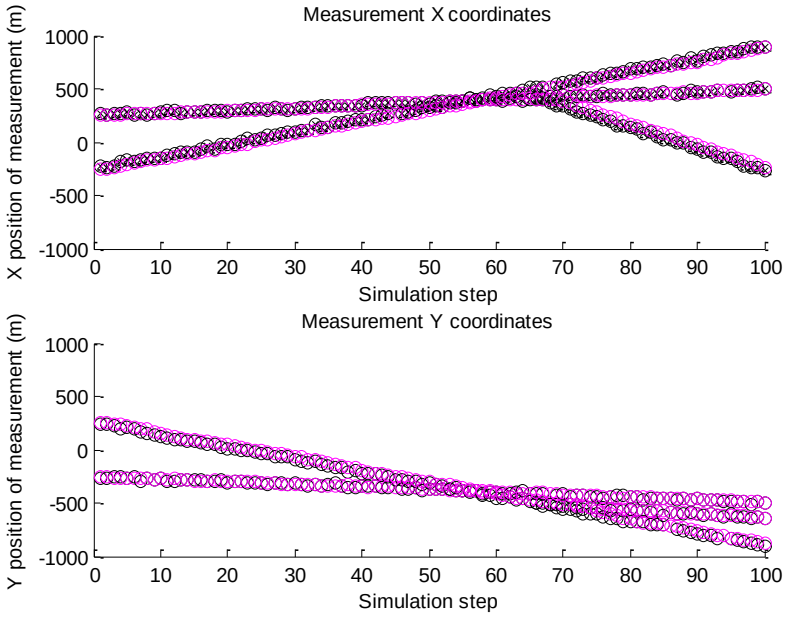

Figure 6. Position estimation for MHE-MHT

To further analysis our algorithm, Figure7 shows a comparison between original Kalman filter based MHT and constrained MHE-MHT using the optimal subpattern assignment metric (OSPA) [31] which considers not only the estimation performance but also association accuracy.

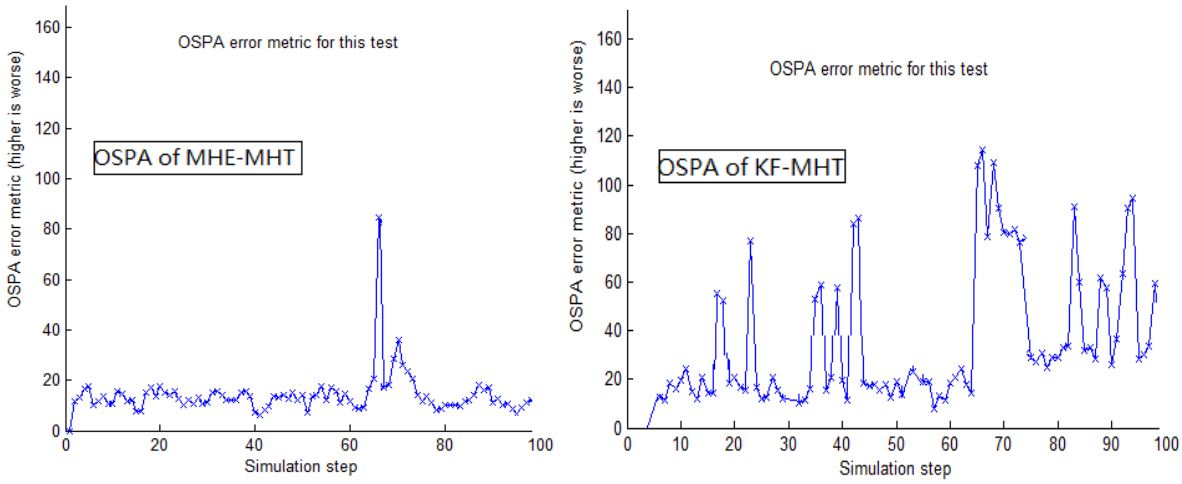

Figure 7. OSPA performance for MHE-MHT and KF-MHT algorithm

From the results, it can be seen that the MHE-MHT algorithm performance is more stable than KF-MHT which is concluded by the variation of the OSPA distance over time. This is because of the more accurate state estimation performance for constrained MHE which also affects the accuracy of new target detection and data association. In the original KF-MHT, road width constraint is not considered which makes the predicted target more likely to associate with clutter and thus generate false new targets. At time k=66, the new target appears which makes OSPA increase significantly. However, the faulty association hypotheses are soon discarded in MHE-MHT by the correct one which has higher hypothesis probability.

CONCLUSION

In this paper, we propose a novel MHE-MHT algorithm for constrained multiple target tracking problems. External road information is employed by MHE filters in state estimation process. A target maintenance logic is designed for MHE-MHT algorithm to track multiple targets efficiently and accurately. Initial simulation studies have shown the effectiveness of the proposed algorithm against conventional algorithms.
The future work will focus on incorporating extra domain knowledge in the MHE-MHT structure especially for target interaction problems since the target are considered moving independently in most target tracking algorithms without having interacting behaviors with other targets or physical environment. Experimental research combing real sensor data and digital map information will also be carried out.

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SAFETY 2.0 – POTENTIALS OF COOPERATIVE SAFETY BY VEHICLE-TO-X COMMUNICATION

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ABSTRACT

Safety Technology has evolved significantly over the last decades. The technological progress, based on the continuous advances in vehicle crash worthiness, restraint systems and active safety functions have made traffic safer than ever before. Latest development has led to a sharp increase in the equipment rates for advanced surrounding sensors, so that on-board surrounding sensors such as camera, radar and lidar sensors have become standard equipment in modern vehicles. Surrounding sensors can provide safety critical information to a vehicle and are thus a pre-requisite for new integrated safety functions such as Forward Collision Warning (FCW) or Emergency Brake Assist (EBA). What if vehicles could communicate with each other and create a network for safety critical information in traffic? What if my vehicle gets real-time information on sudden braking maneuvers 500 meters ahead? What if a vehicle camera detects a cyclist approaching at an urban intersection and shares the cyclist position information with other vehicles? What if vehicles share their mass, velocity and position before a crash to optimize the strategy of airbag deployment? Wouldn`t all this open a new dimension of safety in future traffic – Safety 2.0?
This paper promotes cooperative safety as a new approach based on the exchange of safety critical information in traffic. The underlying thesis is that cooperative safety would dramatically increase the safety for a large number of traffic participants, including vehicles without on-board surrounding sensors and vulnerable road users (VRUs) like children, pedestrians and cyclists.

INTRODUCTION

Traditionally, vehicle users rely on the seat belt and airbag to protect them from harm during an accident, just like a safety net would protect the fall of an acrobat in a circus. Today's approach goes far beyond this safety net. Advanced Driver Assistance Systems (ADAS), tailored to specific driving situations, help to avoid accidents, should the driver fail to take proper action. ADAS are doing an excellent job of this because they have traits that make them perfect co-pilots: They do not get distracted, they don't suffer from mood swings, they don't drink, and they never become tired. The EU commission has in its Vision Zero set the ambitious goal for halving road casualties down to 15,750 by 2020 and moving close to zero fatalities in road transport by 2050 [1]. An increasing number of ADAS is a significant move towards more driving safety, fewer accidents, and fewer fatalities – towards the EU target of Vision Zero.

So, are we nearly there yet? No, we are not. After all, on-board surrounding sensors are subject to similar limitations as they apply to the human senses. Due to many reasons the practical range of an automotive sensor can be limited just as much as human eyesight, for instance. Ultimately, the human eyesight needs a "line of sight" to detect objects, traffic signs or road markings. At low visibility e.g. due to bad weather or fog, with the support of different surrounding sensor technology, ADAS can help to recognize vehicles and obstacles more accurately than the human eye could do. However, hidden objects, like approaching vehicles hidden by trucks, or vehicles behind buildings in an inner-city crossing situation, cannot be recognized. Even the most advanced surrounding sensors have a line of sight. If there is no such line of sight, ADAS cannot help.

This is a non-satisfying situation, considering the enormous benefit that could be reaped, if the "line-of-sight" problem was finally overcome. According to a study of the U.S. Department of Transportation (DOT), Federal Highway Administration [2], in 2007, approximately 2.4 million intersection-related crashes occurred in the U.S.A., representing 40% of all crashes and 21.5 % of traffic fatalities. Therefore, the ultimate integrated approach to driving safety needs to address just that – integrating new technologies to close the gaps of visibility and enable powerful and effective safety functions.

The answer lies in an exchange of safety critical data between vehicles (V2V) and between vehicles and infrastructure (V2I). Such V2X communication is based on IEEE 1609 Standard (in EU: ITS-G5) [3], also known as automotive WLAN technology. In V2X communication vehicles become cooperative by exchanging relevant information with each other and with the infrastructure (like traffic lights, construction sites, etc.). Based on cooperative safety, imminent collisions can be recognized and prevented, even when collision objects are hidden and even at higher speeds over a broader range than vision and radar based systems can do.

SHORT RANGE AND LONG RANGE COMMUNICATION

With the use of V2X communication a wider scope of cooperative safety functions can be evaluated and initiated, ideally before a situation even gets critical. This data flow can take driving safety to a whole new dimension that can be called "Safety 2.0".

As the timeline for this type of V2X communication can be very short, and initiating a safety function may have to be done in split seconds, it is unlikely that drivers will want to rely on the instantaneously available bandwidth for internet access and a communication flow via a backend. True, this long-range networking of vehicles will be of immense importance during normal driving. Actually, vehicle drivers and passengers will probably consider being "always on" to be the most useful part of wireless communication. However, when there is immediate danger to life and health, short range V2X is essential. Long and short range communication complement each other because they have different strengths to offer during different driving scenarios (see figure 1).

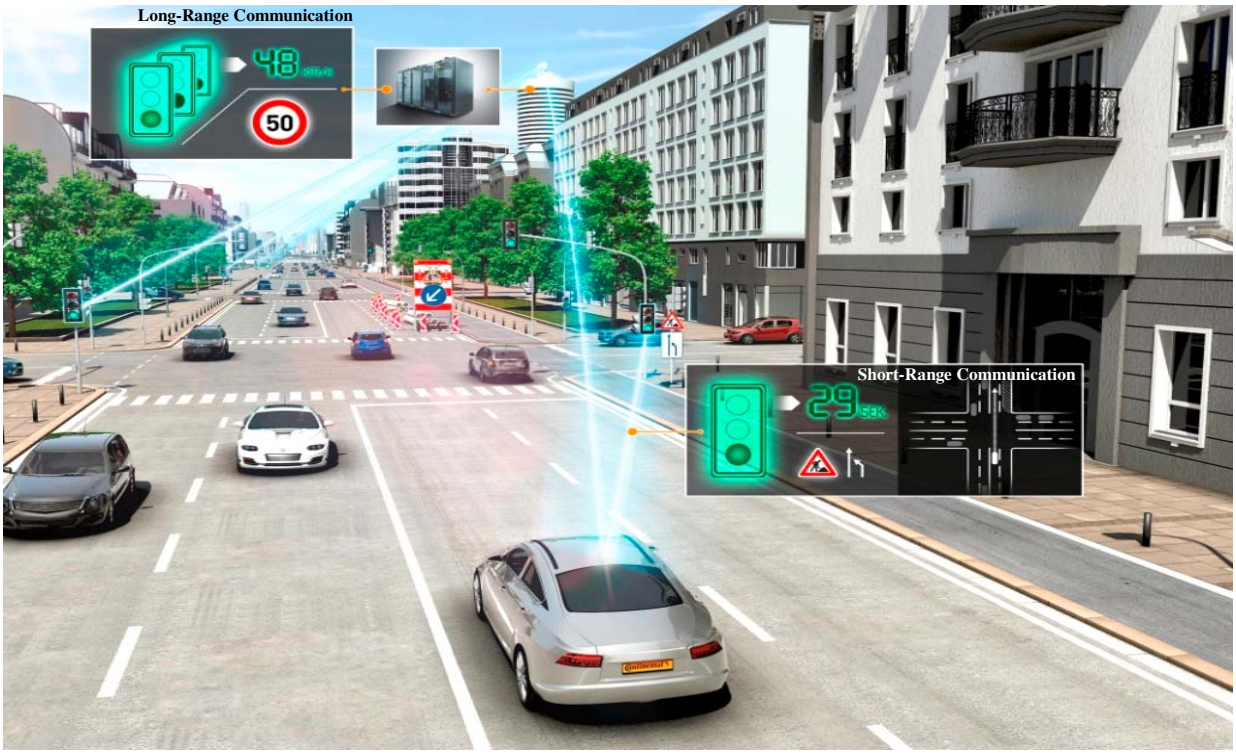

Figure1. Short range V2X communication and long range communication via backend complement each other

VEHICLE-TO-X HAS PASSED THE TEST

Short range V2X is no longer a vision. Since the successful conclusion of the Safety Pilot field trial in the US and the large sim^{TD} (Safe Intelligent Mobility – Field Test Germany) pilot project on V2V communication in Germany [4], it is clear that the underlying technology works. A V2X unit has been developed during the sim^{TD} project and is close to serial production at Continental. With this unit safety critical data such as vehicle speed, location, precise time (time stamp), or brake status, can be communicated within a spontaneous "ad-hoc" network of vehicles (compare ETSI specification [5]). As a further enhancement, objects or traffic situations (e.g. broken vehicles, accidents or slippery road conditions) detected by the sensors of another vehicle, can also be communicated to the ego vehicle before the situation becomes visible to that vehicle. By receiving and processing data from other vehicles, V2X communication turns into a new cooperative "sensor" that complements the existing on-board surrounding sensors.

Imagine a scenario, where a truck and a sports utility vehicle are at risk of colliding because the drivers are unable to see one another approaching the intersection (the stop sign is disabled). With V2X, both drivers would receive warnings of a potential collision, allowing them to take actions to avoid it. The Intersection Movement Assist (IMA) warns the driver of a vehicle when it is not safe to enter an intersection due to a high probability of colliding with one or more vehicles at intersections both where a signal is present (a "controlled" intersection) (see figure 2) and at those where only a stop or yield-sign is present (an "uncontrolled" intersection).

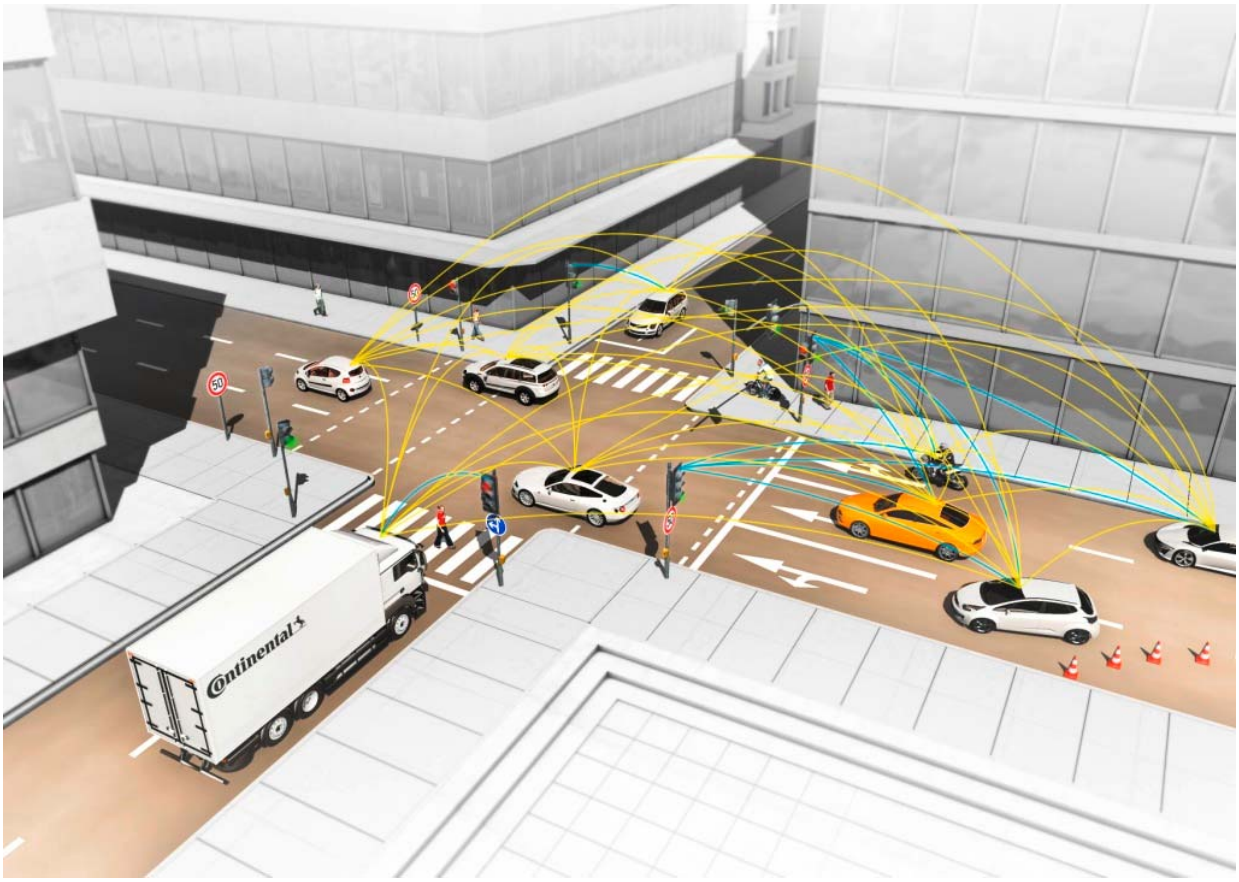

Figure2. Example of V2V Intersection Movement Assist warning scenario

Also scenarios with oncoming traffic in the opposite direction can be addressed: A Left Turn Assist (LTA) can warn the driver of a vehicle, when they are entering an intersection, not to turn left in front of another vehicles traveling in the opposite direction. Even in overtaking scenarios hidden “blind spot” vehicles driving in the opposite direction can be detected and signalized with a warning. A cooperative V2X communication can even detect a vehicle traveling towards you when it is hidden behind a curve (see figure 3).

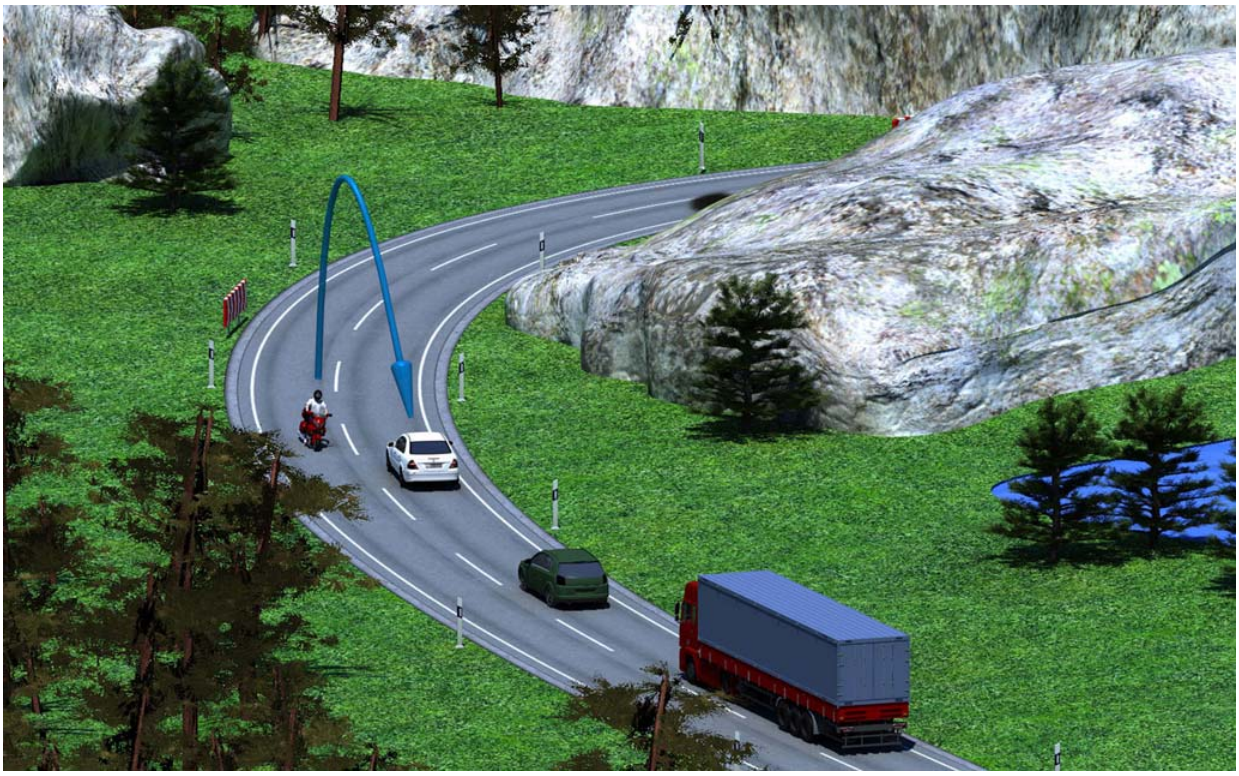

Figure3. Avoiding an accident at a hazardous location through short range V2X (image courtesy of Car2Car Communication Consortium)

Imagine a motorway where traffic going in the opposite direction will have passed an accident on the ego vehicle’s side of the motorway long before the ego vehicle gets to the accident (see figure 4). As soon as this information is available, the driver can be warned and the lateral and longitudinal dynamics of the ego vehicle can be adjusted to the situation. Other use cases include crossroads where another vehicle may have a good field of vision while the ego vehicle next to it has not. The other vehicle will therefore be able to detect the approaching truck and will share this bit of information with the vehicles around. During this mutual information sending and retrieval process one vehicle tells the other what it “sees”.

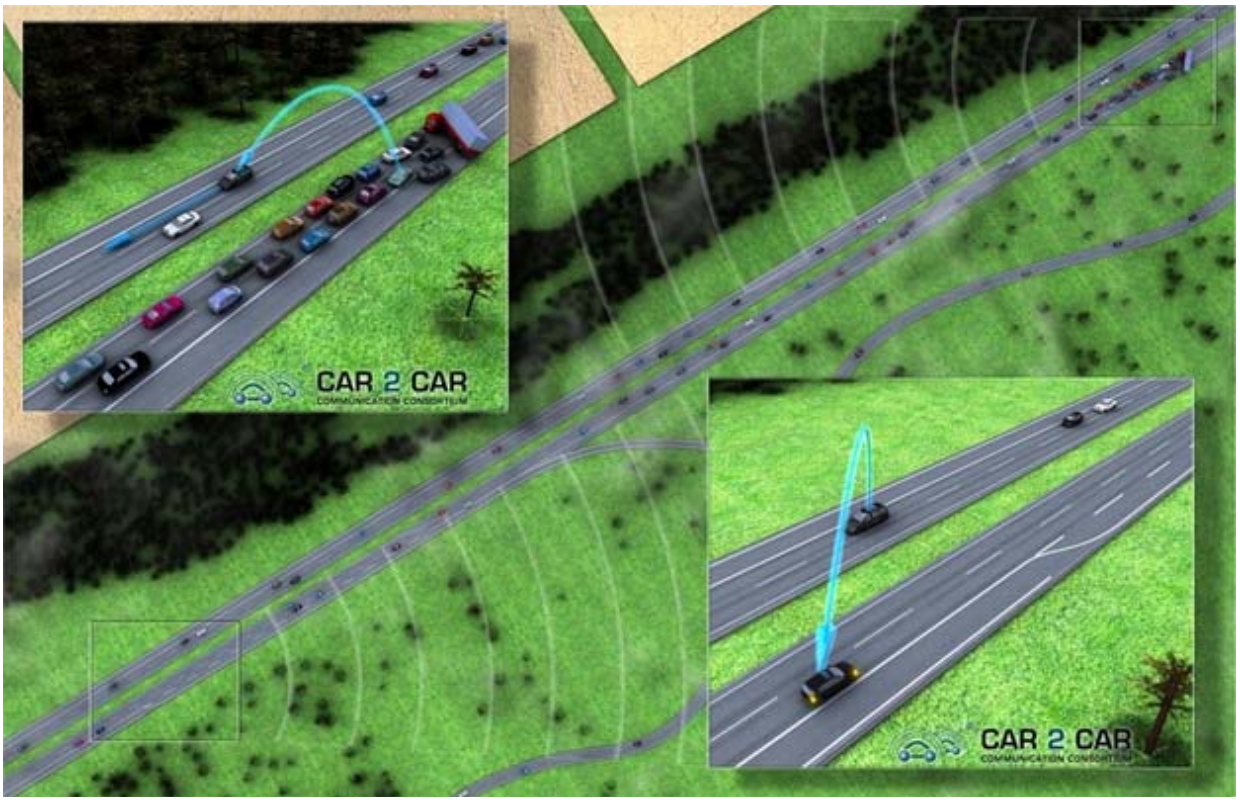

Figure4. Avoiding a traffic jam through short range V2X (image courtesy of Car2Car Communication Consortium)

NHTSA STUDY ON EFFECTIVENESS OF V2V COMMUNICATION

According to a new report on the readiness of V2V technology, initiated by DOT's National Highway Traffic Safety Administration (NHTSA) [2], V2V safety technology can help drivers avoid or reduce the severity of four out of five unimpaired vehicle crashes.

In order to measure the potential impact of V2V technology, the NHTSA report looks at rear end collision scenarios, lane change scenarios and intersection scenarios (see figure 5). In the scenarios new safety functions based on V2V communication help to avoid accidents. These functions include Forward Collision Warning (FCW), Intersection Movement Assist (IMA) and Left Turn Assist (LTA). In terms of safety impacts, the report estimates that Intersection Movement Assist and Left Turn Assist would per year prevent up to 592,000 crashes and save up to 1,083 lives. And in addition the severity of accidents would be reduced significantly [2].

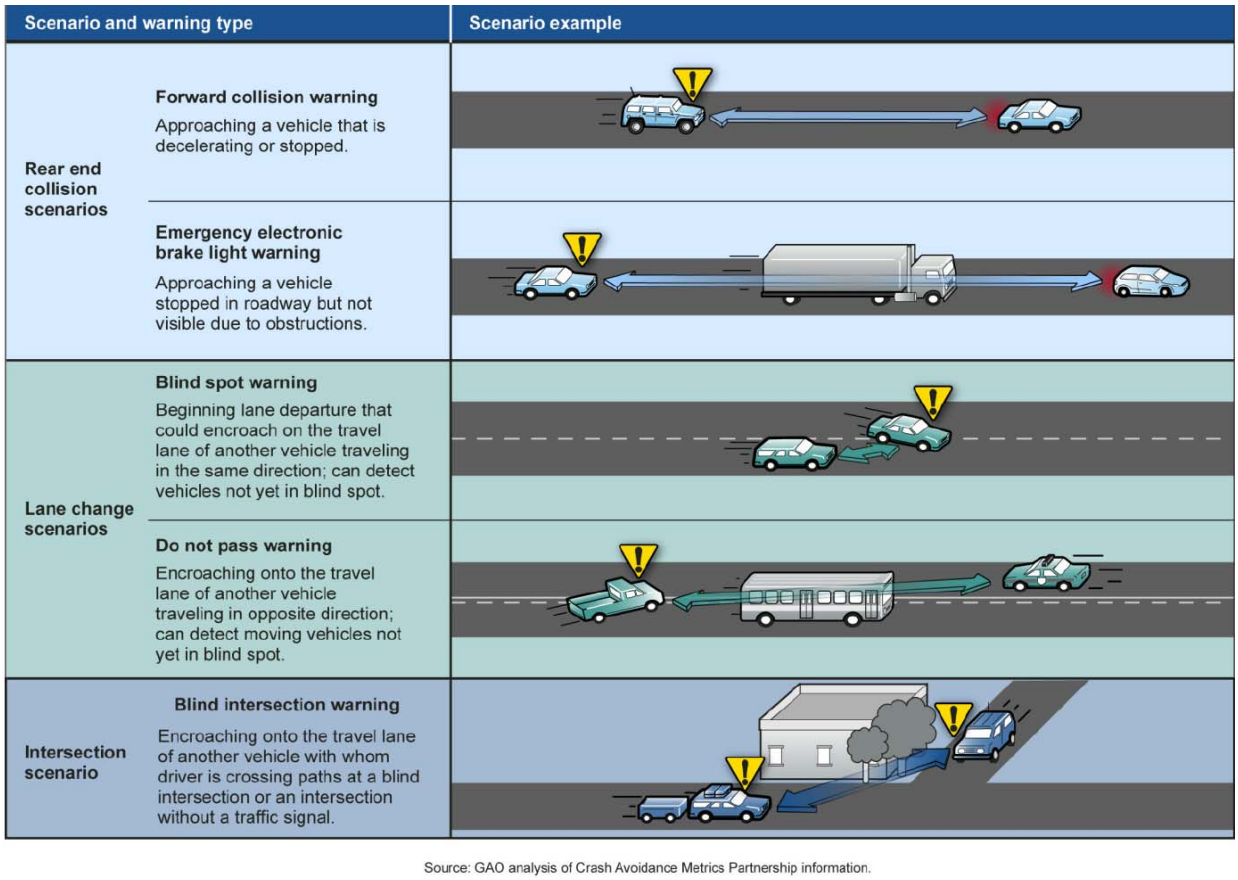

Figure5. Examples of crash scenarios and Vehicle-to-Vehicle applications (image courtesy of [2])

PROTECTION FOR VULNERABLE ROAD USERS (VRU)

Let's turn to another important group of road users besides vehicles and their drivers and passengers: vulnerable road users (VRUs) such as children, pedestrians and cyclists, suddenly appearing from behind an object, are one of the major concerns to developers. In comparison to vehicles, they have no or almost no protection systems, but they operate in more complex traffic scenarios: between two parking vehicles, behind an obstacle, in a crowd, at crossings, etc.

Vision or radar based sensors can detect VRUs as long as the "line of sight" (compare above) is given. Is the VRU hidden by other objects, V2X communication can help to identify VRUs and to trigger the right warning or vehicle function. At Continental several technological approaches are under research. Within the German Ko-FAS research project Continental has developed and tested new hardware and software which facilitates an innovative approach to cooperative driving safety. In addition to conventional radar the research vehicles were equipped with a secondary radar system. In principle this is aircraft technology that has been modified for automotive requirements. A transponder (receiver and transmitter), called Ko-TAG 2.0, installed in each vehicle sends out an interrogating signal and receives active replies from other road users [6]. During the project pedestrians were equipped with an early version of a Safe-TAG 1.0 transponder so that they too could be identified and located. During extensive testing, which included equipping a complex crossroads in the town of Aschaffenburg (Germany) with stationary transponders, this type of tagging and short range V2X communication demonstrated enormous accident avoidance potential. Alternative technologies to the transponder developed in Ko-TAG could be promising for an ad-hoc communication between the vehicle and the VRU [7].

BUILDING SAFETY 2.0

The vehicle architecture required for Safety 2.0 adds new sensors and controllers to the vehicle. As described by the above mentioned NHTSA report [2], a typical setup of a V2X system would consist of DSRC (Dedicated Short Range Communication) radios and a GNSS receiver (see figure 6). Furthermore a V2X Control Unit is needed to process and interpret all sensor data and to trigger required safety functions.

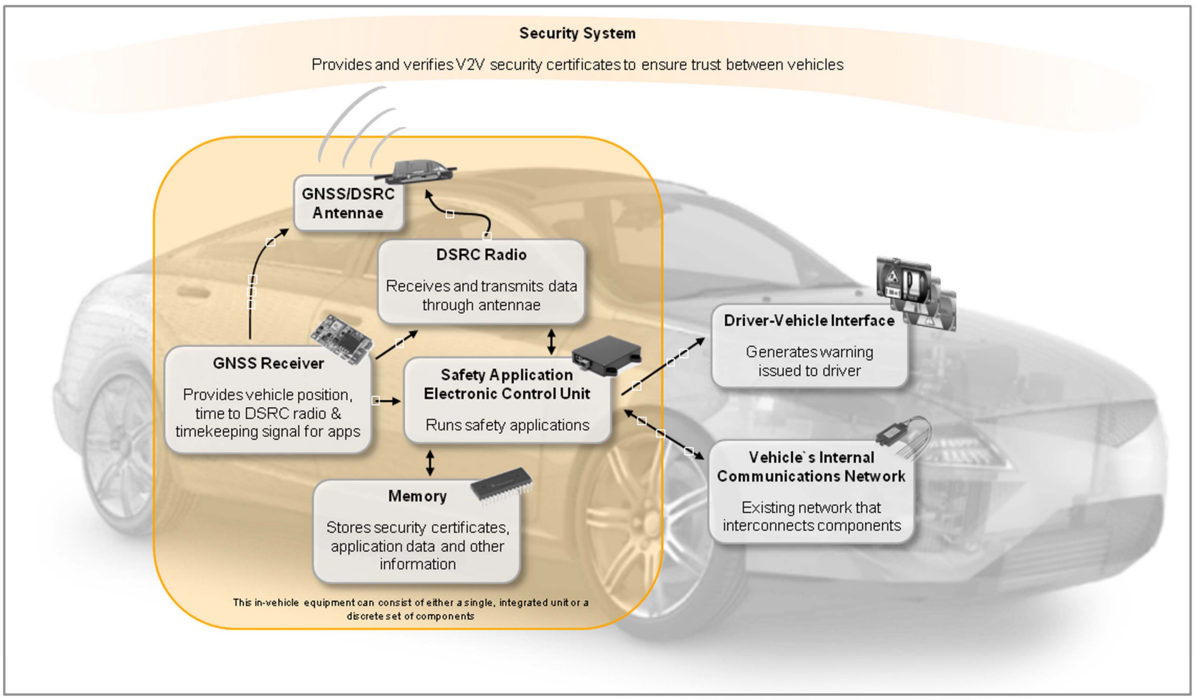

Figure6. In-Vehicle components of a generic V2V System (based on [2])

ACCURATE POSITION IDENTIFICATION IS BECOMING AVAILABLE

In Safety 2.0 knowing the exact position of vehicles will become essential to any cooperative safety function. Up to now, the guidance of the vehicle was realized by the identification of landmarks and traffic – by the driver. Two main challenges can be distinguished: to reach the desired target by choosing the best routes (macro navigation) and to guide the vehicle in order to follow the route, which means longitudinal and lateral guidance while keeping the traffic regulations, avoid collisions etc. (micro navigation).

Safety 2.0 is addressing cooperative safety at the level of micro navigation. To achieve this, the position of all vehicles involved in the V2X communication network needs to be known at all times. Continental has developed the sensor "M2XPro®" (Motion Information to X Provider), which is designed to fulfill positioning requirements of V2X functions and of future systems for automated driving.

In order to achieve an effective and affordable solution, the concept of the M2XPro® positioning algorithm builds on existing standard sensors in the vehicle. By fusion of the vehicle-typical sensors Inertial Measurement Unit (IMU), Wheel Speed Sensors, Steering Angle Sensors (Odometry) and GNSS sensor, the existing redundancy of these sensors can be utilized to determine the accurate position of a vehicle.

Sensors can be disturbed due to their measuring principles, depending on the surrounding conditions. Using a fusion approach, those disturbances can be compensated by the strengths of the other sensors. For example wheel-slip or a

reduced number of visible satellites of the GNSS sensor can be weighted lower based on their increased noise or the given sensor information can be canceled out of the motion calculation by means of plausibilization.

This M2XPro® sensor can either be used as a stand-alone unit, or it can be integrated into a specific V2X unit – whichever suits the architecture best (compare [8]). The data provided by M2XPro® is completed by an integrity measure, which indicates what sensor data is actually available and how consistent the sensors are to each other and to the values the algorithm has calculated. The integrity measure is of high value for any safety function. At a high integrity measure a safety function can produce a precise warning or can trigger the correct reaction of the vehicle. However, at a low integrity measure a safety function might decide to stop any further execution due to uncertainty.

Overall the concept of M2XPro® leads to a significant improvement for information on the position and motion of a vehicle. Compared to a GNSS-only position information M2XPro® is improving availability, accuracy and reliability. Thereby M2XPro® is a requirement to any safety function in Safety 2.0.

OUTLOOK

As safety technology has evolved and modern ADAS contribute to a safe driving in most traffic scenarios, V2X communication can close a missing gap: by the cooperative exchange of safety critical data, other vehicles or Vulnerable Road Users (VRU) become visible, even when they are out of the "line of sight" for the on-board surrounding sensors. Closing this gap carries the potential of developing a new level of cooperative safety functions - Safety 2.0. Eventually this new level of functions will bring us a big step further towards the vision of zero accidents.
V2X technology is ready to be applied and with the underlying potential of this technology it will be exciting to develop new safety functions. To speak with the words of David Strickland, NHTSA Administrator: "[…] Vehicle-to-vehicle communication has the potential to be the ultimate game-changer in roadway safety" [9].

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Key Considerations in the Development of Driving Automation Systems

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Abstract

The historical roles of drivers, vehicle manufacturers, federal and state regulators, and law enforcement agencies in automotive safety is well understood. However, the increasing deployment of driving automation technologies to support various comfort, convenience, efficiency, productivity, mobility, and possibly safety features has the potential to alter this understanding. In order to facilitate clarity in discussing the topic of driving automation with other stakeholders and to clarify the level(s) of automation on which the agency is currently focusing its efforts, the National Highway Traffic Safety Administration (NHTSA) released a Preliminary Statement of Policy (SOP) concerning Automated Vehicles that included its automation levels.

In this paper, we present key factors for consideration in each automation level which are based upon SAE J3016. These factors focus on adding more specificity with regard to the distribution of the driving tasks between the driver and the automation system. The result of this effort has led to a refinement of our understanding of the automation levels based on the nature of the vehicle control aspect provided by the feature, the nature of the environmental sensing and response, the fallback strategy employed, and the feature's scope of operation.

Introduction

The Automated Vehicle Research (AVR) for Enhanced Safety Project (i.e., the AVR Project) was initiated in September 2013. The project is being conducted by the Crash Avoidance Metrics Partnership (CAMP) AVR Consortium (Ford, General Motors, Nissan, Mercedes-Benz, Toyota, and Volkswagen/Audi). It is sponsored by the National Highway Traffic Safety Administration (NHTSA) through NHTSA Cooperative Agreement No. DTNH22-05-H-01277, Project Order 0009 and is scheduled to run 19 months through April 30, 2015.

The AVR Project, initiated within the electronic control systems segment of NHTSA's research program, has the following goals:

- Develop a list of potential driving automation applications that may be emerging on vehicles in the future
- Develop detailed functional descriptions for emerging operational concepts within each automation level
- Develop potential test and evaluation methods that map to the functional description of the automation levels
- Coordinate activities with other driving automation research projects

Task 3 focused on describing functional characteristics of driving automation systems. It also maps the sets of automation functions to the defined automation levels. This report presents the results of the work conducted in Task 3.

The AVR project is focusing on the functional building blocks and interactions between functions at the vehicle level as well as the dependencies on, and interaction with, the environment which define different levels of automation.

Rationale on Why Driving Automation Levels Are Needed

The increasing deployment of driving automation systems may begin to alter the historical roles of drivers, vehicle manufacturers, federal and state regulators, and law enforcement agencies in maintaining automotive safety. Maintaining safety throughout this transition is an important concern. In order to support the development and deployment of driving automation technologies it is important to consider and communicate the way in which these roles may change. The task of driving can be divided into three types of activities necessary to operate a vehicle (Michon, 1985):

- Operational behaviors such as longitudinal and lateral control as well as object and event detection and classification
- Tactical behaviors such as speed selection, lane selection, object and event response selection, and maneuver planning
- Strategic behaviors including destination planning and route planning

The operational behaviors of longitudinal and lateral control refer to the actions that drivers traditionally perform using closed-loop control of vehicle speed (using the accelerator and/or brake pedals) and position within the driving lane (using the steering wheel). Object and event detection, classification, and response (OEDR) refers to the perception of any circumstance relevant to the immediate driving task, and the appropriate reaction to such circumstance. In the remainder of this report, object and event detection, classification, and response is referred to as OEDR.

Within the overall task of driving, the operational and tactical behaviors relate directly to the dynamic aspects of driving and are thus grouped into what is referred to as the dynamic driving task, or DDT (SAE, 2014). An examination of changes in the driver's role can become the basis for categorizing driving automation systems.

It is important to clarify the difference between the systems for which these categories are intended and those for which these categories are not intended. For purposes of this paper, driving automation systems are designed to provide sustained operation of those subtasks of the DDT allocated to the system for extended periods of time, thus changing the driver's role. (The driver's continued involvement includes such things as engaging the system and resuming control.) Non-driving automation systems do not complete a subtask of the DDT, but do provide temporary or partial support to the driver by augmenting driver operation or intervening in critical situations, and hence the driver's role does not change. For example, a system such as electronic stability control (ESC) only provides temporary support to the driver for short periods of time by intervening in specified situations, enhancing the driver's performance rather than altering their role. Thus driving automation systems differ fundamentally from non-driving automation systems in their intent, extent and/or duration, and the role of the driver.

Traditionally, the design of the machine or automobile has focused around responding to the driver inputs in a predictable and prescribed way with high reliability. The use of the machine and the commands issued to the machine are a role entirely performed by the driver based upon their perception, experience, and desired outcomes. Figure 1 depicts the combined man-machine interface that constitutes the traditional DDT for human operation of a vehicle without a driving automation system.

Automation of elements of the DDT is not new to the automotive industry. However, successful automation to date has focused on rather specific functions designed to provide assistance to the driver while he or she otherwise maintains overall authority of the vehicle. These functions improve the interface between the driver and the vehicle in such a way as to provide better control or more convenient operation but do not fundamentally alter the roles of the driver and vehicle in executing the DDT. Consider conventional cruise control as an example. The driver must turn the feature on and select a desired speed. Once turned on, the automation system (conventional cruise control) will maintain that speed until cancelled by the driver. The automation system is not assessing the driving environment to decide appropriate speed limits, nor making an attempt to assess the safe speed for the current conditions. The automation system is also not considering potential collisions with other vehicles or infrastructure objects.

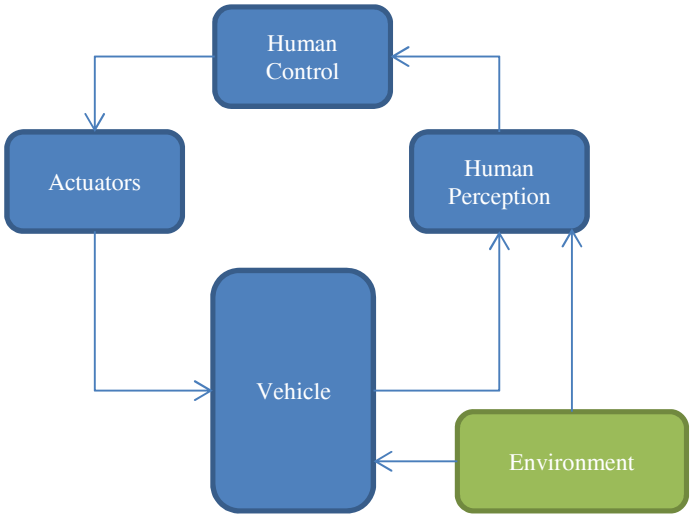

Figure 1: Human Operation of a Traditional Vehicle – the Dynamic Driving Task

Thus for conventional cruise control, avoiding safety-related hazards is a role entirely performed by the driver even though the machine executes its task, i.e., maintains the driver set speed. In this sense, safety is an outcome of the man-machine combination executing all facets of the DDT in unison. The advent of new driving automation technologies which enable additional portions of the driving task to be reallocated from the driver to the vehicle could potentially alter the traditional driver-vehicle relationship. Consider Figure 2 where both the human driver and the machine may have the ability to control the vehicle.

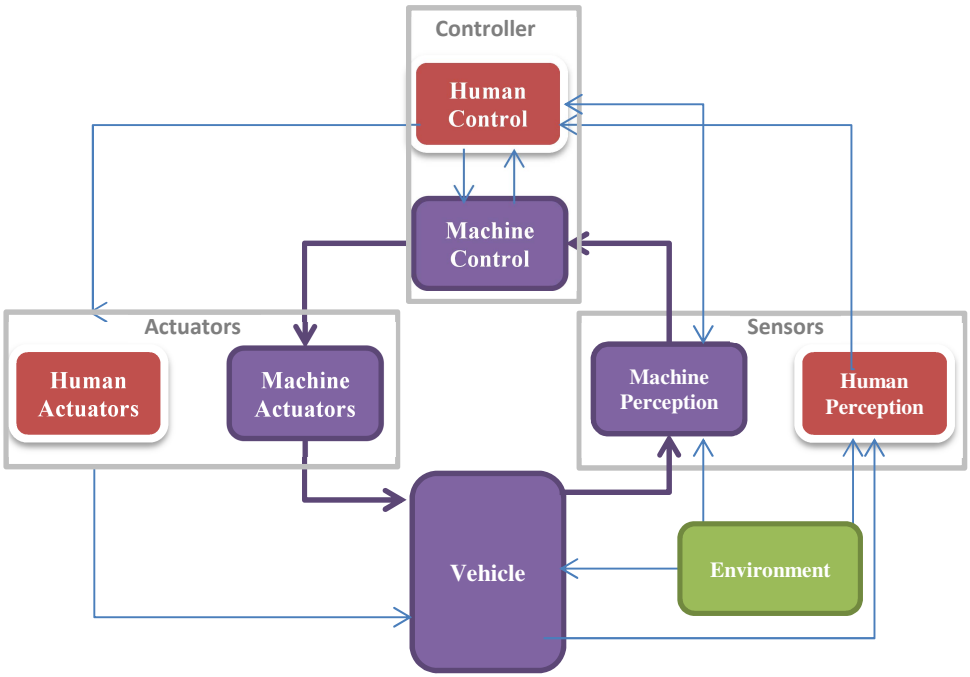

Figure 2: The Introduction of Machine Automation to the Dynamic Driving Task

As previously noted, the DDT includes lateral control, longitudinal control, and object and event detection and response (OEDR). These have not necessarily been altered in number or scope but they may now be expected to be

performed by the human driver, the automated machine, or both. It is this design allocation of the various subtasks which make up the DDT (and the subsequent role of the machine and the human driver in performance of the DDT) that motivates the discussion of categories or "levels" of automation. Engineers, designers, and policy makers benefit by having a way to categorize degrees of automation of the DDT in order to assist in communications between these stakeholder groups. However, it may also help drivers understand their role in the DDT in relation to the designers' intended usage of a driving automation system. The coordination of the driver and the driving automation system in the execution of the DDT (i.e., which elements of it are distributed between man and/or machine) is key to the safe operation of the vehicle.

Consider, for example, an automated parallel parking application. Some current production implementations require the driver to engage the system to look for a parking space on a particular side of the vehicle. Upon scanning an available parking space, the system provides either a confirmation of the ability to park or a denial if no suitable physical space is found. If the system finds a space and the driver confirms the desire to park, the system will automate the lateral control portion of the DDT to enter the space while the driver performs the longitudinal control as well as OEDR portions of the DDT. In making the decision to allow the vehicle to park, the driver is also judging the performance of the automation and ultimately maintaining control of the vehicle. If the steering might lead to a collision or makes the driver uncomfortable, the driver has the ability and is expected to stop the parking maneuver. The system is assisting the driver in executing a steering maneuver just as cruise control assists the driver in maintaining a desired speed, but the driver has the role and ability to make decisions and take actions to avoid collisions. The elements of Figure 2 are preserved, but the functions expected of the driver and system are different than parallel parking executed according to Figure 1.

As driving automation technologies begin to alter the allocation of subtasks that make up the DDT between driver and vehicle, the coordination of the driver and the driving automation system in the execution of the DDT is key to the safe operation of the vehicle. The automation system manufacturer should be conscious of all aspects of the DDT when considering the safety of these systems and consider how the system and the driver individually or together perform all of the dynamic driving task.

This paper discusses the categorical divisions (or "Levels") for driving automation based on the different roles for the driver and driving automation system.

Rationale for Specific Levels of Driving Automation

As discussed in the prior section, the driving automation system and the driver must individually or together perform all facets of the DDT. In addition, it should be noted that this may occur in some or all driving conditions, modes, and/or geographical locations. Under all these circumstances, either the driver or the automation system needs to provide fallback capability in the event that the automation system reaches the limits of its operational authority, or an automation system or vehicle failure occurs.

The most basic level of driving automation only has the functional capability to perform either longitudinal or lateral control with limited sensing capability. With these systems, the driver continues to perform the other motion control task (lateral or longitudinal) as well as the remainder of the object and event detection and response subtask of the DDT. Such systems have been widely researched and deployed (e.g., adaptive cruise control and advanced parking assistance (steering only) systems). Thus, with less capable driving automation where only part of the DDT can be automated, the functional capability to perform either or both longitudinal and lateral control is the relevant distinction to determining the level of the automation. With somewhat more capable driving automation, the system performs both longitudinal and lateral control simultaneously, but cannot perform the complete OEDR subtask. With these systems, the driver continues to perform the remainder of the OEDR subtask.

With highly capable driving automation, the systems can perform the complete DDT, providing appropriate responses to relevant objects and events. However, some systems may only be operational under specific driving conditions, such as during specific driving modes, under prescribed conditions, and/or in limited geographical locations. These systems have "conditionality." Additionally, such a system expects the driver to be able to take over in the event certain types of failures occur (i.e., under conditions that exceed its operational capabilities).

More capable automation systems are able to bring the vehicle to a "minimal risk condition" (SAE, 2014) without driver action in the event that the system is no longer operating in the conditions for which it is designed or the system and/or vehicle experiences a failure, and no driver intervenes. This is also sometimes referred to as "fallback" capability. Thus, conditionality and "fallback" capability are the characteristics that separate higher

levels of automation. Therefore, the automation levels are differentiated according to the following functional characteristics (which are further defined within SAE J3016 as well as German BASt documents):

- These subtasks of the Dynamic Driving Task:
  - Lateral control subtask
  - Longitudinal control subtask
  - OEDR subtask
- These Functional Capabilities:
  - Driving mode, circumstance and location capabilities
  - Fallback capability

Using these functional characteristics, and considering that higher degrees of automation exceed and include lesser automation capabilities, the following defines step-wise levels of increasing driving automation that provide a framework for creation of an automation classification method.

Table **1** provides a visual overview of the SAE/BASt levels and illustrates the distribution of functions by automation level to either the driver or the automation system. Following the table is a detailed description of each level in the taxonomy that are used for the purposes of our research project.

Table 1: Distribution of Functions by SAE/BASt Driving Automation Level

Automation Level Name	Dynamic Driving Sub-Tasks		Functional Capability	
	Sustained Execution of Lateral and/or Longitudinal Control	Object & Event Detection and Response (OEDR)	Fallback Performance of Dynamic Driving Task	Driving Mode Circumstance, Location Capabilities
0 No Automation	Driver	Driver	Driver	None of the DDT is automated
1 Driver Assistance	Driver and system	Driver	Driver	Some driving modes
2 Partial Automation	System	Driver	Driver	Some driving modes
3 Conditional Automation	System	System	Driver	Some driving modes
4 High Automation	System	System	System	Some driving modes
5 Full Automation	System	System	System	All driving modes

Level 0: No Automation – Vehicle features in this level do not automate any of the dynamic driving subtasks on a sustained basis. Thus, it has no driving automation. The driver of a vehicle without any automation performs the complete dynamic driving task. The driver provides the appropriate responses to all driving conditions. Additionally, alert systems that support the driver's OEDR performance, and systems that intervene momentarily in affecting lateral and/or longitudinal control of the vehicle to prevent or mitigate collision (e.g., crash imminent braking systems, electronic stability control, anti-lock brake systems, dynamic brake support, etc.) are included in this level of automation, as they do not automate any part of the DDT on a sustained basis.

Level 1: Driver Assistance – Driving automation systems in this level automate, on a sustained basis, either the lateral control subtask of the DDT, or the longitudinal control subtask of the same. It does not automate both simultaneously. In conjunction with performance of either the lateral or longitudinal control subtask, a Level 1 automation system does perform part, but not all, of the OEDR subtask associated with that aspect of vehicle control. That is, the driver of a vehicle equipped with an active Level 1 automation system performs the remainder of the DDT in all on-road conditions.

Level 2: Partial Automation – Driving automation systems in this level automate, on a sustained basis, both the lateral and longitudinal control subtasks of the DDT simultaneously. In conjunction with performance of the lateral and longitudinal control subtasks, a Level 2 automation system may also perform part, but not all, of the OEDR subtask. That is, the driver of a vehicle equipped with an active Level 2 automation system performs the remainder of the dynamic driving task (i.e., the remainder of the OEDR subtask) in all on-road conditions.

> **Note on Terminology**
>
> It should be noted that at this point in the hierarchy of levels, we are distinguishing preceding and following levels. Namely, Levels 0-2 encompass features that automate either none or some of the DDT, but not all of it, whereas Levels 3-5 encompass features that automate the entire dynamic driving task, whether on a part-time basis (limited range of on-road operational capability) or full-time basis (unlimited range of on-road operational capability). Because automation systems in Levels 3-5 are capable of performing the complete DDT, providing appropriate responses to relevant objects and events, they are referred to in this report as higher automated vehicle systems.

Level 3: Conditional Automation – Higher driving automation systems in this level automate the complete DDT, providing appropriate responses to relevant objects and events. However, the automation is situationally-limited in functional capabilities both in terms of driving modes, circumstances, and/or locations and in terms of fallback performance capability. That is, Level 3 higher driving automation system applications are capable of performing the complete DDT under limited conditions, outside of which the driver performs the complete DDT. In the event that the driving automation system is nearing the end of its operating capabilities (i.e., is about to transition out of the driving mode, conditions, and/or location(s) for which it is designed or experiences a relevant failure in the automation system), the system will warn the driver of the need to resume performance of the DDT far enough in advance to permit an orderly and controllable transfer. If the driver fails to respond in time to such a takeover warning, the automation system may not be able to achieve a minimal risk condition in all cases. In addition, the driver's fallback role includes detecting vehicle failures. The driver's role here includes passive monitoring, both for automation system-initiated takeover requests. Active supervision of the automation operation or the driving environment is not part of the driver's role in Level 3 automated operation. This differentiation may be operationalized with respect to driver visual attention. The driver's visual attention is not required to monitor the roadway for purposes of performing the OEDR subtask of the DDT in Level 3 operation. However the driver still has the role to sense (through visual, auditory, haptic and/or kinesthetic senses) if there is a takeover request issued by the automated driving system. The details of this driver fallback capability are a human factors topic and is outside the scope of the project. Other NHTSA research efforts (e.g., the current Human Factors Evaluation of Level 2 and Level 3 Automated Driving Concepts Project) will address some of the issues in this topic.

Level 4: High Automation – Driving automation systems in this level automate the complete dynamic driving task, providing appropriate responses to relevant objects and events. However, the automation is situationally-limited in operational capabilities in terms of driving modes, circumstances, and/or locations. In the event that the system is nearing the end of its operating capabilities (i.e., is about to transition out of the driving mode, conditions, and/or location(s) for which it is designed *or* a relevant failure in the system and/or vehicle occurs), the automation system

will warn the driver of the need to resume performance of the DDT far enough in advance to permit an orderly transfer. If the driver fails to respond in time to a such a takeover warning, the system will automatically achieve a minimal risk condition. (Note that the difference between a Level 3 and a Level 4 driving automation system is that the latter will reliably achieve a minimal risk condition without driver support, whereas the former will not reliably do so.)

Level 5: Full Automation – A driving automation system in this level automates the complete dynamic driving task, providing appropriate responses to relevant objects and events without situational limits in functional capabilities. That is, Level 5 systems are capable of completely performing the dynamic driving task under all on-road conditions in which a human driver can legally drive a motor vehicle today.

Methodology for Classifying Features to Driving Automation Levels and Example Classifications

As shown previously in

Table **1**, there are four important characteristics, which differentiate the levels of automation:

1. The performance of the DDT (lateral and longitudinal subtasks)
2. The nature of immediate, situationally-relevant environmental sensing and response
3. The fallback capability
4. The scope and range of operational capability

By their very nature, these factors address the system design and driver role in mitigating the hazards associated with on-road performance of the complete dynamic driving task (DDT). The basic hazards to be considered are as follows:

1. Staying on the road surface
2. Avoiding collisions with other objects on the roadway
3. Maintaining the stability and controllability of the vehicle during normal operation
4. Maintaining the stability and controllability of the vehicle in failed conditions

Discussion of Levels

A Level 0 feature is characterized by no sustained automation of the DDT, it is the driver's role to execute the basic functions of, and to mitigate the basic hazards associated with, the DDT at all times. Vehicle design can support the driver with these roles through intervention and monitoring aids such as stability control, forward and/or lateral collision warning or crash imminent braking, but the driver performs the DDT.

As automation begins to relieve the driver of certain functions such as longitudinal spacing or lateral positioning, the role of the machine and the driver in avoiding hazards may become less easily distinguishable. It is, therefore, through these definitions of higher automation levels that we seek to clearly define the distribution of driving tasks between the driving automation system and the driver at each level of automation.

A Level 1 driving automation system is characterized by sustained longitudinal or lateral control subtask performance of the DDT. It may be capable of avoiding some collisions within its control and sensing capabilities but it cannot completely avoid all possible crashes with objects. Thus, the driver supervises the automated vehicle system performance and intervenes as necessary to perform all remaining aspects of the DDT. For instance, adaptive cruise control traditionally performs longitudinal control within limits of maximum acceleration to mitigate stability issues on wet or slippery roads. However, it cannot make lateral avoidance maneuvers nor unlimited braking applications. It may also only respond to metallic objects moving within certain operational constraints. The feature automates a limited scenario and the driver is tasked with maintaining lateral control to stay on the road, maintain lanes, and avoid objects laterally and longitudinally if required. By the nature of the driver's role in the complete system operation, drivers are attentive to the external driving environment (ACAS FOT, 2005). Objects not within the defined operational set, such as accelerations required above the system limitations and vehicle dynamics limitations due to road surface conditions, are monitored, and responded to, by the driver. The vehicle

may warn if adverse conditions are detected but the driver intervenes when the system limitations are, or imminently may be, exceeded.

A Level 2 driving automation system is characterized by sustained lateral and longitudinal control subtask performance of the DDT but again within a defined boundary of operation. For example, pending conditions, the system may see some road lines but perhaps not road edges. It may see vehicles with large metallic content but it may not see pedestrians or small animals particularly those entering the scene laterally from behind an occluding structure. A Level 2 system has lateral and longitudinal control capability that may appear expansive but has limits both in actuator and sensing capability that may make it suitable only for some specific automation tasks and only under prescribed operating conditions. Drivers still monitor the external environment and make judgments about the suitability for use of the automation with Level 2 systems. Drivers intervene as needed if the limits of the automation system's design range of authority are reached, or if a system or vehicle failure occurs, to ensure all possible hazards are mitigated.

A Level 3 driving automation system has full sensing and actuation capability to mitigate all of the DDT -associated hazards but within a prescribed operating envelope. An example might be low-speed parking operations with all vehicle functions operating normally, or an application designed to operate the vehicle in dense traffic conditions on limited access freeways. The driver does not monitor the driving environment but responds to prompts from the automation system directing him/her to resume control in a reasonable time frame. These prompts would occur in the event that the system operational range has been exceeded (e.g., no longer in a parking area), or a relevant system or vehicle malfunction has occurred. It is worth noting that at the machine level, the appearance of a Level 2 and a Level 3 feature may be indistinguishable to drivers not aware of the design intent. Subtle limits of sensing capability or handling of particular vehicle failures might distinguish a Level 2 from a Level 3 system and without detailed design documentation and access to specific internal data, a driver may not be able to properly classify a new feature.

Level 4 and Level 5 driving automation systems are distinguished from lower levels because the driver does not intervene or play any role in the avoidance of the hazards associated with the DDT. A Level 4 system may have a limited scope of operation such as highways only, but it will have authority to achieve its mission and avoid all hazards associated with that mission within its scope of operation and also have the capability to reach a minimal risk condition. A Level 5 system will have these same capabilities except without a limit of scope other than the confines of the legal road system and infrastructure. Thus it will provide full-function, point-to-point driving automation with the ability to use all surface streets as it deems appropriate to the mission.

Given these characteristics of driving automation features and automation levels, the following methodology can be used to assign a new automation feature to one of the automation levels described above Figure 3 shows a flow-chart which distills the methodology for classifying automation features to levels of automation. The encircled numbers shown in the figure are the automation levels, resulting from following the Y(es) or N(o) paths when answering the specified questions sequentially from top to bottom.

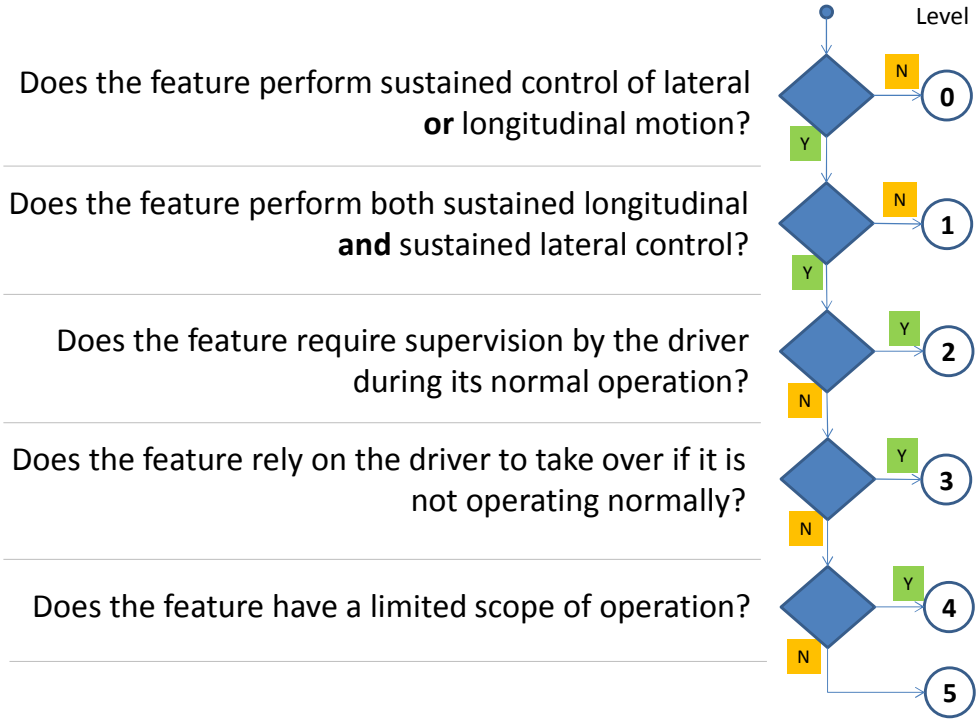

Figure 3: Flow Chart Illustrating the Methodology for Classifying Automation Features to Levels of Automation

Example Classification of Driving Automation Features Using the Methodology

The following list of driving automation features is provided to illustrate the use of the classification methodology. The descriptions are reproduced from the corresponding references, whenever available:

- Cruise Control (CC): Once this feature is engaged, the vehicle will perform longitudinal control (i.e., maintain the driver specified speed) within a limited driving domain (e.g., speed range, acceleration and deceleration/coast capability) until disengaged by the driver or due to a detected fault
- Adaptive Cruise Control (ACC): While engaged, it performs longitudinal control within a limited driving domain (e.g., speed range, acceleration and deceleration/coast capability, environmental conditions). ACC may perform distance (headway) control to some detected objects (again within its limited domain) in addition to its speed control capabilities. As with conventional cruise control, the driver supervises.
- Cooperative Adaptive Cruise Control (C-ACC): Same as ACC except the ACC-equipped vehicle and other vehicles in front of it are equipped with vehicle-to-vehicle (V2V) communication capabilities so as to inform each other of their current speed and other operationally relevant parameters (Nowakowski et al., 2010).
- Super Cruise: "Super Cruise is capable of semi-automated driving including hands-off lane following, braking and speed control under certain driving conditions. The system is designed to ease the driver's workload on freeways only, in bumper-to-bumper traffic and on long road trips; however, the driver's attention is still required" (General Motors, 2013).
- Automatic Parking:
    - "Toyota's Intelligent Parking Assist (IPA): This system assists with the steering wheel operation while parallel parking or parking in garages. When the driver sets the designed parking position on the monitor, the system assists the steering wheel operation" (Toyota Motor Corporation, 2014).

- "The Audi technology works through a mobile app. A driver exits the car at the entrance to a parking garage, then simply touches the app on a mobile device so the driverless car can scour the garage for an open space. It then parks itself. When the driver returns, he or she simply selects the app again and like valet parking, the car returns to the entrance" (Mearian, 2013).

- Traffic Jam Assistant: "The traffic jam assistant helps you in monotonous situations on the motorway. In dense traffic at speeds of up to 40 km/h, the system allows you to move easily along with the traffic and stay relaxed. It automatically maintains the desired distance from the vehicle ahead and regulates the car's speed right down to standstill – as well as providing active steering support, too. This helps you stay on track, providing you keep at least one hand on the steering wheel" (BMW AG, 2013).
- Highway Driving Assist: "Toyota's Automated Highway Driving Assistant: The first part of the system is the Cooperative-adaptive cruise control, essentially a next-gen automated cruise control. The system uses 700 MHz band vehicle-to-vehicle ITS communications to gather acceleration/ deceleration data from the vehicles ahead and maintain a safe, uniform following distance. The second part of AHDA is Lane Trace Control, which Toyota described to us as a more advanced form of its Lane Keeping Assist system. Current-generation lane systems simply provide a warning or minimal amount of steering feedback when the vehicle begins to stray from the lane, but Toyota's Lane Trace adjusts the steering angle, torque and braking in order to maintain a driving line within the lane" (Weiss, 2013).
- Closed Circuit Automatic Shuttle/Delivery Vehicle: A vehicle that drives along a fixed route (i.e., a particular form of limited driving domain, limited to a specific route; the system may have other domain limitations such as weather conditions). The passenger (or goods) can enter and exit the vehicle at a set of stops (i.e., point-to-point). The system does not need an on-board driver control interface to operate within specified operational conditions.

Table 2 illustrates example features derived from the automation features listed above, as well as additional information available to the project team. A generic description based on the information above is provided for each feature in the table. Automation feature descriptions are also provided to illustrate the nature of the variation and facilitate classification of the feature to an automation level. The feature descriptions needed to categorize the levels are shown in the columns on the right side of the table.

Table 2: Exemplar Driving Automation Features

		Descriptions required to categorize levels			
				Only required if driver does not have supervisory role	
Feature	**Description**	Sustained Control	Sensing and Response Capability (Driver's supervisory role)	Fallback	Operational conditions
Cruise control	Once this feature is engaged, the vehicle will perform longitudinal control (i.e., maintain the driver specified speed) within a limited driving domain (e.g., speed range, acceleration and deceleration/coast capability) until disengaged by the driver or due to a detected fault (see also in Section 2 of this report).	Sustained Longitudinal control	Driver must supervise		
Adaptive Cruise Control (ACC)	While engaged, it performs longitudinal control within a limited driving domain (e.g., speed range, acceleration and deceleration/coast capability, environmental conditions). ACC may perform distance (headway) control to some detected objects (again within its limited domain) in addition to its speed control capabilities. As with conventional cruise control, driver supervision is required (see also in Section 6.1 of this report).	Sustained Longitudinal control	Driver must supervise		
Cooperative Adaptive Cruise Control (C-ACC)	Same as ACC except the ACC-equipped vehicle and other vehicles in front of it are equipped with vehicle-to-vehicle (V2V) communication capabilities so as to inform each other of theirs current speed and other parameters (Nowakowski et al., 2010).	Sustained Longitudinal control	Driver must supervise		
GM Super Cruise	"Super Cruise is capable of semi-automated driving including hands-off lane following, braking and speed control under certain driving conditions. The system is designed to ease the driver's workload on freeways only, in bumper-to-bumper traffic and on long road trips; however, the driver's attention is still required" (General Motors, 2013).	Sustained Lateral and Longitudinal control	Driver must supervise		
Toyota Intelligent Parking Assist	"This system assists with the steering wheel operation while parallel parking or parking in garages. When the driver sets the designed parking position on the monitor, the system assists the steering wheel operation" (Toyota Motor Corporation, 2014).	Sustained Lateral control	Driver must supervise		
Audi Parking System	"The Audi technology works through a mobile app. A driver exits the car at the entrance to a parking garage, then simply touches the app on a mobile device so the driverless car can scour the garage for an open space. It then parks itself. When the driver returns, he or she simply selects the app again and like valet parking, the car returns to the entrance" (Mearian, 2013).	Sustained Lateral and Longitudinal control	No driver required, therefore no supervisory requirements	Driver is not required	Low speed, parking lot only
Traffic Jam Assistant	"The traffic jam assistant helps you in monotonous situations on the motorway. In dense traffic at speeds of up to 40 km/h, the system allows you to move easily along with the traffic and stay relaxed. It automatically maintains the desired distance from the vehicle ahead and regulates the car's speed right down to standstill – as well as providing active steering support, too. This helps you stay on track, providing you keep at least one hand on the steering wheel" (BMW AG, 2013).	Sustained Longitudinal control	Driver must supervise		
Toyota Highway Driving Assistant	"Toyota's Automated Highway Driving Assistant: The first part of the system is the Cooperative-adaptive cruise control, essentially a next-gen automated cruise control. The system uses 700 MHz band vehicle-to-vehicle ITS communications to gather acceleration/ deceleration data from the vehicles ahead and maintain a safe, uniform following distance. The second part of AHDA is Lane Trace Control, which Toyota described to us as a more advanced form of its Lane Keeping Assist system. Current-generation lane systems simply provide a warning or minimal amount of steering feedback when the vehicle begins to stray from the lane, but Toyota's Lane Trace adjusts the steering angle, torque and braking in order to maintain a driving line within the lane" (Weiss, 2013).	Sustained Lateral and longitudinal control	Driver must supervise		
Robotic Taxi	A vehicle that can pick up passengers (or goods), then drive them to the place of their choosing (i.e., point-to-multi-point). The system is not required to have an on-board driver control interface to operate within specified operational conditions. The system does not have limited domains of operation, it can operate within any legal road system and under any environmental conditions deemed acceptable by road system authorities (i.e., when roads are open). This hypothetical vehicle is claimed to be one of the future products of Google's self-driving car program (see, e.g., Fitzsimmons, 2013).	Sustained Lateral and Longitudinal control	No driver required, therefore no supervisory requirements	No driver required	any publicly available roads
Closed Circuit Automatic Shuttle/Delivery Vehicle	A vehicle that drives along a fixed route (i.e., a particular form of limited driving domain, limited to a specific route; the system may have other domain limitations such as weather conditions). The passenger (or goods) can enter and exit the vehicle at a set of stops (i.e., point-to-point). The system is not required to have an on-board driver control interface to operate within specified operational conditions.	Sustained Lateral and Longitudinal control	No driver required, therefore no supervisory requirements	No driver required	fixed route

Table 3 illustrates the application of the developed methodology to map the features into the automation levels. The methodology question from Figure 3 is shown in the first row. The feature's automation level results from answering "Yes" or "No" to the appropriate question. The arrows indicate whether to move to the next question (right-arrow) or to stop at the resulting level (up-arrow). Comments are also provided regarding assumptions made based on the feature description, whenever necessary.

It should be noted for the given feature, it is very important to have sufficient information in the description to be able to answer the methodology questions unambiguously. Consider Toyota's Automated Highway Driving Assistant as an example of classifying a feature to an automation level. According to the flow chart in Figure 3, the first question asked is whether the feature is capable of sustained control of either lateral or longitudinal motion in lieu of the driver. Clearly, the answer is yes, therefore, the logical flow proceeds to the next question. The answer to the second question is again yes, because the feature can control the vehicle both laterally and longitudinally on a sustained basis in lieu of the driver, according to the feature's description. The next question is whether the feature requires a driver's supervision during its normal operation. The feature description as provided above is not complete, however Toyota's current view is that the human supervision is necessary, meaning that the answer is yes and that the feature is thus classified as Level 2.

Table 3: Mapping Automation Features into Driving Automation Levels

Automation Methodology Question	Sustained Lateral **OR** Longitudinal control?	Sustained Lateral **AND** Longitudinal Control?	Driver supervision required?	Driver required outside normal operation?	Limited scope of operation?	
Automation characteristic	**Control**		**Sensing and response**	**Fallback**	**Operational conditions**	
Answer confirms level or proceeds to next question	Yes →	Yes →	No →	No →	No →	
	No ↑	No ↑	Yes ↑	Yes ↑	Yes ↑	
Automated level	**0**	**1**	**2**	**3**	**4**	**5**
Cruise control	Yes →	No ↑				
Adaptive cruise control (ACC)	Yes →	No ↑				
Cooperative Adaptive cruise control (C-ACC)	Yes →	No ↑				
GM Super Cruise	Yes →	Yes →	Yes ↑			
Toyota Intelligent Park Assist	Yes →	No ↑				
Audi Parking System	Yes →	Yes →	No →	No →	Yes ↑	
Traffic Jam Assist	Yes →	No ↑				
Toyota Highway Driving Assistant	Yes →	Yes →	Yes ↑			
Robotic Taxi	Yes →	Yes →	No →	No →	No →	↑

Conclusions

The introduction of higher levels of driving automation technologies has the potential to alter the traditional driver-vehicle relationship. However, in order to facilitate discussion about automated vehicle technologies, it is beneficial to define categorical divisions for driving automation based on the functional capabilities of the automation and the role of the driver in the DDT.

While there are several different automation level definitions under consideration at the time of this writing, this paper and the methodologies discussed have been based on the SAE J3016 (2014) and BASt levels. In addition, the automation levels developed in this research, including supporting terms and definitions, focus on:

a) The functional capability of the automation system (and the subsequent role of the driver vs. the automation system) to perform the complete DDT

b) The ability of the driver and the automation combined to provide the appropriate responses to relevant objects and events

c) The driving mode

d) The fallback capability of the automation system

Once a clear definition of the automation is provided, the minimum set of automation functions for each level of automation can be defined. It is important to note that the higher levels of driving automation include those functional capabilities found at the lower levels of automation, and that each increasing level of automation includes functions aimed at reducing the driver's role in completing the DDT.

Lastly, the methodology in this report that allows classification of new automation applications into the automation levels is based on the automation functions provided by the feature. These functions include the nature of the vehicle control aspect provided by the feature, the nature of the environmental sensing and response, the fallback strategy employed, and the feature's scope of operation. Given this information about an automation application, it is possible to classify potential automation features to an automation level by following the approach outlined in this paper. However, a detailed understanding of the driving automation system design is needed to make this classification correctly.

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Analysis of Vehicle-Based Security Operations

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Abstract

Vehicle-to-vehicle (V2V) communications promises to increase roadway safety by providing each vehicle with 360 degree situational awareness of other vehicles in proximity, and by complementing onboard sensors such as radar or camera in detecting imminent crash scenarios. In the United States, approximately three hundred million automobiles could participate in a fully deployed V2V system if Dedicated Short-Range Communication (DSRC) device use becomes mandatory. The system's reliance on continuous communication, however, provides a potential means for unscrupulous persons to transmit false data in an attempt to cause crashes, create traffic congestion, or simply render the system useless. V2V communications must be highly scalable while retaining robust security and privacy preserving features to meet the intra-vehicle and vehicle-to-infrastructure communication requirements for a growing vehicle population.

Oakridge National Research Laboratory is investigating a Vehicle-Based Security System (VBSS) to provide security and privacy for a fully deployed V2V and V2I system. In the VBSS an On-board Unit (OBU) generates short-term certificates and signs Basic Safety Messages (BSM) to preserve privacy and enhance security. This work outlines a potential VBSS structure and its operational concepts; it examines how a vehicle-based system might feasibly provide security and privacy, highlights remaining challenges, and explores potential mitigations to address those challenges.

Certificate management alternatives that attempt to meet V2V security and privacy requirements have been examined previously by the research community including privacy-preserving group certificates, shared certificates, and functional encryption. Due to real-world operational constraints, adopting one of these approaches for VBSS V2V communication is difficult. Timely misbehavior detection and revocation are still open problems for any V2V system. We explore the alternative approaches that may be applicable to a VBSS, and suggest some additional research directions in order to find a practical solution that appropriately addresses security and privacy.

Section 1: Introduction

Dedicated Short-Range Communication (DSRC) can support V2V and V2I communications; however, bandwidth and range limitations challenge integration of safety and privacy features. In order to ensure interoperability between different OEMs, vehicle safety messages (i.e., Basic Safety Messages or BSMs) must be trusted while protecting the identity of the driver or vehicle.

In a traditional public key infrastructure (PKI), participants create, receive, manage, and revoke certificates. A certificate encapsulates a participant's public key and identifies that participant within the system. Each participant signs data using their private key. When a message recipient receives a signed message, the recipient verifies the message signature using the sender's public key to ensure the message has not been altered. Assuming that the sender's private signing key has not been compromised or exposed, the recipient will trust that the sender signed and sent the received message.

The proposed Public Key Infrastructure (PKI) for the Intelligent Transportation System (ITS) Vehicle-to-Vehicle (V2V) safety initiative will be the largest PKI ever deployed. The PKI needs to address the basic security properties (authentication, integrity, and non-repudiation) of a traditional PKI while protecting individual privacy. In the rest of this document, assume that unless otherwise stated, a PKI refers to a PKI for use in a transportation infrastructure and will be used for V2V and V2I. As in most PKIs, revocation is

needed. Revocation typically requires participant identification. For this PKI, the revocation authority would be identifying certificates associated with a particular vehicle or device.

Participant population estimates in a PKI provide a foundation for network traffic, storage, and infrastructure analyses. Using a linear model of U.S. vehicle registration numbers from 2000 to 2012 [FHWA11], the number of registered vehicles in 2016 will be approximately 257 million; this includes public and private automobiles, buses, and trucks. The population of private and public vehicles will be dynamic; vehicles will be added and removed from the system for several reasons. U.S. vehicle population increases on average 1.97 million vehicles per year. This implies that more than 15 million new vehicles are purchased on average each year in the U.S. [NADA14]. When the V2V system is fully deployed, the VPKI system is expected to accommodate more vehicles as the overall U.S. vehicle population is projected to grow. Furthermore, the VPKI needs to manage certificates from the end-of-life, misbehaving, and/or malfunctioning vehicles in order to ensure the integrity of the V2V system and protect the remaining participants from mishaps. The 2011 Automotive Recycling Association Report estimated 12.61 million vehicles are recycled per year; this value is very close to our end-of-life vehicle projections (i.e., 12.96 million per year). The certificates in end-of-life vehicles may potentially be compromised and used maliciously. Vehicles that intentionally use compromised certificates maliciously, or unintentionally malfunction, are classified as misbehaving vehicles; this class of vehicles may cause mishaps intentionally or unintentionally based on their broadcast safety messages.

The deployment of a PKI system relies on a supporting infrastructure. The components and authorities within this infrastructure manage and distribute certificates so participants can communicate in a trustworthy way. However, addressing privacy concerns requires a different certificate management and distribution approach from a traditional PKI that uses inherently identifying credentials. A recently proposed Security Credential Management System (SCMS) for North America adds infrastructure components to provide privacy protection. [Whyte13] attempts to address privacy by building an infrastructure whose architectural design mitigates the possibility of an internal privacy breach, and this work is the basis for the current VPKI, the Security Credential Management System (SCMS) being explored for North America. Several promising alternative strategies have been developed that may allow

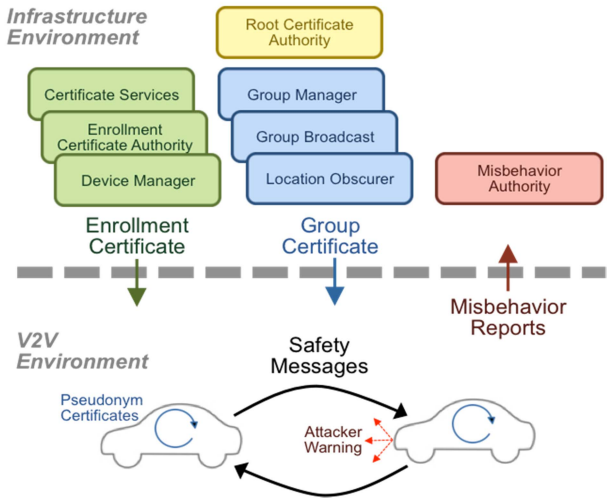

Figure 1: Vehicle-Based Security System

for a reduced level of infrastructure and associated communications with the vehicle. These include privacy-protecting group credentials, shared certificates, and functional encryption [Delgrossi12].

To reduce the supporting infrastructure size and to increase a vehicle's independence from the infrastructure, ORNL has been investigating the potential for a Vehicle-Based Security System (VBSS) to provide security and privacy at the scale of a fully deployed V2V system. Figure 1 is an overview of the operations and components in our VBSS concept.

Communication between the infrastructure components does happen but is not illustrated. Instead of a trusted authority issuing ephemeral certificates, the proposed VBSS uses group credentials, and they facilitate short-lived pseudonym certificate generation on the vehicle. Vehicles form groups, and a vehicle will sign a message using its group signing key while maintaining anonymity. Unlike a traditional PKI message, in order to verify a message, a recipient does not need to know who exactly signed a message.

Group credentials also integrate mechanisms to add and remove participants in an efficient way; this feature can be used for vehicle revocation.

This paper outlines the VBSS structure and its operational concepts; it examines how a vehicle-based system might feasibly provide security and privacy, highlights remaining challenges, and explores potential mitigations to address those challenges. We suggest some additional research directions that will further validate a vehicle-based approach to V2V credential management.

Section 2: Towards a Feasible VBSS

A PKI that addresses privacy must also scale to meet the needs of the U.S. vehicle population. In a PKI, identifying a signer is counter to the goal of maintaining a driver's (signer's) privacy. We assume that a driver wants to ensure the safety messages they transmits cannot be used to expose private details about that individual's movements. If a vehicle used a single private key to sign every safety message, then the associated, publicly available, certificate could be used to identify that driver's safety messages. Such a PKI must manage over 250 million identifying credentials. Scaling to manage this many credentials is a significant challenge. Short-lived pseudonym certificates have been adopted as a way to obfuscate an individual's identity; numerous pseudonyms are used by each driver, multiplying the credential management challenge.

There are many potential cryptographic approaches to achieving a PKI that addresses privacy and scalability. These include functional encryption, shared certificates, and group signatures [Delgrossi12]. Although functional encryption in Vehicle Ad-hoc NETworks (VANETs) has recently received attention [Huang09], the maturity of the technology lags behind the other two approaches.

With shared certificates, a collection of vehicles (sharing group) share a single unique private key to sign safety messages. The verifying certificate of all vehicles within the sharing group provides equal anonymity; however, revoking a single bad participant will have the collateral effect of revoking all the members in the sharing group. To mitigate this collateral damage, each vehicle is given multiple keys. A new shared private signing key can be selected from the "backup" keys when the signing key being used is revoked. With this scheme, all of a vehicle's signing keys could be revoked without any evidence of the vehicle's misbehavior (i.e., a vehicle that unintentionally has behavior that does not conform to an expected adjudicated behavior). While no one has data on the expected or actual misbehaving vehicle rate, we anticipate that the number of misbehaving vehicles will be large requiring extensive mitigation of the collateral damage effect.

Group signatures have been prototyped in VANETs, although they can be computationally demanding. However, other work shows that the computational burden of group signatures does not preclude its use in vehicular networks: Instead of using group credentials to sign each and every message, they could be used to anchor ECDSA certificate trust [Calandriello11]. The group signatures are combined with Elliptical Curve Digital Signature Algorithm (ECDSA) signatures to decrease computational and network consumption. With this strategy, the vehicle acts as a subordinate certificate authority and generates its own ephemeral ECDSA certificates: each vehicle signs a generated ECDSA public key with its group signing key.

The combined use of ECDSA and group signatures is shown in Figure 2. In Figure 2, Alice creates a BSM and signs that BSM with a private pseudonym ECDSA signing key, k_A. This yields the signature Sig $_{k_A}$ (BSM). In this example, Alice also signs the pseudonym certificate with her group signing key and attaches the corresponding signature, $<A>_G$. Then, Alice sends the message and signatures to Bob. If Bob has received a message from Alice in the past, then Bob will trust the message once he verifies the BSM's signature. If Bob has not previously received a message from Alice, Bob will first verify the group

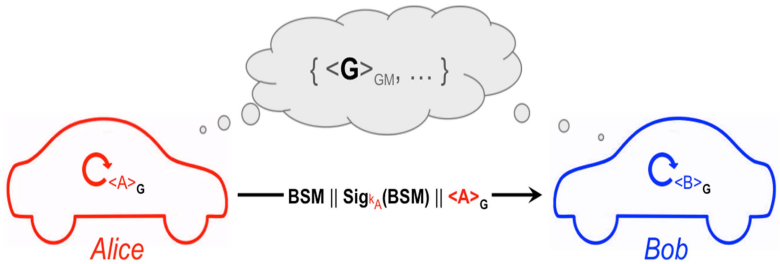

Figure 2: Two Vehicles Communicating Using Group Signed Pseudonyms

signature of the pseudonym, $<A>_{G,}$ by using the group public key. Then, Bob can check the BSM signature using <A>. The circular arrow in Figure 2 signifies the vehicle's ability to generate pseudonyms. Pseudonyms can be created on-demand or in small, custom-sized batches. When a sender transitions to a new pseudonym certificate, the BSM recipient must obtain and verify that certificate prior to authenticating messages.

Section 3: A Group-Based VBSS

In a group signature scheme, a group manager has a role similar to a root certificate authority [Chaum91, Ateniese00, Bellare05]. Any party in the PKI may receive a message signed by a particular group member. If the message recipient is in the same group as the message sender, then their common group public key can be used to authenticate the message. If the message recipient is in a different group from the message signer, he or she must first obtain the sender's group public key and then verify the message (We anticipate that it will be feasible to store all group public keys on a vehicle, and every vehicle starts with all group public keys). Group signatures are anonymous: the group public key, or certificate, only identifies the group and not an individual. When verifying a message, the recipient verifies that the message signer was a valid group member when they signed the message, but no additional identifying information about the message signer is learned.

To form a group, a group manager must be designated and several public parameters chosen. When a potential participant requests assignment to a group, the participant's private pseudonym signing key must either be self-generated or generated by the group manager. In earlier work [Ateniese00], a group member takes part in an interactive group join protocol and receives a membership certificate tuple: a signature in the form of a pair, (A_i, e_i); A_i is computed as part of a zero-knowledge proof (ZKP) that shows that the prospective member knows a secret value, and random prime integer, e_i, usable for member revocation. The group manager creates groups, manages revocations, and identifies group members when needed by revealing a particular signatory. Using the group membership certificate, a participant sends and signs messages. Message verification proves the message signer is part of the group; no other details are provided by the sender.

The number and size of groups is a design choice. Some of the factors that might be used in determining how the U.S. vehicle population is partitioned include: geographic boundaries, vehicle manufacturer, and vehicle make. In other PKI systems, designers have created revocation mechanisms that can address vehicle recalls. Similarly, large subsets of a vehicle population can be revoked directly by removing an entire group when the group partitioning strategy is designed properly.

Table 1 details an example nation-wide group design in the U.S. In this design, there are fifteen thousand groups (and 15,000 corresponding group public keys). This design facilitates recalling a specific make and model of a vehicle in certain geographic regions. In the Table, Local Group Size accounts for all the groups within one of the fifty geographic regions, a state.

Description	**Quantity**
U.S. States	50
U.S. Automobile Manufacturers	30
Manufacturer Models	10
Groups	15,000
System Participants	250,000,000
Participants Per Group	16667
Local Group Size	300

Table 1: Notional VPKI Group Design (U.S.)

One issue with the group credential approach is internal privacy. The group manager can determine who signed a message using the signature and the information it retains about the entire group, a breach of internal privacy. However, internal privacy could be enhanced by splitting the group manager into two logical (or physical) entities; the collusion of both entities would be needed to identify a particular message signatory. In the most recent SCMS specification document [SCMS14], a Trusted Platform Module (TPM) was suggested to isolate and protect linkage authority operations, and this could be done in the same machine. A similar approach could be used to provide internal privacy for the group credential approach.

Group Revocation. Three alternative approaches to revoke a group member using Certificate Revocation List (CRL) are considered. A CRL is a list that grows and shrinks to ideally contain all those participants that could possibly be acting in the system and should be ignored. In one approach, the group manager

issues a CRL to identify revoked participants. The CRL also contains updated group public keys [Ateniese02]. Each unrevoked user uses the same CRL to identify revoked participants and verifies new messages. These CRLs have high overhead and transmission bandwidth costs. More specifically, verification is linear to the number of revoked participants, and the CRL is .proportional to the number of revoked participants [Ateniese02]

In a more recent approach, a revocation list is issued that includes each revoked participant's private key [Boneh04]. This approach may allow an adversary to link messages to a single vehicle. This linking weakness is eliminated in another scheme at the cost of increased computation [Nakanishi05].

In a different approach [Camenisch02], each group public key characterizes its members by accumulating individual, identifying member values; however, the final accumulated value cannot be used to identify any single member. When a group member signs a message, their signature contains a proof, verifiable using the group public key, that some member of the group generated the signature. A group member can be removed, or revoked, from a group. The group manager revokes the member by removing their identifying number from the accumulated value included in the group public key. Although the revoked group member can still sign messages, message recipients will not be able to authenticate the message using the new group public key, since the individual has been removed from the group. New group public keys must be distributed efficiently to all participants that may receive a message from the revoked participant to facilitate this revocation alternative .

Section 4: Trusted Hardware

The cryptographic operations for VBSS will require high performance on-board vehicle computation to sign messages at 10Hz and verify messages at 1000Hz. In research trials, 400 MHz [DOT811492D], 1 GHz, and 3 GHz (i.e., a desktop CPU [DOT811492D]) processors have been used to experimentally evaluate system performance requirements. Exact hardware computational requirements are yet to be established. However, due to added computational burden from group signatures, the VBSS concept may require a custom Application Specific Integrated Circuit (ASIC) to perform trust-critical computation along with another processor (or a core) for additional general computation. We anticipate a 10-15x speedup with new ASICs.

We discuss three possible options for protecting on-board security elements and increasing computation: a TPM, the ARM TrustZone [ARM09], and a Hardware Security Module (HSM). Of these three options, TPMs will not meet the needs of VBSS, since they are resource-limited in computation and I/O. For instance, the ST19NP18-TPM can store only nine keys [ST13]. TPMs often interface over the Low Pin Count (LPC) bus (33 MHz). This limited interface can potentially create a bottleneck for computation. While TPMs are resource constrained, they are an attractive option with an estimated cost of about $1 [Kursawe04].

If ARM chips are used for computation (over 50 billion ARM chips have been produced [ARM14]), the ARM TrustZone architecture could potentially meet VBSS requirements. ARM TrustZone is a proprietary trusted computing architecture that is integrated in many modern ARM chips. In the ARM TrustZone architecture, applications execute in two zones: a Secure World and a Normal World. Sensitive computations are executed in the Secure World. However, when multiple applications execute in the Secure World, establishing trust among secure world applications will add complexity to the system. Some manufacturers are already making automotive compute platforms based on ARM chips [NVIDIA15].

An HSM is a separate and distinct trustworthy computing device. Depending on the HSM, it may have more mitigations against physical tampering, and it may have more powerful computational capabilities. Depending on the features, it may meet VBSS message signing, message verification, key management, and policy enforcement operational constraints. HSM cost varies from the IBM 4765 [IBM4765] that costs several thousand dollars to HSMs for more specific applications cost less. For this application, a custom design produced at scale should be cheaper than more general HSMs; the cost should be feasible for connected vehicle technology. Additional HSM experimentation is needed to verify HSM suitability.

Section 5: VPKI Revocation Goals

The trust among vehicles will be depend on the effectiveness of misbehavior detection and revocation subsystems within the PKI. With imperfect revocation, vehicles may trust an untrustworthy BSM. Traditional CRLs attempt to address all abnormal actors. There are three basic problems with this approach: first, list growth; second, determining when an actor on the list can be removed; and third, checking the list efficiently. These basic problems are particularly hard to contend with in a large, dynamic

environment. There are several properties of this environment that may call for examination of different methods to revoke misbehaving vehicles:

Area of Concern: Vehicles are only concerned about those vehicles that are immediately within their range (e.g., 300m to 1000m range for DSRC is realistic); this area is small, and it is always changing.

Population of Concern: For most drivers, the subset of vehicles that they will encounter over the life of their vehicle will be significantly smaller than the set of all participating vehicles. In other words, most traditional CRL-identified actors are irrelevant for particular drivers. The core challenge is the variation in participating vehicle travel patterns in the U.S. Some drivers will encounter significantly more actors on the CRL than others; therefore, placing restrictions on which misbehaving vehicles are added to the CRL based on geography may cause drivers to trust vehicles they should not.

Immediacy of Concern: Of those vehicles within our area of concern, V2V systems should only focus on vehicles whose trajectory will bring them close to our immediate position; a vehicle may be in our area of concern but its trajectory may never pose a safety problem to our vehicle.

Duration of Concern or Duration of Misbehavior. Malfunctions may occur in the devices that provide data to include in safety messages and in devices used to corroborate vehicle misbehavior. Malfunctions may be short-lived. In the case of a short-lived malfunction, it would be a huge inconvenience for the driver to have to re-enroll in the VPKI for something that was caused by environmental factors.

The misbehavior and revocation goals for a PKI follow. Many of these goals may not be completely achievable in a system of this scale:

Correct detection and classification of participants. In an ideal system, the false positive (incorrectly labeling a vehicle as misbehaving when it is not misbehaving) rate is zero. The false negative rate (not labeling a vehicle as misbehaving when it is misbehaving) is also zero. If there are too many false positives, drivers may ignore safety warnings. With too many false negatives, the opportunity for accidents grows but well-behaved participants may never notice the existence of the unrevoked bad actors. In both cases, trust erodes. In addition to perfect actor classification, an ideal system should correctly identify unintentionally misbehavior and intention misbehavior.

Immediate removal of misbehaving participants. This goal relates to the immediacy of revocation – ideally, detection and revocation happen simultaneously along with notifying the remaining participants in the system of the revocation. In short, identified misbehaving vehicles are immediately unable to interact with others in the PKI; there is no delay. With a system of this scale, this goal cannot be met.

Removed unintentional abnormal actors can immediately rejoin after their vehicle is fixed. If an unintentional misbehaving vehicle is revoked and then fixed, the driver would expect that the vehicle's communication would be restored. Authenticating the unintentional misbehavior is important; this relies on correct detection and classification of participants, and it may be difficult to do.

Upon one or more revocations, remaining non-revoked vehicles continue to function without interruption or extra work. When a vehicle is revoked, the good vehicles that remain should be able to participate in the PKI without interruption and without extra work (except CRL use). In some potential VBSS schemes [Tengler07, White09, Haas09], a normal non-misbehaving vehicle may have to do some amount of extra work to remain in the system. When comparing revocation systems, the amount of extra work that a non-misbehaving vehicle must perform to remain part of the PKI is a potential metric of comparison.

Section 6: Misbehavior Detection: From Local to Global

The number of vehicles that will be revoked over some defined time period is a valuable estimate when determining the feasibly of a vehicular credential management system. In a traditional PKI, revocation strategies are used to handle inappropriate or malicious use of credentials. In a VPKI, revocation strategies are needed to address malfunctioning vehicles, as well as malicious vehicles that could cause vehicle mishaps. Since this system has not been realized or simulated at scale to our knowledge, estimates are hard to derive and justify. Four classes were identified to stratify the broader estimation problem. These numbers are used to estimate the degree to which revocation will be required in the VPKI being considered for the U.S.

Malicious vehicle. Total elimination of malicious actors is improbable. A malicious participant may avoid detection by learning how global misbehavior detection is performed, for instance the period of time over which misbehavior reports are retained. We hypothesize vehicle credential compromise will be very difficult initially based on the diversity of vehicles, hardware, access points, and communication protocols.

The security posture in this domain makes it hard to estimate the likelihood of certificate compromise. We anticipate that this number will be low compared to the population of malfunctioning vehicles.

Malfunctioning vehicles. Electronic components typically fail early in their lifecycle due to manufacturing defects that escaped quality control and much later when the device reaches its time-to-failure. In between those times, component failure rates remain fairly constant. Component failure rate is also hard to estimate, since many of the components used in these systems are still being developed. Depending on a component's function, it may be possible for the vehicle to self-validate information and avoid broadcasting inaccurate BSMs. Assuming that this capability is possible, we anticipate that the number of resulting revocations will be low.

Environmental-Impacted Malfunctioning Vehicles – vehicles whose component accuracies are affected by environmental conditions. Environmental conditions could lead to a wide range of issues. We do not estimate the impact here.

End-of-life Vehicles: This class of vehicles presents a dilemma: on one hand, we can assume that these vehicles have been completely removed from the system; on the other hand, parts are routinely harvested from end-of-life vehicles and security credentials are potentially valuable resources for bad actors. When the credentials do have value, attackers may harvest certificates from end-of-life vehicles, and then find a way to use them to broadcast targeted messages. We estimated that there are approximately 1 million end=-of-life vehicles per month. Identifying these vehicles and revoking them is a challenge.

Previous estimates put the total population estimates from these three vehicle populations at a relatively low value [Whyte13].

Figure 3 identifies the infrastructure entities involved with misbehavior detection and revocation. The operations involved in misbehavior detection and revocation start with local misbehavior detection and misbehavior reporting. Misbehavior reports are generated by a vehicle that detects an anomalous safety message; the message has a prescribed format; it is encrypted and sent through the infrastructure to the

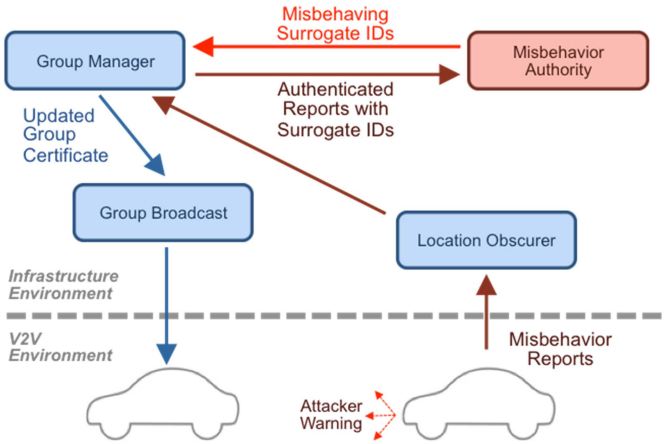

Figure 3: Misbehavior Reporting and Group Certificate Updates

group manager. Global misbehavior detection operates on a collection of misbehavior reports. Finally, group credentials must be modified and redistributed to the participant population.

Local misbehavior detection is a vehicle's intrinsic ability to use on-board hardware (e.g., vehicle-resident sensors) and software to detect safety messages that do not conform to physical reality. This locality is opposite a global system where a central networked system performs misbehavior detection. Local misbehavior detection can be done using software that detects simple safety message anomalies, or in a more complex system corroborate information collected from a vehicle's organic sensors (e.g., radar, lidar, sonar) with received safety messages to determine irregularities more accurately. In global misbehavior detection, other infrastructure components (e.g., a RSU or misbehavior authority) determine if a vehicle is misbehaving.

In recent work, using vehicle-resident sensors, researchers have explored attacker-warning systems that can be used independently or in conjunction with misbehavior reporting and revocation [Calandriello11]. The attacker-warning concept that we outline can extend the range of a vehicle's inherent warning sensors; on-

board sensors may have line-of-sight range or be blocked by surrounding vehicles. Attacker warnings need be within the range of DSRC communications. One of the challenges in realizing an attacker-warning system is trust. Much of the information is provided by sensors whose readings may be suspect (e.g., GPS). Additionally, this is a consensus-based concept without a central trusted authority; this is a significant obstacle. A conceptual attacker warning might employ three operations:

1. Local, or inherent, misbehavior detection
2. Warning transmission: Vehicles and roadside equipment should broadcast warning messages over DSRC to other vehicles in their area of concern. The following information may be important for vehicles able to receive these warnings:
    - The actor's pseudonym certificate. Although these certificates are short-lived, one or two certificates may be sufficient to span the time over which the warned vehicle may encounter the actor.
    - Report time. Due to immediacy of concern and duration of misbehavior, it may be appropriate to limit a warning message's valid time.
    - Reporter position. A vehicle's location changes and may not impact a given situation. This proximity information may help validate the warning or the need to consider the warning. While this could impact privacy, there may be ways to not report the position globally but use this information locally.
    - Consensus information. As a measure to improve warning system trust, warning recipients could rebroadcast validated warning messages with an updated confidence value. Warnings with higher confidence should be more trustworthy.
3. Warning processing: Vehicles should be able to receive and evaluate warnings, and then use these warnings in conjunction with safety messages to improve their safety posture.

There are motivations to combine several approaches. A vehicle can enforce a local policy based on local misbehavior detection. Local misbehavior adjudication helps use valuable DSRC resources more efficiently, decreases the computation required during global adjudication, and it has the potential to reduce global misbehavior detection errors.

Since the effectiveness of using any revocation scheme is unknown in this large-scale VPKI deployment, an incremental approach to handling misbehavior may be worth consideration. In this incremental approach, local misbehavior detection is the most critical; an attacker-warning system might be introduced next; finally, misbehavior reporting to a global authority might be required to improve the overall trustworthiness of the system at the expense of significant communication and processing overhead.

Each misbehavior report contains details from one or more safety messages that the vehicle used to determine local misbehavior. The reporting vehicle must sign all reports to avoid malicious reports from being processed; encryption may also be necessary to maintain the confidentiality of the reporter. In our conceptual VBSS, misbehavior reports flow through a network traffic obfuscator, similar to one that was previously introduced [Whyte13]. Reports are then handed off to the group manager. The group manager verifies the report using the appropriate version of the group certificate making sure the reporting vehicle has not been removed from the group. Then, the group manager will "open" a signed BSM to identify the misbehaving vehicle that signed that BSM and assign it an ephemeral proxy identifier. The purpose of the proxy identifier is to provide a way for the misbehavior authority to aggregate reports on a specific vehicle and not have secret information on a particular driver. A collection of reports on a vehicle does not automatically imply misbehavior; therefore, the misbehavior authority should know as little as possible about the identity of the vehicles it is analyzing in the aggregate. Proxy identifiers will be short-lived, so they do not become unique persistent identifiers and allow the misbehavior authority to break the privacy of vehicles that are found to be behaving correctly. Authenticated reports with a proxy identifier are then passed to the misbehavior authority.

The Misbehavior Authority is responsible for gathering misbehavior reports globally from all the participants in the connected vehicle system. Ideally, the misbehavior authority should be a central entity within the infrastructure; however, misbehavior authorities that are collocated with distributed group managers should be investigated. Global misbehavior detection algorithms are an open area of research [Delgrossi12]; however, one critical property of these algorithms will be their true positive and true negative rate.

Once the misbehavior authority has identified misbehavior, the group manager will remove that vehicle from the group by distributing updated public data including an updated group certificate that will disallow revoked vehicles from continued participation. A removal operation is performed for each validated misbehavior report. In other words, the number of operations necessary to update the trust elements in the

system is linear in the number of revoked vehicles. After a number of removals have been made, group certificate updates will be distributed to system participants. However, the size and number of trust elements is fixed with groups.

Section 7: VBSS Revocation

If a BSM sender or receiver has an outdated group certificate, messages sent between the parties may not be verifiable. This issue holds with many of the group signature schemes. One way to address this issue is to assign vehicles to multiple groups. Assume that a given vehicle is a member of two groups. If one of its two group public keys is old, then the user can use the other corresponding private signing key to create message signatures that can be authenticated. Alternatively, assume both group public keys are old (i.e., the group manager has revoked at least one member in each group). The user may not be able to communicate with other users that are using the most recent public group keys.

As a possible alternative to addressing unsynchronized public key updates, we propose that revocation be staggered. For example, rather than each group member storing a single group public key for a given group, the group member stores the current group public key and the previous group public key. If a group member updates her group public key, she can then verify messages from senders that have updated to the latest group public key, and she can also verify messages from senders who use the previous group signing key. By staggering group public key updates, the immediacy of user updates can be relaxed.

In a traditional PKI, participants may submit certificates to a central authority to check whether they are on the CRL. CRLs may be broadcast to users, so users can check the certificates they receive locally. CRL updates are usually promulgated using delta lists to decrease the amount of communication overhead. When short-lived certificates are used, a central authority can utilize a blacklist to identify those participants whose certificate expirations should not be extended or renewed. The primary issues with these traditional approaches are list management (additions and removals), list size, and list distribution. CRLs have global context: all participants must have knowledge of the complete list since they may interact with a revoked participant.

In a group-based VBSS, the group manager can identify a message sender, since they can "open" a de-identified group signature on a pseudonym certificate. Their role can be split to further distribute the trust elements and make it harder to break privacy, but ultimately when a misbehaving vehicle has been identified its privacy is assumed to be forfeit.

Misbehavior reporting, adjudication, and revocation synchronization challenges exist in the real-time and distributed V2V environment. Because the identification and revocation of a bad participant is not immediate, we now examine how delayed revocation impacts a group revocation system. Figure 4, depicts the evolution of the V2X environment over a period of time where two vehicles have been reported as misbehaving and subsequently revoked from the group. While this figure illustrates some of the synchronization challenges in a VBSS based on groups, other designs [Whyte13] may be susceptible to synchronization issues. In the Figure, time progresses from left to right; the dotted arrow delineates the state of the infrastructure (top) and the state of the vehicular environment (bottom). For simplicity, all vehicles are part of one group. Both environments start in a good state (green) at the left: all parties are using group certificate one (GC1).

In VBSS, vehicle revocation can only occur when misbehavior has been reported, and the misbehavior authority classifies the identified vehicle as misbehaving. These actions will not occur instantaneously. In the Figure, there is a time gap between the Vehicle A misbehavior report and misbehavior adjudication and creation of GC2. Since we have perfect hindsight and Vehicle A is truly misbehaving, the trust state of the V2V environment is degraded at the point in time when Vehicle A started misbehaving – Vehicle A will be

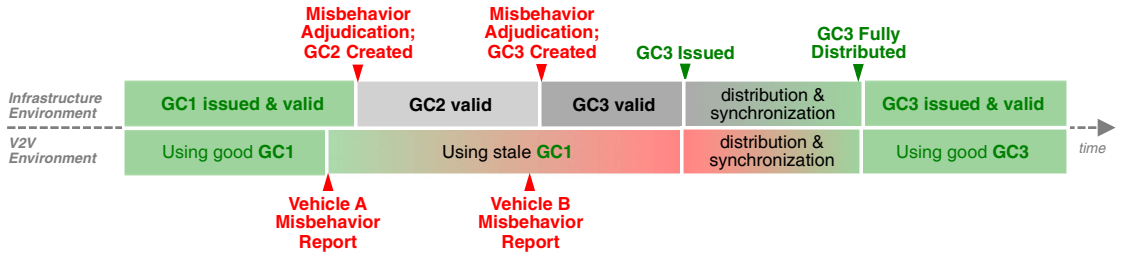

Figure 4: Misbehavior Reporting and Revocation Synchronization

trusted by other vehicles, but it will be transmitting potentially untrustworthy messages that will be verified by recipients. The gradual transition from green to red in the lower portion of the Figure illustrates the effect of this state; more and more vehicles encounter the misbehaving vehicle and will trust its broadcast safety messages. In an ideal system, this transition would not exist; however, misbehavior reporting, misbehavior adjudication, and distribution of updated credential will require time. Decreasing the transition from green to red and back to green is a goal.

When a vehicle is revoked, the group public key must be updated. The infrastructure may not issue new group certificates every time a vehicle is revoked. The propagation of new group certificates consumes communication resources and time.

The gray color in the Figure indicates the time period when the infrastructure's group certificate state differs from the group certificate's state in the V2V environment, because GC2 was not issued by the infrastructure. After the second misbehavior adjudication has been integrated into the group certificate, GC3 is ready to be issued. The group manager then re-issues updated group certificates on a schedule to minimize synchronization problems. Once new credentials are released, vehicles and roadside equipment can transmit these updates to vehicles that have not received the update yet.

In the Figure, the trust of the system is degraded from the time the first vehicle misbehaves until GC3 has been fully distributed. At this point, both environments are synchronized. Any group-signed messages the misbehaving vehicles broadcast will not be verifiable using the updated credentials.

To protect against misbehaving vehicles that have not been revoked, local misbehavior detection is a potential first line of defense. During the distribution and synchronization period, the system gradually returns to a fully trusted state. Certificate caching can be introduced to alleviate the problem of unsynchronized group certificates. Let GC_x be group certificate x, and let each vehicle cache two GC versions: GC_{x-1} and GC_x. We assume the sender is using pseudonyms generated using their most recent GC. Each signature includes a signed identifier (e.g., the value one for a message signed by GC_1, the value two for a message signed by GC_2, etc.). A vehicle can quickly check if it has the most recent GC by checking the identifier.

We consider six abnormal cases where four GC versions have been issued (GC_1, GC_2, GC_3, and GC_4), where GC_4 is the most recent GC. In each case, vehicle A is sending a basic safety message to a receiver, vehicle B. Both vehicles can store up to two certificates. To enable communication between two vehicles, they must have at least one GC_x in common.

Case 1: Functioning with Old Certificates. Both vehicles have cached GC_1 and GC_2. Vehicle B can validate vehicle A's message. If vehicle A has not been revoked, their interaction is equivalent to the case where the most recent update is GC_2 despite both vehicles being out of synchronization with the infrastructure. If vehicle A has been revoked, GC_3 or GC_4 should reflect their removal from the group. However, in their current state vehicle B's trust will be misplaced. To remedy this situation, B should update to GC_4 as quickly as possible.

Case 2: Delay in Revocation. Both vehicles have GC_3 and GC_4. B can validate A's message. It is possible that A could have been reported as misbehaving, but a new update has not been issued – this case must be handled by local misbehavior detection.

Case 3: Partially Unsynchronized Old Sender. A has GC_1 and GC_2 in its cache; B has GC_2 and GC_3 in its cache. B can validate A's message using GC_2. If A has not been revoked, the exchange is equivalent to the case where the most recent update is GC_2. If A has been revoked in GC_3 or GC_4, then B's trust will be misplaced. In all situations, B can notify A that its certificates are out of date since it had to use an outdated certificate to validate the pseudonym. This should cue A to pull the GC_4 update (from a road-side unit or nearby vehicle) and generate new pseudonyms. This case is the main reason more than one GC is cached. B could not verify A's messages if B could only store the latest GC, GC_3. With the caching of GCs, A and B can still communicate.

Case 4: Partially Unsynchronized Old Receiver. Vehicle A has GC_2 and GC_3; vehicle B has GC_1 and GC_2. B can only verify A's signatures if A is using old pseudonyms; this would be abnormal for A. If A were using updated pseudonyms, B will not be able to authenticate A's pseudonyms. In the first case (A uses GC_2), B would still be unaware that it needs to update its certificate but could continue communicating with A; in the later case, B will know to update its certificate when it finds GC_3 was used.

Case 5: Unsynchronized Old Receiver: A has GC_3 and GC_4; B has GC_1 and GC_2. B cannot verify any signed messages from vehicle A. This does not mean that vehicle A's messages are untrustworthy. The signature identifier is a cue for B to check for an updated GC.

Case 6: Unsynchronized Old Sender. A has GC_1 and GC_2; B has GC_3 and GC_4. B cannot validate messages from A. This may mean that A's messages cannot be trusted, or if A is trustworthy it is due to B not having GC_2 in its cache. The signature identifier cues B to obtain an updated group certificate.

Significant communication savings may be possible by using group certificate revocation strategies instead of more traditional certificate revocation lists. When a new vehicle joins a VBSS, it will receive an initial load of group certificates that enable it to authenticate the vehicles within its geographic area. However, only being able to communicate to vehicles in its own geographic area may be insufficient for vehicles that travel outside of their local area. How groups are determined and established is an important area of research. The design must incorporate several factors including the type of large-scale revocation (e.g., recalls) that might be required, laws, and the capabilities of stakeholders to perform certain group manager functions. One possible configuration involves dividing the vehicle population by states, manufacturer, and model.

Because the size of the group certificate is fixed, the storage needed for all of the group certificates is the constraining factor. A group certificate is approximately 900 bytes [Calandriello11] (could potentially use smaller key sizes for reduced certificate sizes). We can use this information to reason about how many groups a VBSS should support. Based on our notional group partitioning strategy, vehicles must store 15,000 group certificates to cover the entire U.S. This will be unnecessary for almost all vehicles in the system. However, if these certificates were stored on the vehicle, the total storage capacity needed would be approximately 13 MB. If we cache the previously used group certificate, then the total amount of storage would be almost 27 MB. These certificates are public and not identifying, so they do not need to be stored in memory whose access is restricted to trusted software and hardware. Our concept includes a mechanism for distribution of trust updates; therefore, storage of this number of group certificates may not be necessary.

End-of-life vehicles. Scaling to address end-of-life vehicle revocation is difficult. As previously noted, there are approximately 1 million vehicles that reach their end-of-life each month in the U.S. Adding these vehicles to a traditional revocation list is prohibitive. To address these vehicles in a group PKI, group certificate size remains fixed independent of the number of updates. The group update distribution process benefits from the fixed group public key size. Traditional CRLs grow linearly in the number of vehicles. In a traditional PKI approach, accommodating end-of-life revocations will make revocation infeasible.

Section 6: Conclusion

Traditional PKIs have been designed and used for specific types of problems where privacy is not a concern (e.g., email). This lack of privacy is an issue for a vehicle PKI. Parties in a traditional PKI will exchange keys and later send and receive messages. When a recipient verifies a message, they assumes that the sender is trustworthy. In a vehicle PKI, a receiver must trust the sender without identifying the sender – the sender should remain anonymous. This is a challenging problem at a large scale, and a different way of approaching the problem is needed. To provide privacy at a large scale, we suggest the use of a group-based approach for VBSS. Our initial analysis shows that using groups in a vehicle PKI helps mitigate some of the issues that we see in other systems.

A great deal of work has been done to address vehicle security and privacy; however, more work and field trials are necessary. Trustworthy hardware may be required on all connected vehicles to protect credentials; it will certainly be necessary to protect a group signing key and the pseudonym generation process in a VBSS. The BSM transmit and receive rates envisioned in high density V2V environments may require high performance trustworthy hardware in vehicles. This system's trust is predicated on the acceptable operation of a misbehavior detection and revocation system. The right balance of local and global misbehavior detection is critical, and more misbehavior simulation and experimental results will help us establish what will be an acceptable operational state. By integrating group certificates, VBSS may address some of the revocation overhead issues in a system of this size; staggered (or cached) group certificate updates offer additional benefits.

An operational VPKI that provides an acceptable level of security and privacy would be a groundbreaking achievement. We are optimistic about the possible solutions VBSS offers: Putting pseudonym generation in the vehicle has benefits; the inherent privacy preserving properties of group signature cryptography mitigates certain types of infrastructure growth. We encourage research that enables a vehicle to produce its own ephemeral certificates while protecting privacy. Using groups, vehicle privacy is maintained through the anonymity afforded by a group. As vehicle PKI research and technology becomes more focused, the unique challenges this environment presents will be addressed and the promise of safer vehicles will be realized.

Acknowledgements

This research was funded by the National Highway Traffic Safety Administration (NHTSA). To date, NHTSA has posed questions and provided insight that has helped guide this work. We would also like to thank Lawrence MacIntyre and Jarilyn Hernandez, our colleagues at the Oak Ridge National Laboratory, for their valuable feedback on this research.

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HUMAN FACTORS EVALUATION OF LEVEL 2 AND LEVEL 3 AUTOMATED DRIVING CONCEPTS

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ABSTRACT

This project evaluates how drivers interact with different automated vehicle functions under various concepts of Level 2 and Level 3 automation. The objective is to determine whether principles for human-machine interface (HMI) design for automated vehicles could be based on things such as timing, sequence, and presentation of automated functions produced by this study. Methods involve test track evaluations of participants using three distinct automation concepts, two involving automation Level 2 and one involving automation Level 3 (as defined by the National Highway Traffic Safety Administration [NHTSA] policy paper on vehicle automation; NHTSA, 2013). Data sources included both objective and subjective data from participants' responses to the different portions of the experimental protocols. Results will be produced from parametric linear regression analyses and qualitative evaluations of participants' subjective responses to questionnaires. Where appropriate, statistical techniques will be applied for conditioning the sample data to ensure that the assumptions underlying these analyses are met. The detailed timing, sequence, and presentation measurements from the various research efforts involved herein will be used to specify human factors design principles for automated vehicle HMIs. The resulting principles would benefit from subsequent naturalistic evaluations for fine-tuning the performance metrics, and for addressing any gaps or new questions arising from this research. Crash avoidance technologies are evolving rapidly toward increasing automation, involving a higher complexity of interoperability between user and vehicle functions than what has previously been known. Understanding the detailed human factors capabilities and limitations of these users and the impacts of the timing, sequence, and presentation of information presented to the users will be important for shaping the safety policies.

INTRODUCTION

Technological advancements over the past decade have led to the emergence of advanced driver assistance systems. Current features such as Adaptive Cruise Control (ACC), collision warning, and automatic braking systems are becoming commonplace in modern automobiles. Furthermore, automated systems that combine limited lateral and longitudinal control over a vehicle are becoming commercially available. Some of these systems incorporate various methods to ensure driver participation.

While automated systems offer the potential for increased safety and reduced human error, their use may create issues which could benefit from further investigation. These issues may include negative adaptations based on misunderstanding, misuse, over-reliance on the automated systems, and distractions from the driving task due to interaction with the automated system. These issues should be examined in order to address any potential for unforeseen consequences of increased automation.

Of specific interest is how an automated system will impact operators' willingness to engage in non-driving-related tasks. As noted in previous work, (e.g., Llaneras, Salinger, & Green, 2013), the current generation of automated systems is designed to support, rather than replace, the driver. The presence of automated systems may create the perception to free an operator's attention, which may then be directed at non-driving tasks. The redirection of the operator's attention to non-driving tasks may also impact an operator's situational awareness, including the ability to perceive critical factors in the environment or to detect issues with the automated systems (e.g., system state changes or failures).

As automated driving technology advances, the "driver's" role is shifting from active vehicle control to passive supervision of the automated system and/or the environment. The current study focused on the human factors issues that arise when vehicles equipped with automation technologies shift the human from the role of driver to that of operator. Automated vehicle systems must be designed to instruct and prompt the operator to act, if and when needed, in a timely and appropriate way in order to ensure safety. This study investigated how operators interact with partial automation under National Highway Traffic Safety Administration (NHTSA) Levels 2 and 3 (NHTSA, 2013). Level 2 (Combined Function Automation) and Level 3 (Limited Self-Driving Automation) were of particular interest because this is the point at which the driver's role transitions from one of driving to one of operation.

Objective

The purpose of this study was to examine the interaction between human users and automated vehicle systems. Specifically: how do human users interact with vehicles that have L2 and L3 automated systems, can these users take over control of the driving task when required, and can they determine the acceptable balance between controlling the vehicle when necessary and letting the automated system function as designed to perform the driving task when appropriate? The ultimate goal of this research was to ascertain how operators interact with automated vehicles and determine how automated vehicle technology can best support safe driving.

Project Research Questions

This study centered on six key research questions developed by NHTSA. The focus of this research was to address each question based on sound empirical research findings. The research questions were:

1. How do drivers interact with and operate vehicles that offer Level 2 and Level 3 automation; e.g., what is the driver performance profile over length of time in continuous or sustained automation?
2. What are the system performance risks from driver involvement with, and interruption from, secondary tasks (such as portable electronic device use) that could arise when operating Level 2 or Level 3 automated vehicle systems?
3. What are the most effective hand-off strategies between the system and the driver, including response to faults/failures?
4. How do drivers engage, disengage, and reengage with the driving task in response to the various states of Level 2 and Level 3 automation?
5. How do drivers perform under various operational concepts within Level 2 and Level 3 automation, such as systems intended for everyday driving on open roadways in mixed traffic or systems intended for dedicated roadway-vehicle applications (e.g., automated lanes, remote highways)?
6. What are the most effective human-machine interface concepts, guided by human factors best practices, which optimize the safe operation of Level 2 and Level 3 systems?

The six aforementioned research questions were addressed in three experiments. Experiment 1 examined how best to alert operators to regain control of the vehicle, Experiment 2 examined the system prompt effectiveness (i.e., how effectively the HMI communicated to the operator) over time, and Experiment 3 examined operator behavior over time. Experiments 1 and 2 were conducted using a vehicle equipped with an L2 system, while Experiment 3 was conducted with a vehicle equipped with an L2 system that can simulate L3 driving on a test track. The details of the experiments and their expected findings are presented in the following sections.

EXPERIMENT 1: ALERTING OPERATORS TO REGAIN CONTROL OF AN L2 AUTOMATED VEHICLE

Purpose

There are numerous ways to notify operators that they need to regain control of a partially automated vehicle. The purpose of this experiment was to investigate which human-machine interface (HMI) characteristics are most effective at issuing a Take-Over Request (TOR) and to identify the transition times between the operator and the automated functions in regard to the driving tasks.

Participants

Data were collected from 35 participants recruited from the greater Detroit, Michigan area; however, 10 participants were considered invalid (i.e., session cancellation due to adverse weather, track closures, or technical issues associated with the prototype vehicle). As such, the analysis will represent data from 25 participants (16 males, 9 females). The mean age of participants was 44.3 years old (S.D. = 19.24), with ages ranging from 18 to 72 years old.

Method

A single, long-exposure, experiment was conducted. Participants were provided with a thorough familiarization of the vehicle and its operation, followed by a single, approximately 90-minute, exposure to the vehicle in L2 automated driving. During the driving session, participants were instructed to perform non-driving-related tasks (e.g., e-mail, web browsing) and were, at times, presented with alerts stating that they must take control of the vehicle. Three forms of alerts were presented: Cautionary, Imminent, and Staged. The Cautionary alerts provided information to the participants that a potential problem was detected. The Imminent alerts provided the participants with a message that an active fault was detected. The Staged alerts transitioned from a cautionary alert phase to an imminent alert phase. Participants' reactions to these messages, both in duration and method of response, were among the variables examined in this experiment.

Experimental Design

The study was performed as a within-subject design. All participants completed one 90-minute driving session during which they received a total of 19 system alerts. For each of the alert types, participants experienced three unimodal alerts (visual only) and three multimodal alerts (visual + haptic). The study was designed to mimic worst-case scenarios when the operator was not monitoring the roadway due to the non-driving tasks.

The alerts were presented to participants in six different orders. Each order consisted of the six different combinations of alert type and alert modality, and this was repeated three times within the experimental session. Using all six possible alert type and alert modality combinations, a Latin square was developed to create six different orders of alert presentation. The order was repeated three times within the 90-minute driving session, resulting in 18 alerts. After receiving these 18 alerts, each participant received an Imminent multimodal alert coupled with an experimenter-triggered lane drift, resulting in a total of 19 alerts. The alerts were presented at random times between 2 and 8 minutes; thus, participants were less likely to be able to anticipate when they would occur.

Venue

This experiment was conducted at the Milford Proving Ground circle track in Milford, Michigan. This facility is owned and maintained by General Motors (GM) and includes a 4.5-mile banked circle track with five travel lanes. The travel speed for each lane falls within a designated speed range, with the innermost lane allowing for stop and go traffic and the outermost lane being restricted to speeds of 100 mph and above. Experiment 1 was conducted in Lane 3, which allowed speeds of between 50 - 70 mph.

Vehicle

A 2009 Chevrolet Malibu equipped with a prototype L2 automated driving system was used (See Figure 1). As part of the automated driving system, several HMI components were installed and the vehicle was modified to include ACC and lane centering along with a flexible driver interface. Additionally, the vehicle was equipped with a researcher's control console, which was designed to allow the in-vehicle experimenter to trigger various displays and to change the operation of the automation systems, including simulating erroneous behavior and equipment failures.

Figure1. 2009 Chevrolet Malibu with a prototype L2 system used in Experiment 1.

The vehicle was also equipped with a data collection and recording device. These key variables were collected: status of the automation (e.g., off, on and actively controlling, failure mode), vehicle speed, lane position, and flags indicating the presentation of messages and system failures. In addition, video views which included the operator's face, forward roadway, and HMI were collected.

Study Session

Prior to beginning the study session, participants were provided with a static orientation to the experimental vehicle, which included information about the basic controls and the L2 automation features. Following this, participants received an on-track orientation consisting of four laps on the test track. During the 90-minute driving session, participants were instructed to perform a variety of non-driving tasks using a tablet computer when the L2 automation was activated. Participants were presented with three types of non-driving tasks to complete using the tablet computer: navigation, email, and web-browsing. At approximately 5-minute intervals (in random values ranging from 2 to 8 minutes), participants were provided with unimodal (visual only) or multimodal (visual + haptic seat vibration) alerts (Cautionary, Imminent, or Staged) instructing them to take control of the vehicle. Details pertaining to the Cautionary, Imminent, and Staged alert timings are depicted in Figure 2.

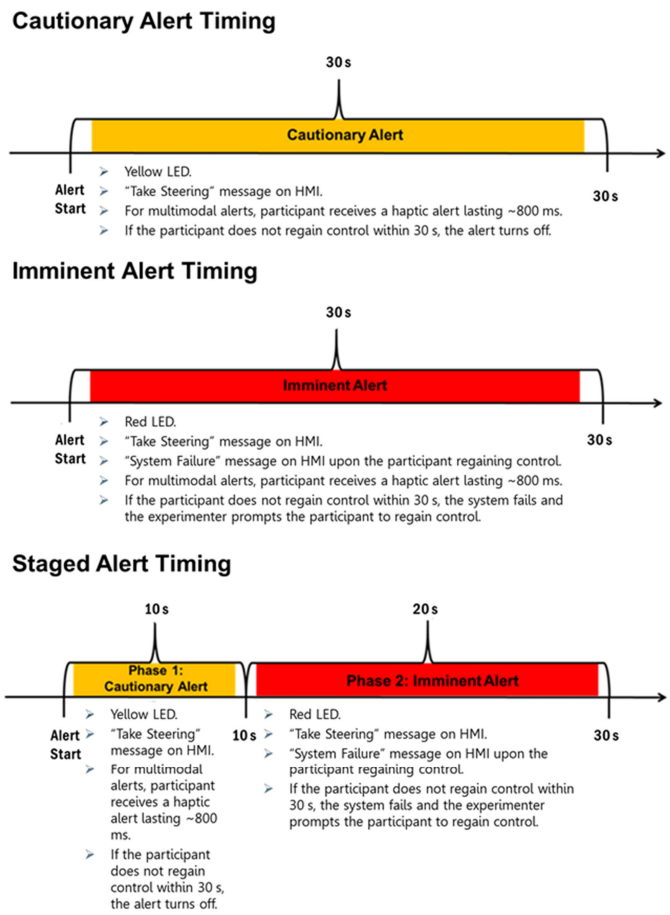

Figure2. Cautionary, Imminent, and Staged take control alert timelines for Experiment 1.

A trust scale was administered 10 times throughout the experimental session at approximately 9-minute intervals. Participants were asked to rate their trust in the ability of the automation to function properly while they engaged in non-driving tasks using a 7-point Likert-type scale. In addition to the 10 trust ratings collected throughout the experimental session, participants were asked to complete the after-experience trust scales and participate in an open-ended interview upon completing the driving session. Compensation was provided for participation in the study.

EXPERIMENT 2: SYSTEM PROMPT EFFECTIVENESS OVER TIME

Purpose

The second experiment investigated how to prompt operators to monitor the driving environment when engaged in a non-driving-related task during the operation of an L2 automated vehicle. A secondary purpose was to investigate the effectiveness of the prompts over time.

Participants

Data were collected from 56 participants recruited from the greater Detroit area (28 males, 28 females) with a mean age of 41 years old (S.D. = 16.3), with ages ranging from 18 to 72 years old.

Method

A single, long-exposure experiment was conducted. Participants were provided with a brief familiarization with the vehicle and its operation, followed by three 60-minute experimental sessions. During the sessions, participants were given tasks to be completed using a tablet computer. During these tasks, participants received prompts based on their predetermined prompt condition (either 2-second, 7-second, or No Prompts). For the 2- or 7-second prompt conditions, participants received prompts after periods of inattention to the driving environment for the corresponding amount of time. Participants given the No Prompts condition did not receive any prompts and they were free to behave as they thought was appropriate.

In addition to these prompts, at a random time during one predetermined session, the participant received an alert for a surprise left lane drift, consisting of a haptic seat alert and a flashing red LED. In a different predetermined session, the participant experienced a surprise lane drift with no alert, which consisted only of a left lane drift without any alert and with the prompting system disabled. The experimenter-injected lane drift was used to simulate a lane-keeping performance issue combined with a failure of the prompting system. Note that, to the participants with the 2-second and 7-second prompt conditions, the alert that they received along with the lane drift was indistinguishable from the prompts that they had been receiving based on their attention state. Participants' reactions to these prompts, alerts, and lane drifts, both in duration and method of response, were examined in this experiment.

Experimental Design

The study was performed as a 3 x 3 x 3 mixed factorial design. Each participant completed three successive driving sessions, and each session included one of the following: a lane drift with an alert, a lane drift without an alert, or no lane drift. Participants experienced each of these conditions once during the experiment. In addition, there were also three different prompt conditions that were used with the driver monitoring system, and each participant experienced only one prompt condition, either: 2-second, 7-second, or No Prompts. The prompt timing was based on previous distraction research (2-second prompts) (e.g., Klauer et al., 2006) and expert opinion (7-second prompts). Additionally, the study was designed to mimic worst-case scenarios when the operator was not monitoring the roadway due to the non-driving tasks.

Venue

As was the case for Experiment 1, Experiment 2 was also conducted at GM's Milford Proving Ground circle track in Milford, Michigan. However, this experiment utilized Lane 2, which allowed speeds of between 30-50 mph.

Vehicle

A 2010 model year Cadillac SRX equipped with a prototype L2 automated driving system was used as the experimental vehicle (See Figure 3). As part of the automated driving system, several HMI components were installed. These included an instrument panel binnacle-mounted screen providing information on the automated driving system, and two steering wheel buttons to control the automation: one ACC button, and one button for the lane-centering system, a prototype automated vehicle system.

Figure3. 2010 Cadillac SRX with a prototype L2 system used in Experiment 2.

The vehicle was equipped with Virginia Tech Transportation Institute's (VTTI) data acquisition system (DAS). The variables collected by the DAS included status of the automation, vehicle speed, and lane position. In addition, video views including the operator's face, forward roadway, and HMI were collected.

Study Session

Prior to beginning the study session, participants were provided with a static orientation to the experimental vehicle, which included the basic controls and the L2 automation features. Following this, participants received an on-track orientation consisting of four laps on the test track. Participants then completed three driving sessions, with each lasting approximately 60 minutes. Participants were instructed to begin interacting with a variety of non-driving tasks during the driving session upon activating the L2 automation. Participants were presented with three types of non-driving tasks: navigation, email, and web-browsing. These tasks were similar in terms of the visual/manual demand required and they were presented in a random order.

Each participant was assigned a prompt condition: either 2-second, 7-second, or No Prompts. The driver monitoring system provided three stages of prompts based on the assigned prompt condition and the participant's attention state. If the participant's attention state was not on the driving environment, the system provided alerts based on the assigned prompt condition. For the 2-second prompt condition, the prompts began after the participant's attention state was not on the driving environment for 2 s. For the 7-second prompt condition, the prompts began after the participant's attention state was not on the driving environment for 7 s. Participants who were assigned to the No Prompts condition did not receive any prompts. The driver monitoring system provided three progressive stages of alerts. Details pertaining to the prompt stages are detailed in Figure 4 below.

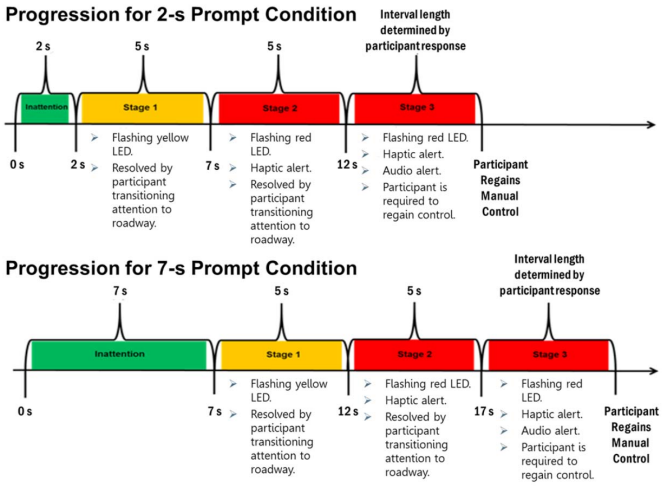

Figure4. Alert timelines for 2-second & 7-second prompt conditions for Experiment 2.

During the experiment, each participant experienced both types of lane drift (with and without an alert) and no lane drift—one time each—in different driving sessions, and at random times. All of the surprise lane drifts were prescribed and injected into the condition of interest using the experimenter console. The lane drifts with the alerts represent the condition of a lane-keeping performance issue in which the system warns the vehicle operator in order for him/her to regain control. The situations with no alerts represent conditions where there is a lane-keeping performance issue and a simultaneous failure of the prompt system, but the system does not warn the vehicle operator. Participant responses to the attention state prompts and experimenter-injected lane drifts were measured using visual evidence from the DAS. After completing three driving sessions, participants were instructed to exit the circle track and return to the preparation area. Participants were then interviewed, asked to complete the after-experience trust scales and interview, and provided with a debriefing as to the purpose of the study. Compensation was provided for participation in the study.

EXPERIMENT 3: HUMAN-AUTOMATION SYSTEM PERFORMANCE OVER TIME

The purpose of the third experiment was to investigate what HMI characteristics are effective at alerting operators to regain control of an L3 automated vehicle and to identify the transition times between the operator and the automated functions in regard to the driving tasks.

Participants

Data were collected from 37 participants recruited from the greater Roanoke, Virginia area; however, 12 participants were considered invalid (i.e., session cancellation due to adverse weather or technical issues associated with the DAS or the prototype vehicle). The analysis will consist of data from 25 participants. The mean age of the participants was 38.8 years old (S.D. = 13.77), with ages ranging from 18 to 69 years old.

Method

A single-exposure experiment was performed. Participants were provided with a thorough familiarization with the vehicle and its operation, including use of the automated features. Training was followed by three 30-minute experimental sessions. During the sessions, participants had free exposure to a non-driving-related task (i.e., use of their own cell phone or the provided tablet, as they felt was appropriate) and were presented with a message stating that they must take control of the vehicle. Participants' reactions to these messages, both in duration and method of response, were examined in this experiment.

Experimental Design

The study was performed as a within-subject design. Each participant completed three successive driving sessions, each session with one of three alert types; all participants received all alert types exactly once. The three alert types were: Staged, Imminent–No External Threat, and Imminent–External Threat. They received a Staged alert in the absence of an external threat, an Imminent alert in the absence of an external threat, and an Imminent alert in response to an external threat (i.e., a revealed box on the road). The Staged alert was composed of four phases: 1) a short tone followed by an informational message asking operators to prepare for manual control (including a countdown timer), 2) a Cautionary verbal alert played in addition to an animated HMI display with the instruction to "please turn off autodrive" presented for 10 s, 3) a repeated cautionary tone played in addition to an orange visual alert stating to "turn off autodrive now" presented for 10 s, and 4) a repeated imminent tone played in addition to a red visual alert stating to "turn off autodrive now" presented for 10 s combined with the automation beginning to apply the brakes. The Imminent alert was composed of a red visual alert stating to "turn off autodrive now" presented for 10 s along with the automation applying the brakes.

Venue

This experiment was conducted on the Virginia Smart Road test track, which is located at VTTI in Blacksburg, Virginia. The test track is constructed to state and federal roadway standards and has a length of 2.2 mi, with looped turns at either end. The straight section of the track is approximately 0.5 mi in length. Two lanes run the duration of the track, with the exception of the looped turns. Wireless Internet coverage is available on the track. The facility is closed to outside traffic and only study-related vehicles were present during the experiment.

Vehicle

A 2012 Lexus RX450h was used as the experimental vehicle for Experiment 3 (See Figure 5). This L2 vehicle was equipped with a prototype automated driving system that can simulate L3 driving on a test track. As part of the prototype system, several HMI components were installed. These included an instrument panel binnacle-mounted screen providing information on the automated driving system, and two steering wheel buttons to control the automation: one ON button on the left side of the wheel and one OFF button on the right side of the wheel.

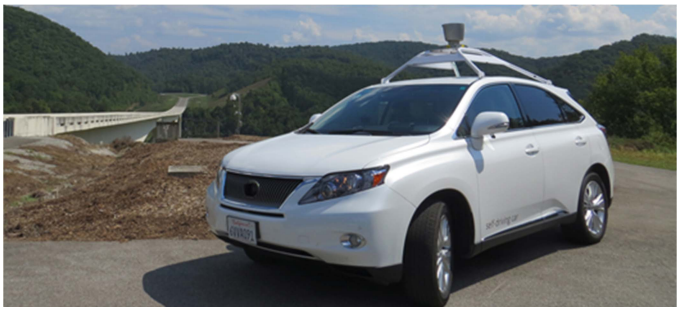

Figure5. 2012 Lexus RX450h with a prototype L3 system used in Experiment 3.

The vehicle was instrumented with VTTI's DAS. The variables collected by the DAS included throttle/brake input and automation state. In addition, video views including the operator's face, the forward roadway, and the HMI were collected.

Study Session

Prior to receiving any hands-on training, the participants viewed a 10-minute video summarizing the vehicle's features with a specific focus on the automated components and operation of the vehicle. This video was a training requirement of the automated vehicle provider and was consistent with the recommendation in NHTSA's *Preliminary Statement of Policy Concerning Automated Vehicles* in the section entitled "Recommendations Concerning State Activities Related to Self-Driving Vehicles" (NHTSA, 2013; pp. 10-11). This video was intended to detail the prototype system's operating capabilities and limitations. The participants were also shown the different

types of the alerts (i.e., Staged, Imminent–External Threat, and Imminent–No External Threat) during the video. Following this, participants received an on-track orientation consisting of four laps on the test track.

The experiment consisted of three 30-minute driving sessions. Participants were able to freely engage in non-driving tasks (i.e. tablet computer and cell phone use) when the automated system was activated. At a randomly selected point within each session, one of the three alert types was presented: Staged, Imminent–External Threat, or Imminent–No External Threat. The alerts happened at a predetermined location and participants experienced all three alert types during the experimental session. While each participant experienced all of the alert types, they were not always experienced in the same order. Details pertaining to Staged and Imminent alert timing and presentation are shown in Figure 6.

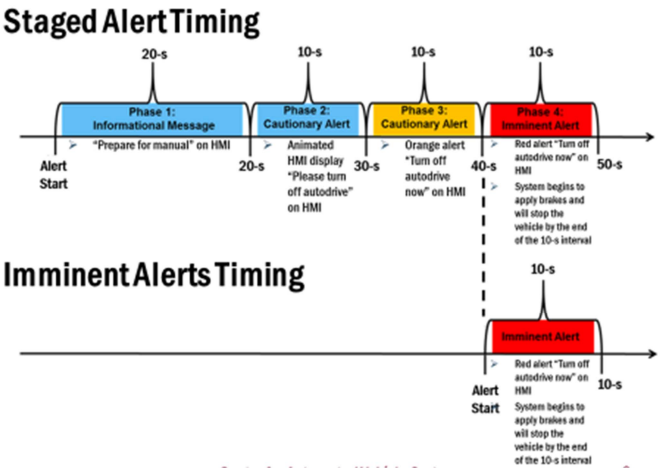

Figure6. Staged and Imminent take control alert timelines for Experiment 3.

A 15-minute break was offered after each session to allow for participant comfort; however, some participants chose to forgo the breaks. The maximum speed for all sessions was 45 mph, with lower speeds used for the turns at both ends of the track.

The trust scale was presented at 10-minute intervals during each session (at the beginning of the session, followed by administrations after 10, 20, and 30 minutes). Upon completion of the third session, the participant was instructed to deactivate the vehicle's automation, assume manual control over the vehicle, exit the track, and return to the preparation area. An interview was performed at that point. Compensation was provided for participation in the study.

PLANNED STATISTICAL ANALYSES

Because the data are measured repeatedly on participants over time, longitudinal statistical methods—used widely in experiments with repeated measures—can be used to analyze the data. For the variables that involve a time until the participant performs some action (such as regaining control of the vehicle), continuous data methods can be used, although the presence of extreme values may require the use of a data transformation (such as the logarithmic transformation) to effectively normalize the data to help fulfill the assumptions of these techniques. For other types of variables, such as the number of non-driving-related glances (which are counts) and the monitoring rate (a proportion), more general longitudinal methods can be used that account for the wide variety of distributions that these variables follow.

EXPECTED RESULTS

The detailed timing, sequence, and presentation measurements from the various research efforts involved herein could be used to develop human factors design principles. Crash avoidance technologies are evolving rapidly toward

increasing automation, involving a higher complexity of interoperability between user and vehicle functions than has previously been known. Understanding the detailed human factors capabilities and limitations of these users and the impacts of the timing, sequence, and presentation of information presented to the users will be important for shaping the safety policies.

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An Overview of NHTSA's Electronics Reliability and Cybersecurity Research Programs

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Abstract

This paper provides an overview of the National Highway Traffic Safety Administration's (NHTSA) research programs in electronic control systems reliability and automotive cybersecurity. The agency's electronics reliability research covers methods and voluntary standards both inside and outside the automotive industry. The research looks for such standards and methods that assess, identify, and mitigate potential new hazards that may arise from the increasing use of electronics and electronic control systems in the design of modern automobiles. Cybersecurity, within the context of road vehicles, is the protection of vehicular electronic systems, communication networks, control algorithms, software, users, and underlying data from malicious attacks, damage, unauthorized access, or manipulation.

BACKGROUND

NHTSA's safety role

NHTSA is responsible for developing, setting, and enforcing regulations for motor vehicles and motor vehicle equipment. Many of the agency's regulations are Federal Motor Vehicle Safety Standards (FMVSSs) with which manufacturers must self-certify compliance when offering motor vehicles and motor vehicle equipment for sale in the United States. NHTSA also studies behaviors and attitudes in highway safety, focusing on drivers, passengers, pedestrians, and motorcyclists. Additionally, NHTSA identifies and measures behaviors involved in crashes or associated with injuries, and working with States and other partners develop and refine countermeasures to deter unsafe behaviors and promote safe alternatives. Further, the agency provides consumer information relevant to motor vehicle safety. For example, NHTSA's New Car Assessment Program (NCAP) provides comparative safety information for various vehicle models to aid consumers in their purchasing decisions (e.g., the 5-star crash test ratings). The purpose of the agency's programs is to reduce motor vehicle crashes and their attendant deaths, injuries, and property damage.

Progression of electronics use in vehicles

The first common use of automotive electronics dates back to 1970s and by 2009 a typical automobile featured over 100 microprocessors, 50 electronic control units, five miles of wiring and probably contains close to 100 million lines of code [1]. Use of electronics has enabled safer and more fuel-efficient vehicles for decades and also facilitated convenience functions demanded by the consumers. Electric and hybrid vehicles could not have been developed and produced without the extensive use of electronics. Other proven safety technologies such as electronic stability control could also not be implemented without electronics.

Over time, growth of electronics use has accelerated and this trend is expected to continue as the automotive industry develops and deploys even more advanced automated vehicle features. This trend

results in increased complexities in the design, testing, and validation of automotive systems. Those complexities also raise general challenges in the areas of reliability, security, and safety assurance of increasingly networked vehicles that leverage electronics within a distributed, embedded and real-time control system architecture.

Growing system complexity and abundance of design variants even within one manufacturer over model years and across classes of vehicles raise general questions over whether manufactures can ensure the functional safety of existing processes. Further, anomalies associated with electronic systems—including those related to software programming, intermittent electronics hardware malfunctions, and effects of electromagnetic disturbances—may not leave physical evidence. Thus, they are difficult to investigate without a record of data from the electronic systems. As a result, NHTSA, industry members, and other interested parties are actively researching this issue to better understand these potential new functional safety challenges and identity methods to help address them.

National Research Council Study

In 2010, the National Highway Traffic Safety Administration (NHTSA) funded a National Research Council (NRC) study on how the agency's regulatory, research, and defect investigation programs can be strengthened to help address the safety assurance and oversight challenges arising from the expanding functionality and use of automotive electronics. Proceedings of this research through the NRC appointed 16-member committee was published in the Transportation Research Board (TRB) Special Report 308 [7] by the National Academies of Sciences (NAS) in 2012. It identified five main challenges for the safety of future electronic control systems:

1) An increased amount of complex software that cannot be exhaustively tested;
2) The highly interactive nature of the electronic control system—more interactions exist among system components, and the outcome may be difficult to anticipate;
3) The growing importance of human factors consideration in automotive electronic control system design;
4) The potentially harmful interaction with the external environment including electromagnetic interference; and
5) The novel and rapidly changing technology.

Further, the study offered recommendations to NHTSA on the actions that the agency could take to meet the six challenges they identified. These include:

1. Becoming more familiar with and engaged in standard-setting and other efforts (involving industry) that are aimed at strengthening the means by which manufacturers ensure the safe performance of their automotive electronics systems
2. Convening a standing technical advisory panel; undertaking a comprehensive review of the capabilities that the agency will need in monitoring and investigating safety deficiencies in electronics-intensive vehicles
3. Ensuring that Event Data Recorders (EDRs) become commonplace in new vehicles
4. Conducting research on human factors issues informing manufacturers' system design decisions

5. Initiating a strategic planning effort that gives explicit consideration to the safety challenges resulting from vehicle electronics that give rise to an agenda for meeting them
6. Making the formulation of a strategic plan a top goal in NHTSA's overall priority plan

The program plans we outline in this paper primarily respond to the first NAS recommendation.

Electronics Systems Safety Research

Informed by the NRC study and other internal deliberations on this topic, NHTSA established the Electronic Systems Safety Research Division within the Office of Crash Avoidance and Electronic Controls Research. While our existing investigative and rulemaking processes do cover electronic system (they emphasize performance metrics that apply regardless of whether the vehicle uses a mechanical or electronic way of achieving the performance), we also recognize the increasing industry focus, and processes that govern the safety assurance associated with vehicle systems that are mostly electronic in nature. This type of research can help enhance our understanding of various functional safety issues, fail-safe operations, diagnostics, software reliability, hardware validation, on-board tamper-resistance enhancements, hacking, and malicious external control. Along these themes, NHTSA has developed and is conducting new research in the areas of electronics reliability and automotive cybersecurity (including how these topics affect vehicle automation research). Given the close relationship between electronics reliability, cybersecurity, vehicle automation, our Electronic Systems Safety Research Program are closely considers the relationship between all three topics.

In support of our efforts, NHTSA started building in-house applied electronics research capabilities at its testing facility at the Vehicle Research and Test Center (VRTC) in East Liberty, OH. The purpose of these capabilities is to support testing of electronic systems and potential countermeasures towards developing objective test procedures for electronics related standards, requirements, guidelines, principles, or best practices.

Further, the agency established a Council on "Vehicle Electronics, Vehicle Software, and Emerging Technologies" to coordinate and share information on a broad array of topics related to advanced vehicle electronics and emerging technologies. The Council is managed by senior NHTSA officials. Its mission is to (1) broaden, leverage, and expand the agency's expertise in motor vehicle electronics; (2) to continue ensuring that technologies enhance vehicle safety; (3) review and advise the research program on electronics topics.

The primary goals of the electronics reliability and automotive cybersecurity research programs are similar. The five primary goals are to

1. build a knowledge base to establish comprehensive research plans for automotive electronics reliability/cybersecurity and develop enabling tools for applied research in these areas
2. strengthen and facilitate the implementation of safety-effective voluntary industry-based standards for automotive electronics reliability / cybersecurity

3. foster the development of new system solutions for improving automotive electronics reliability / cybersecurity
4. identify potential minimum performance-based vehicle safety requirements and/or principles for electronics reliability / cybersecurity
5. create foundational materials for future potential NHTSA policy and regulatory decision activities

ELECTRONICS RELIABILITY PROGRAM

NHTSA's electronics reliability research program covers various safety-critical applications deployed on vehicles today, as well as those envisioned on future vehicles that may feature more advanced forms of automation and connectivity.
NHTSA's electronics reliability research activities in support of our five aforementioned primary goals include the following projects.

Functional Safety Process and Requirements Research

This project focuses on examining ISO 26262 process standard and how it can improve the electronics reliability and security through encouraging design best practices at manufacturers. The scope of automotive functional safety, as defined within the ISO 26262 standard, only covers a portion of safety assurance activities associated with the design and manufacturing of a safe vehicle. More specifically, the ISO 26262 process addresses the safety related requirements necessary to meet the identified safety integrity levels of vehicle functions under electrical and electronic failures. While this process is only a piece of the overall vehicle safety assurance process, it is of great interest, because it adds a streamlined functional safety component to the standard systems engineering process that deals with the growingly complex portion of the vehicle architecture, namely the electronics, control system and software design. NHTSA continues to evaluate the ISO 26262 standard [8] and its process steps as well as other approaches used in the industry and those emerging in academic settings such as System Theoretic Process Analysis (STPA).

The agency has research underway that is applying the ISO 26262 standard in conjunction with STPA to safety critical automotive systems that directly govern the motion controls of a vehicle. More specifically, we are researching safety requirements associated with electronic throttle control (various propulsion system variations such as internal combustion engine, diesel, hybrid, electric), electronic brake control, electronic steering control (through electric power steering, pure steer-by-wire and differential braking), and rechargeable energy storage system controls.

Reliability Enhancing Systems Solutions

NHTSA is currently researching areas of advanced diagnostics and prognostics as they pertain to predicting impending system failures (prognostics) and logging critical fault code data (diagnostics) in safety-critical automotive electronic control systems. The agency is seeking to identify the safety improvement opportunities that may be gained from the development and use of enhanced diagnostics and prognostics in automotive applications.

NHTSA is also conducting an assessment of failure-response mechanisms that could help ensure that automotive, safety-critical, electronic control systems are (1) fail safe(i.e. allow driving in a safe-state to

mitigate loss or partial loss of functionality); (2) fail operational(i.e. allow normal driving with loss-of-function warning); and (3) fail secure i.e. disallow the vehicle to be used in the advent of a catastrophic failure. The agency is seeking to gain and provide insight into how automotive technologies address safety beyond system reliability practices (i.e. in addition to preventing the failure, how do systems react to failures?).

Another area of research is the human-factors challenges associated with driver interactions during system failures in safety-critical automotive electronic control systems. Driver notifications/warnings pertaining to an electronic control system failure would ideally be timely, appropriate, and effective.

AUTOMOTIVE CYBERSECURITY PROGRAM

As stated before, NHTSA established five primary goals, based on a systems engineering process, to address cybersecurity challenges associated with the secure operation of motor vehicles equipped with advanced electronic control systems.

Our automotive cybersecurity research activities in support of these goals include the following activities:

Establishing an Automotive Cybersecurity Knowledge-base

NHTSA has been actively researching cybersecurity standards, principles and best practices in automotive and other industries. A mature knowledge base in cybersecurity exists primarily in the information technology (IT) domain, which provides valuable insights for the protection of automotive electronic assets, however, principles adopted from IT security may not fully address the security and safety requirements of cyber-physical systems[1] (CPS) [4]. Because security risks can result in imminent safety concerns in case of CPS such as an automobile, risk tolerance associated with security vulnerabilities differ significantly -particularly for systems that govern the motion controls of a vehicle. As a result, we investigated various threat modeling approaches used in other industries and researched potential threat modeling and characterization methods that may apply to vehicle controls [3].

We also investigated design and quality control processes that focus on cybersecurity challenges throughout the lifecycle of a product. For instance we reviewed various National Institute of Standards and Technology (NIST) publications, and particularly studied NIST's Cybersecurity Risk Management Framework and how it may be applied to modern automobiles [2].

Industry Standards, Best Practices and Cybersecurity Initiatives

To facilitate security-by-design through quality assurance processes, the automotive manufacturers, suppliers, and other stakeholders are collaborating through SAE International to examine the emerging vehicle cybersecurity concerns and considering actions that could include the development of voluntary standards, guidelines, or best practices documents. NHTSA encourages these activities and provides feedback to SAE International Standards committees, such as the Vehicle Electrical System Security committee, and the Electrical Hardware Security committee.

[1] Cyber-physical systems (CPS) are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components. [National Science Foundation's definition of CPS]

Another industry activity that NHTSA strongly encourages is the recent joint effort undertaken by Alliance of Automotive Manufacturers and the Association of Global Automakers with the goal of establishing a voluntary information sharing and analysis center (ISAC) or other comparable program for the automobile industry sector.

NHTSA studied the ISAC model [5] for safeguarding against cybersecurity risks and threats in other industries such as financial services, information technology, and communications. Our analyses indicate that an automotive sector specific information sharing forum, such as an ISAC, is beneficial to pursue. It could advance the cybersecurity awareness and countermeasure development effectiveness among public and private stakeholders. ISACs have a unique capability to provide comprehensive inter- and intra-sector coverage to share critical information pertaining to sector analysis, alert and intelligence sharing, and incident management and response.

Our research across other industries indicates that the *complete prevention* of cyber-threats is unlikely. This fact and the successful use of ISACs in other industry sectors, suggest that it might also be effective for the auto industry to have mechanisms in place to expeditiously exchange information related to cyber-threats, vulnerabilities, and countermeasures among industry stakeholders when threats occur. Such a mechanism would enhance the ability of the automotive sector to prepare for, respond to, and recover from cybersecurity

System Solutions for Automotive Cybersecurity

In terms of system solutions, here are four major pieces to the agency's research approach.

6. <u>*Preventive solutions*</u>: This group of techniques helps to harden the design of automotive electronic systems and networks such that it would be difficult for malicious attacks to take place. Using structured security process standards could help identify vulnerabilities such that necessary design improvements can be identified and implemented during the design phase of the product. These vulnerabilities include possible entry points through accessible physical interfaces (such as the OBD-II port, USB ports, CD/DVD players), short range wireless interfaces, (such as Bluetooth, Wi-Fi, or Dedicated Short Range Communications (DSRC)), and long-range wireless interfaces such as cellular or satellite-based connectivity to the vehicle). Examples of design improvements could include the use of:

    a. encryption and/or authentication of messages on communication networks;
    b. different communication approaches, architectures or protocols;
    c. segmentation/isolation of safety-critical system control networks;
    d. redundant communications , direct measurements and/or message authentication or source validation for safety critical system inputs that can influence the motion controls of a vehicle;
    e. strong authentication controls for remote access vectors to vehicles;
    f. gateway controls and firewalls between interfaced vehicle networks;

g. formal methods for the specification, development and validation of embedded systems; etc.

The primary intents of this category of activities are (1) to significantly reduce the probability of cyber risks; and (2) to limit the impacts of a potential cybersecurity breach (e.g. one part of one vehicle or just one vehicle as opposed to an entire fleet).

7. *Real-time intrusion detection methods*: As a complement to the preventative measures, detecting intrusions into the system would help provide more comprehensive protection. A cybersecurity breach would likely take place on or through a communication network. From an intrusion detection perspective, vehicular network communications are considered fairly predictable and may be well-suited for real-time monitoring to detect anomalous activity with respect to nominal expected message flows. We are initiating research in 2015into real-time monitoring technologies targeted for use in the automotive sector.

8. *Real-time response methods*: Once a potential intrusion is detected, having practical strategies in place would help mitigate potential harmful impacts. Depending on the potential risks and level of intrusion detection confidence, the vehicle architecture could be designed to take a variety of actions such as: (1) temporarily or permanently shutting down the communication network(s) (at the potential cost of disabling various safety functions); (2) informing the driver; (3) recording and transmitting before-and-after trigger point data for further analysis; (4) and counter-measure development, etc. The purpose of this category of cybersecurity defense is to mitigate the potential harmful consequences of detected anomalous activity on the vehicle experiencing the potential breach.

9. *Treatment methods*: While the previous paragraph discussed response methods (dealing with fail-safe operation of the vehicle where an intrusion is detected), treatment methods deal with distributing information related to the subject risk to other potential vulnerable entities even before cybersecurity threat reaches them. Treatment methods involve timely information extraction from impacted parties, their analysis, development of countermeasures, and timely dissemination of that countermeasure to all relevant stakeholders (such as through an ISAC).

Applied Cybersecurity Research

NHTSA's primary objective through the cybersecurity program is to develop cybersecurity performance requirements, principles, best practices, and objective tests to assess conformance with such standards.

In support of this goal, NHTSA has been building applied cybersecurity testing capabilities and a cybersecurity laboratory at its Vehicle Research and Testing Center (VRTC) in East Liberty, OH. Current capabilities support communication bus and RF monitoring, CAN and GPS spoofing, firmware analysis and limited ECU penetration-testing. Planned future capabilities include RF disruption research, which will explore robustness associated with LTE, DSRC, GPS and Radar signals.

SUMMARY

The growth in electronics and software use in the design of automobiles is likely to continue because they support advanced

safety, efficiency, and convenience features. Along with this trend, come the challenges associated with managing safety and security of growingly complex automotive electrical architectures and networks.

NHTSA is continuing to conduct research on safety-critical automotive electronic control systems and collaborating with public and private sector stakeholders to advance its safety mission. The security for safety critical control systems remain a major area of interest for the Agency. Our main goal is to develop facts-based safety and security requirements or guidance for safety assurance of critical automotive systems.

In response to the Moving Ahead for Progress in the 21st Century Act (MAP-21) [6], NHTSA published a Federal Register notice outlining its examination of the need for safety standards with regard to electronic systems in passenger motor vehicles [9] in October 2014 and received public comments. We are in the process of writing a report to Congress, as required by MAP-21, which will also incorporate the received comments.

We have plans to extend ongoing electronics reliability research and cybersecurity research into emerging technologies that offer varying levels of vehicle automation as outlined in NHTSA's Preliminary Statement of Policy Concerning Automated Vehicles [10]. We are conscious of the increased role that electronic systems will play in the driving task in these future vehicles. Thus, NHTSA continues to design its research plans accordingly.

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AUTOMATED DRIVING FUNCTIONS GIVING CONTROL BACK TO THE DRIVER: A SIMULATOR STUDY ON DRIVER STATE DEPENDENT STRATEGIES

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ABSTRACT

Many car companies and other organisations are working hard to get automated driving on the road. Where some prefer driverless cars, most foresee a future where control of the vehicle will be shared between the driver and automated functions in the coming years. Sharing tasks and responsibilities creates the interesting challenge of transition of control of the vehicle between driver and automation. This paper presents research into this transition. By taking into account the attentiveness of the driver, different strategies were evaluated in a simulator study to create an optimal transition given the situation at hand. The study concentrates on an automated platoon system 'Virtual Tow Bar'. The results show that the differences among the tested conditions are small and no large trends are visible in either the subjective or the objective results. Hence it is concluded that the experiment should be repeated with a larger group naïve participants and probably more extreme parameter settings.

INTRODUCTION

Many car companies and other organisations are working hard to get automated driving on the road (see e.g. Hoeger et al. 2008; Jootel 2013; Kameda 2013). Where some prefer driverless cars, most foresee a future where control of the vehicle will be shared between the driver and automated driving functions in the coming years.

Sharing control of the vehicle means that the driver must be able to hand over the control to the automated driving function and either actively regain control from the automation function or get handed over control by the system. These transitions must be designed well as they take place while driving. TNO has taken up research to gain insight in the process of transition of control and the related research questions ('how should the system take over', 'how can the driver take back control', 'can the driver be regarded as a backup if the system fails', etc.). By designing and evaluating the different transitions of control, it is the long-term goal of the research to come to architectures and model-based designs for the transition of control and techniques and guidelines on how to evaluated these transitions.

As a case study, TNO's automated system Virtual Tow Bar (VTB) is taken. The VTB is an automated system that allows a vehicle to follow its predecessor at a relatively short following distance, controlling both the longitudinal and lateral motion. The VTB system is designed to operate on public motorways (i.e. without using dedicated lanes), initially limited to platoons of two vehicles. The first vehicle is driven by a human operator and (once engaged) the second vehicle is controlled by the VTB. The VTB is designed with the goals to reduce fuel consumption (especially for trucks) and improve traffic throughput. To achieve these goals, the system must maintain relatively short headways, in the order of magnitude of 0.2-0.3 s (see e.g. Jootel, 2013), i.e., much smaller than headways normally adopted by drivers.

This paper reports on an explorative driving simulator study conducted to evaluate different strategies to come to an optimal transition from automated driving to manual driving, where the state of the driver is taken into account. The transition was initiated by the automated system when approaching the highway exit to be taken by the driver to contiue his journey on the desired route. The upcoming automatic disconnect was preseded by a warning. The warning process asked for a confirmation from the driver that he/she was ready to regain the driving task. The timing of the warning and the confirmation process was made dependent on the driver state. (Note that the situation where the driver is not capable to regain control must ultimately be dealt with, but is beyond the scope of out current work).

For the driver state we concentrated on the topic of attentiveness of the driver. It was the goal of the project to investigate different strategies to re-involve the driver and not to measure his/her level of attentiveness. In the simulator study the level of attentiveness was maninupated by instructing the participants either to be attentive, or to engage in a secondaty task that was designed to be highly distracting. For next steps in the research eye tracking may be used as a basis to measure driver attentiveness (Ahlstrom, 2013).

Previously research was conducted on finding the most important parameters that influence the transition of control when the driver switches the VTB system on and off, and on driver behaviour after he/she switched the VTB system off (Willemsen et al. 2014a; Willemsen et al. 2014b). Results of this research were taken into account in the reported study in the settings of several parameters of the VTB system and in the driver interface.

VIRTUAL TOW BAR SYSTEM

As explained in the Introduction the VTB system uses short following distances, which means the driver cannot be regarded as a backup to take over in case of system failure or any other emergency. To create a safe transition towards the small following distance, a scheme was designed to let the driver switch the system on from a safe following distance. Once activated, the automated system decreased the following distance to the desired (small) following distance. When switching off, either by the driver or by the automated system itself, the system first increases the following distance to a safe length before giving back control to the driver.

System Model

The VTB was modelled as a combination of a Cooperative Adaptive Cruise Control (CACC) controller (Ploeg et al., 2014) and a Lane Keep Assist (LKA) system. The Cooperate part of the system consisted of short-range communication between the two vehicles in the platoon. Via this channel, the longitudinal following controller had access to the current acceleration command of the lead vehicle, which provides additional damping with respect to an autonomous ACC that only has distance and relative speed as control inputs. The LKA algorithm was used to provide lateral control of the vehicle with respect to the middle of the lane. The controllers were combined and logic was added to create different system modes to switch the system on and off (Willemsen et al. 2014a; Willemsen et al. 2014b).

System Interface

A dedicated user interface was developed for the earlier experiments and improved based on the feedback from these experiments (Figure 1). A touchscreen visual display was mounted in the mid console (see Figure 2) of the mock-up of the driving simulator, as high as possible without blocking the view on the road. On this display the current system status was shown together with a graphical indication of the current time headway and guidance to help te user engage the system. Moreover, this display was used to also notify the driver of an upcoming automated switch off (Figure 2) and request confirmation of this notification of the driver. Lower in the mid-console, within easy reach for the participants, a pushbutton was placed which they could press to engage or disengage the system. Pressing the brake pedal would also initiate a disengagement of the system.

Figure 1. Driver display showing the confirmation request of the driver.

The goal of the study was to develop strategies for the automation to notify the driver of a switch off by the automation, not to develop a specific HMI. We therefore wanted the user experience with the system to be as good as possible, i.e. without flaws in the interface that might disturb the experience. We therefore needed an interface of which we could assume it would be understood and accepted by the user. Experiences in previous studies were taken into account in the design of the basic interface. Using an iterative process we designed, developed and tested the additional warning towards the driver for an automated switch off in a low-fidelity simulator. Besides the visual display, acoustic warnings were provided to the driver at the moment information or warnings were presented to alert the driver to the new visual information.

METHOD

Because of the safety implications of automated driving and the wish to have a natural driving environment (i.e. no test track environment) the experiment was conducted in a moving base driving simulator.

Driving Simulator and Scenario

The experiment was carried out in a high fidelity moving base driving simulator (Van den Horst and Hogema, 2011). It consisted of a BMW mock-up mounted on a 6DOF moving base. The road and traffic environment was projected on cylindrical screens around the vehicle. The projection system for the front view had a horizontal viewing angle of 180 degrees, realized by three projectors. The vertical viewing angle was 41 degrees (22 degrees above and 19 degrees below the neutral viewing direction). The driver could use the existing BMW external rear view mirrors to look at two screens placed behind the vehicle displaying the environment behind. Similar, the internal rearview mirror could be used to look at a 32 inch LCD screen placed in the back of the car. Feedback of steering forces was given to the driver by means of a high-fidelity electrical torque engine.

Figure 2. Setup of displays in the driving simulator.

Participants drove on the right-hand lane (the slower lane) of a two-lane motorway behind a lead vehicle that was driving with an average speed of 120 km/h. The participants were instructed to follow this lead vehicle and switch the automated function on when possible. There were no entries or exits on the route until the very end of the run. The participants were instructed to take this exit after the automated function had switched itself off. Slight curves, surrounding traffic, and two signs indicating the upcoming of the exit made the experience more realistic.

Parameters and Experimental Setup

Goal of the study was to investigate different strategies for the automated function to switch itself off in case of an attentive or an inattentive driver. Hence the participants drove one run where they were asked to stay attentive and two runs where they were asked to perform a demanding secondary task. This secondary task consisted of the HASTE task (Engström, Johansson, & Östlund, 2005): participants were presented with matrices of arrows on an additional LCD touch screen. An example can be seen in Figure 2, in which also the position of the touch screen in the simulator mock-up shown can be seen. The task was to determine whether an arrow pointing upwards was present. Participants gave their answers by pressing ‘‘yes’’ or ‘‘no’’ on the touch screen. A new matrix was presented every 10 seconds. Each matrix remained on the display for 2 s before a new matrix was presented. Participants were instructed perform as good as possible on the HASTE task by getting as much answers right as they could during their whole trip.

The time gap of the VTB system was 0.3 s. Hooking on and off phases took 15 s and the transition just before hooking on and after hooking off were instant (no additional countdown from 5 s as presented in Willemsen et al. (2014b).

At a certain distance upstream from the exit, the participant was warned and requested to provide a confirmation by pushing a button on the touch screen of the interface (Figure 2). If the driver did not confirm within a certain time the warning and confirmation request was repeated. Closer to the exit, irrespective of the driver reacting to the confirmation request, a warning was displayed that provided the amount of meters till the exit (Figure 1 without the confirmation request and button). The timings of the warnings and feedback requests were different between the attentive and inattentive driver states (see Table 1). The unadapted transition strategy was to warn the participant and ask for confirmation the first time at 1000 m before the exit. From 500 m before the exit the participant was continously informed on the distance (‘count down’) till the VTB system would switch off. In the adapted strategy,

the participant was warned and asked for confirmation earlier, at 2000 m before the exit and the 'count down' was shown from 1000 m before the exit. In both strategies, if the participant did not react to the first confirmation request, a second one was issued at 750 m before the exit.

Table1. Parameter combinations in the simulator experiment.

Condition	Driver distraction	Transition strategy
0	-	Familiarization run
1	attentive	Unadapted
2	inattentive	Unadapted
3	inattentive	Adapted

The order of presentation of the second and third condition were balanced over the participants.

Participants

A total of 16 participants attended the experiment. It shoud be noted that all participants were research colleagues with a background outside the automotive domain to prevent they had too much information about automated driving and the transition of control before the experiment. First the subjective results, aqcuired through questionnairs is discussed followed by analyses of the logged signals.

RESULTS AND DISCUSSION

Subjective Results

Drivers judged the amount of information or understanding they had about the environment when they had to take over control to be in the middle between *more than enough* and *not enough*. They rated the unadapted strategy slightly lower than the adapted strategy when they were distracted by the secondary task (see Figure 3, on the left). This suggests that the adapted strategy helped the participants to take over control with more information about the traffic situation.

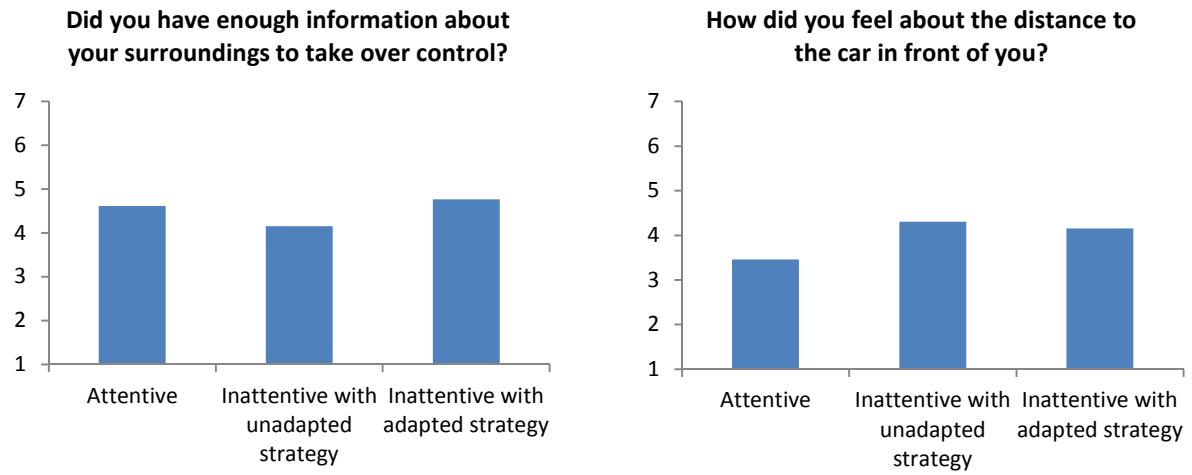

Figure 3. Left: Situational awareness (1 = not enough, 7 = more than enough), right: Experienced time headway (1 = too close, 7 = too far).

Figure 3 on the right shows that the participants experienced the car in front of them too close when they were paying attention. Note that the car was driving at 0.3 s behind the lead vehicle, which is much closer than these drivers would normally drive. Since they always received the attentive condition before both inattentive conditions, this might be an order effect, meaning that drives got used to driving (being driven) so close to a preceding vehicle. It could also mean that when engaged in a secondary task reliance on the system is higher and a closer gap becomes acceptable. This should be investigated in follow-up research.

When asked about their feelings of safety when taking over control, particpants on average answered only slightly above the mid value (4) and with very small differences among conditions, as can be seen in Figure 4 (left). Some participants felt much safer than others, values ranging from 2 to 6. The average not being higher than 4 does suggest there is concern with the drivers about their safety when taking over. Apparantly these concerns were there both with and without the adapted strategy.

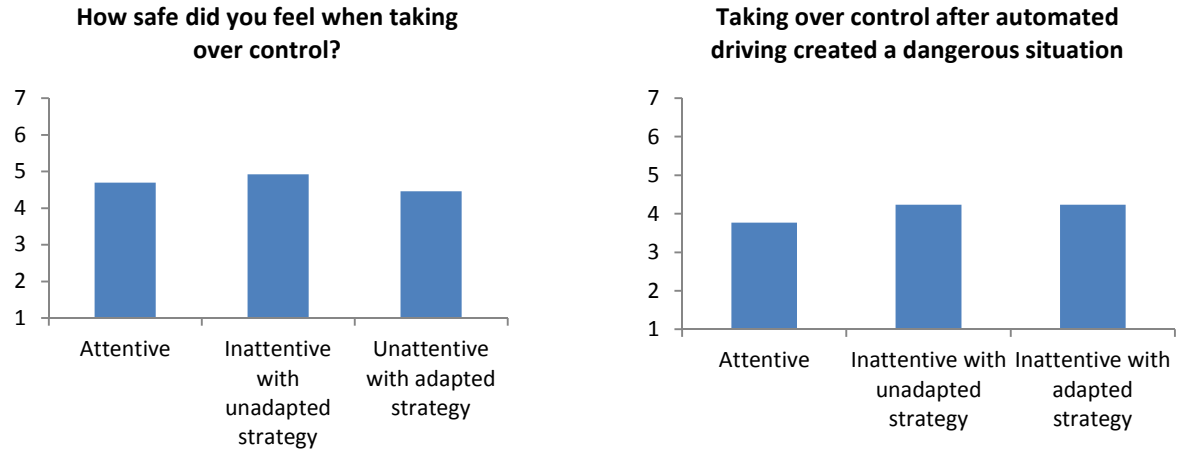

Figure 4. Left: Experienced safety (1 = not safe at all, 7 = very safe), right: Automated driving creates a dangerous situation, (1 = strongly disagree, 7 = strongly agree).

The results for the question about whether taking over control after being driven autonomously created a dangerous situation again suggests the drivers had concerns about safety and dangerous situations. In Figure 4 (right) it can be

seen that they felt a dangerous situation was more likely to arise when they had been inattentive. In contrast to the result from Figure 3 (left), there is no evident difference between the condtion with and without the adapted strategy.

It seems that participants found the amount of warnings neither too few nor too many for any of the conditions (Figure 5). This could mean that the the extreme values of number of warnings was not reached and that drivers accepted both the maximum as well as the minimum amount of warnings. This would mean that the difference between conditions as presented in this experiment was not large and minimal warnings were enough to alert the driver again. This could be different when either the automation switches off more often, making the warning more annoying, or when the time of distraction becomes longer or more intense, which means that the minimum amount of warnings is not sufficient anymore.

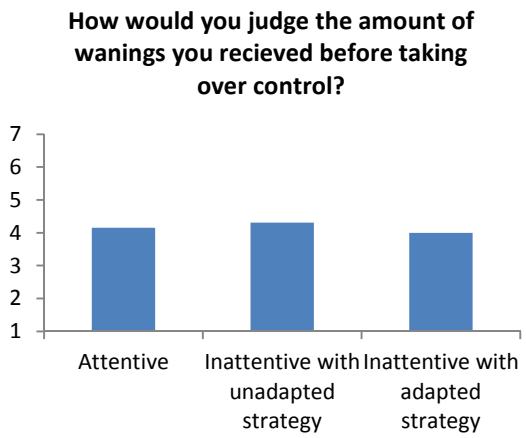

Figure 5. Amount of warnings (1 = too few, 7 = too many).

Objective Results

The effect of the additional task is evaluated through the reaction time of the drivers on the confirmation request, and the steering behaviour after regaining control and taking the exit. This is shown in Figure 6.

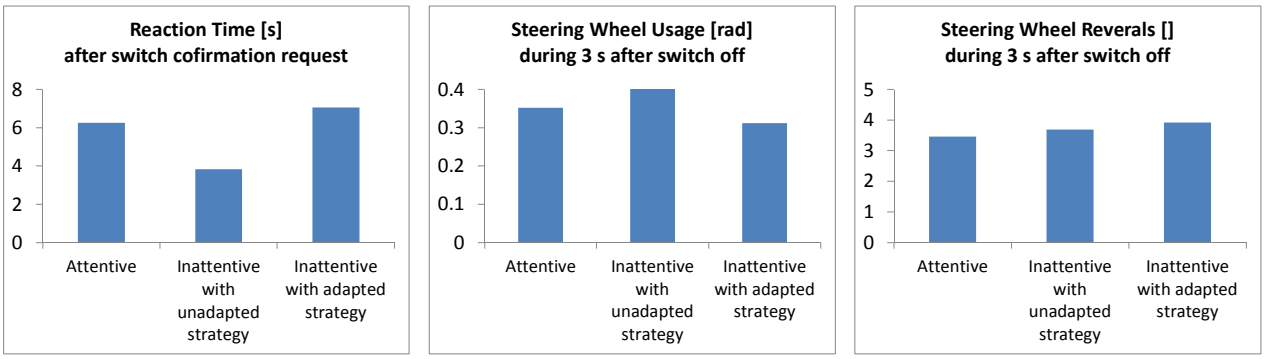

Figure 6. Left: Reaction times, Middle: Steering Wheel usage, right: Steering Wheel Reversals (cond1: attentive, cond2: inattentive with unadapted strategy, cond 3: inattentive with adapted strategy).

The reaction time was calculated as the time between the first confirmation request and the driver pushing the confirmation button. In some cases the driver did not react to the confirmation request: one in each tested condition. These data were not taken into account.

In the inattentive case the reaction time is lower than in the attentive case for the unadapted warning strategy, for the adapted warning strategy (earlier warning) the reaction times are larger. This could mean that the drivers were anticipating the warning, however, in the adapted warning strategy the warning may have come earlier than expected by the drivers, as they drove at least the attentive run before the other inattentive runs. Furthermore a large reaction time is not critical as the situation is not urgent. Moreover in the adapted strategy the warning was even 1000 m earlier than in the other two cases, so even with an increase of the reaction time of about 3 s, the reaction is in fact still further upstream from the merging point.

For the calculations of the steering wheel usage, data of three participants were excluded as they switched off the VTB bar system too early. In that case they were not at the highway exit they should steer onto and the required steering was less than for the other cases.

The amount for steering used after switch off (middle chart in Figure 6) shows differences: the inattentive participant with the unadapted warning strategy uses largest steering angle range and the inattentive paricipant with the adapted strategy the smallest. This may suggest that earlier warnings prepare the driver better to take over the steering of the vehicle. This needs further detailted research.

Regarding the steering wheel reversals the results are quite the same for the different conditions. Although it was expected that the first run would show more reversals as the participants would learn to take over control after more practice and this seems not to be the case.

CONCLUSIONS

Results of a small driving simulator (16 participants, runs of nearly 5 minutes) experiment are shown, in which an automated driving system hands back the control to the driver on initiative of the automated driving system. Immediately after getting back the control the drivers had to take an exit. Different timings of take over warnings were tested with attentive and inattentive participants.

Overall it can be concluded that the differences between the tested conditions are small and no large trends are visible in either the subjective or the objective results. Probably the participants were able to rebuild their situation awareness in a short time. Further, only distraction was differed over the tests (fatigue, drowsiness, absence were not investigated). In general the participants were moderately positive about the system, though there were concerns about the safety with the short following distances. Hence it is concluded that the experiment should be repeated with a larger group naïve participants and probably more extreme parameters (longer distraction times, larger difference between conditions).

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AUTOMATIC CONTROL OF VEHICLE STEERING SYSTEM DURING LANE CHANGE

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ABSTRACT

Mechatronic systems assist drivers in safe driving of cars more and more often. A vision of a totally automated car realizing many manoeuvres without driver's participation becomes closer and closer. The lane change manoeuvre is one of the basic manoeuvres on the ground of which sequences of complex manoeuvres can be composed, e.g. vehicle passing or obstacle avoidance manoeuvre. For those reasons, automation of lane change manoeuvre appears to be essential for automation of vehicle driving and is a subject of numerous research studies. Within a research project, the authors have undertaken extensive analytical studies on application of active steering system EPS in automatic driving of a two-axis truck equipped with typical elements of ESC system and obstacle detectors, as well as road monitoring systems.
The present paper focuses on theoretical aspects of the synthesis of an automatic controller for the EPS active steering system. Simulation studies of an automatically controlled lane change manoeuvre illustrate the application of the methodology. The basis for theoretical considerations and numerical studies is the mathematic model of the controlled system (vehicle) and the controller. A complex, detailed description of the dynamics of a two-axis truck, taking into account nonlinearities and vehicle motion in 3D space, is included in the simulation model. The model of the controller is based on a reference model which is significantly simplified and hence is highly effective for carrying out necessary computations in real time. An algorithm of the controller operating as a Kalman regulator in a closed loop system is developed on the basis of this model. The time decomposition of the automatic control process into two phases –lateral displacement of the vehicle and stabilization of its position – is an essential, original distinguishing feature of the algorithm. Thanks to this decomposition, the structure of the control system is relatively simple. Feedback signals provided by the sensors available in a typical ESC system (lateral acceleration, yaw velocity) are used in the control process. The vehicle reference model and resulting control algorithms are presented in the paper. Simulation results refer to a two-axis truck travelling with a constant velocity on a straight, uniform road. At certain time instant the vehicle starts executing the lane change manoeuvre. Simulations were carried out for a number of cases with varying model parameters. That allowed estimating the sensitivity of the control algorithm to both perturbations of vehicle's physical and operational parameters and to perturbations of parameters related to the obstacle. The results of simulations show that the proposed concept of the vehicle automatic control performs well in computational tests. The method of automatic execution of the lane change manoeuvre presented in the paper can offer an attractive alternative for vehicle control engineers and researchers working in the fields of active steering systems of vehicles, including commercial trucks.

INTRODUCTION

Development of modern automotive technology results in an increasing use of mechatronic systems assisting drivers in safe driving of road vehicles. The prospect of a totally autonomous vehicle performing a range of manoeuvres without driver's participation nears. The lane change manoeuvre is one of basic manoeuvres on the basis of which more complex manoeuvres such as vehicle overtaking or obstacle avoidance can be undertaken. Obstacle avoidance is necessary when an object suddenly appears on the vehicle path in a distance smaller than the estimated travel needed to stop. For these reasons, automation of the lane change manoeuvre is essential to achieve the goal of fully autonomous vehicle control. It is a subject of numerous research programs as well as prototype development and testing.
Publications on automation of lane change manoeuvre usually refer to the concept of automatic control including optimal path planning and then trajectory tracking [2, 4, 9, 10, 11, 12]. Trajectory planning is sometimes treated as a problem of parametric optimization of heuristically assumed forms of the desired path (segments of sinusoidal function, composition of arcs, line segments, parabola segments etc.). Optimization of the desired path should not only achieve short manoeuvre duration, desired smoothness of the trajectory, limitation of side jerks, but also ensure that the planned path will be feasible for efficient trajectory control. As known, trajectory tracking errors depend on

the quality of the desired path. Trajectory tracking controllers proposed in publications cited above are based on known algorithms from the control theory. Obviously, parameters of the vehicle, as well as parameters of its steering system, have significant influence on the optimal path and the choice of the tracking controller [13, 14].
Within the research project [7], comprehensive analytical studies have been carried out on the application of the active steering system EPS (Electric Power System) in automatic driving of a commercial truck of medium load capacity. Considered traffic situations included suddenly appearing obstacle potentially causing collision. The truck under consideration was equipped with typical elements of ESC (Electronic Stability Control) and obstacle detectors, as well as road monitoring systems.
This paper is based on a portion of the aforementioned studies [7]. It focuses on theoretical aspects of the synthesis of an automatic controller for the EPS active steering system. Simulation studies of an automatically controlled lane change manoeuvre illustrate the application of the methodology.
The basis for theoretical considerations and numerical studies is the mathematical model of the controlled system and the controller. A complex, detailed description of the dynamics of a two-axis truck, taking into account nonlinearities and vehicle motion in 3D space, is included in the simulation model representing the real system to be controlled. Complex nonlinear dynamics of the steering mechanism is included in the model, with free play and friction in the joints. The model of the controller is based on a simple reference model – known in the literature as a bicycle model of a car. Desired path as well as the structure and parameters of the controller are determined using this model.
An essential, distinguishing feature of the control algorithm is the decomposition of the lane changing manoeuvre into two phases: vehicle turning to move swiftly into the adjacent lane and then stabilization in the direction of the new lane. Owing to this decomposition, the structure of the control algorithm is relatively simple. Feedback signals provided by the sensors available in a typical ESC system (lateral acceleration, yaw velocity) are used in the control process. The vehicle reference model and resulting control algorithms are presented in the paper. Simulation results refer to a two-axis commercial vehicle of medium load capacity travelling with a constant velocity on a straight, uniform road. At certain time instant the vehicle starts executing the lane change manoeuvre. Simulations were carried out for a number of cases with varying model parameters. That allowed estimating the sensitivity of the control algorithm to both perturbations of vehicle's physical and operational parameters and to perturbations of parameters related to the obstacle. The results of simulations show that the proposed concept of the vehicle automatic control performs well in computational tests.

LANE CHANGE MANOEUVRE IN THE FRAMEWORK OF THE CONTROL THEORY

Assumptions

An obstacle suddenly appears on a straight stretch of the road in front of the travelling vehicle. The vehicle starts braking (manual or automatic process) until the time instant the control system discovers that further braking inevitably leads to a crash. After automatic monitoring of obstacle surroundings, if conditions allow for that, the rotation of the steering wheel is activated automatically in order to avoid the obstacle while travelling with a constant velocity that was reached at the final stage of braking. At the end of the manoeuvre vehicle should travel on the lane parallel to the primary lane. In that way, the control of the vehicle moves from the braking phase to the lane changing phase.
The purpose of the study presented in this paper is to show the concept of the steering wheel controller that would execute the lane change manoeuvre once it was automatically initiated. The method of setting controller parameters knowing the parameters of the vehicle reference model and allowable variable ranges will also be presented. The often challenging strategy of decision making to activate the automatic lane change operation will not be considered.

Strategy for Steering Wheel Rotation Control

The control task involves two output variables – displacement of the centre of mass and angular position of the vehicle body in relation to the trajectory of the centre of mass – and is to be carried out with one control input (steering wheel rotation). It is convenient to divide the process of steering wheel control into two successive phases of "lateral displacement" and then "stabilization".
Realization of the task of vehicle lateral displacement allows for some level of vehicle yaw with respect to the roadway axis after required lateral displacement of the vehicle centre of mass has been achieved, ensuring obstacle avoidance with certain safety margin. The priority is on the fast execution of this phase of the manoeuvre.

The task of stabilization involves adjusting the angular orientation of the vehicle to become parallel to the roadway axis. Here, the priority is on accurately performing the procedure to ensure that the vehicle follows the new lane.
Such decomposition of the control tasks is consistent with practice of driving a car by experienced race drivers. Control in the first phase of the process can be carried out partly in an open loop ("blindly", "as quickly as possible") by generating an appropriate steering wheel rotation. Accuracy at this phase of the manoeuvre is ensured by the use of the earlier identified reference model. An additional corrective control will also be present during this phase. Namely, the correction of the steering wheel rotation angle is to be carried out in a closed loop, through the comparison of the lateral displacement of the vehicle (according to the reference model) with the measured position. Control in the second phase must be carried out completely in the closed loop, by regulating the angular orientation of the vehicle with respect to the roadway axis.
The concept of the control strategy based on the decomposition into two phases is shown in Fig.1.

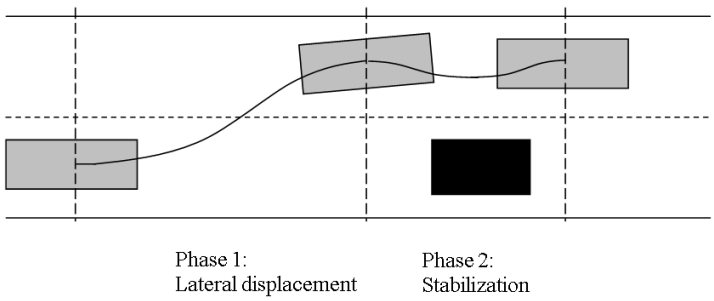


Figure 1. Decomposition of the lane changing manoeuvre.

Theoretical validation of this control strategy is presented in the subsequent part of the paper.

The Reference Model

Theoretical considerations will be conducted using the bicycle model of a car. The model describes the lateral dynamics of the vehicle travelling with constant velocity in the presence of small disturbances. This model is used in many studies related to the automatic control of vehicles. The bicycle model concept is illustrated in Fig. 2.

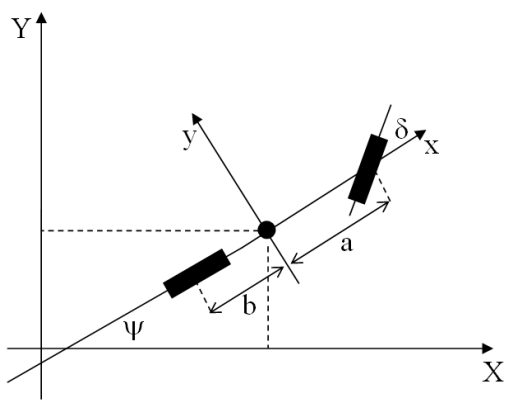


Figure 2. Concept of the bicycle model of a car.

Nomenclature of model variables and parameters:

t	–	time (t = 0 denotes the start of control),
δ(t)	–	steer angle of front wheels,
ψ(t)	–	vehicle yaw angle,
Ω(t)	–	yaw velocity of the vehicle ($\Omega(t) = \dot{\psi}(t)$),
U(t)	–	lateral velocity of the vehicle in the local coordinate frame,
V	–	longitudinal velocity of the vehicle (constant) in the local coordinate frame,
X(t), Y(t)	–	vehicle centre of mass coordinates in the global coordinate frame,

m	–	mass of the vehicle,
J	–	moment of inertia of the vehicle with respect to the vertical axis passing through its centre of mass,
a, b	–	distances from the front and rear wheel axes, respectively, to the projection of the centre of mass,
k_A, k_B	–	cornering stiffnesses at the front and rear wheel centres, respectively.

The mathematical model for the subsequent formulation is represented by linearized equations of motion derived from the balance of forces and moments acting on a two-wheeled vehicle. The equations expressed in the moving coordinate frame are:

$$m\dot{U}(t)+\frac{k_A+k_B}{V}U(t)+\frac{mV^2+k_Aa-k_Bb}{V}\Omega(t)=k_A\delta(t) \tag{1}$$

$$J\dot{\Omega}(t)+\frac{k_Aa^2+k_Bb^2}{V}\Omega(t)+\frac{k_Aa-k_Bb}{V}U(t)=k_Aa\delta(t) \tag{2}$$

Transformation from the moving coordinate frame to the frame connected to the road is described by the following relations:

$$\psi(t)=\int_0^t\Omega(\tau)d\tau \tag{3}$$

$$\dot{X}(t)=V\cos(\psi(t))-U(t)\sin(\psi(t)) \tag{4}$$

$$\dot{Y}(t)=V\sin(\psi(t))+U(t)\cos(\psi(t)) \tag{5}$$

Trajectory of the vehicle's centre of mass Y(X) can be determined from the following relationships:

$$X(t)=\int_0^t\dot{X}(\tau)d\tau=\int_0^t\left(V\cos(\psi(\tau))-U(\tau)\sin(\psi(\tau))\right)d\tau \tag{6}$$

$$Y(t)=\int_0^t\dot{Y}(\tau)d\tau=\int_0^t\left(V\sin(\psi(t))+U(\tau)\cos(\psi(\tau))\right)d\tau \tag{7}$$

The relationships (1-7) will be treated as an initial reference model of the vehicle.
With small and short time duration disturbances occurring during obstacle avoidance it is allowed to use linearized form of the transformation equations. Applying the Taylor series approximation gives:

$$\cos(\psi(t))\approx 1 \qquad \sin(\psi(t))\approx\psi(t) \tag{8, 9}$$

$$U(t)\sin(\psi(t))\approx 0 \qquad U(t)\cos(\psi(t))\approx U(t) \tag{10, 11}$$

Therefore, on the basis of (4-5):

$$\dot{X}(t)=V \tag{12}$$

$$\dot{Y}(t)=V\psi(t)+U(t) \qquad \ddot{Y}(t)=V\dot{\psi}(t)+\dot{U}(t) \tag{13, 14}$$

and also:

$$U(t)=\dot{Y}(t)-V\psi(t) \qquad \dot{U}(t)=\ddot{Y}(t)-V\dot{\psi}(t) \tag{15, 16}$$

After substitution into the equations of motion (1-2) and rearranging one gets:

$$m\ddot{Y}(t)+\frac{k_A+k_B}{V}\dot{Y}(t)+\frac{k_Aa-k_Bb}{V}\dot{\psi}(t)-(k_A+k_B)\psi(t)=k_A\delta(t) \tag{17}$$

$$J\ddot{\psi}(t)+\frac{k_Aa^2+k_Bb^2}{V}\dot{\psi}(t)-(k_Aa-k_Bb)\psi(t)+\frac{k_Aa-k_Bb}{V}\dot{Y}(t)=k_Aa\delta(t) \tag{18}$$

The trajectory of the vehicle's centre of mass Y(X) is determined by the relationships:

$$X(t)=\int_0^t\dot{X}(\tau)d\tau=\int_0^t Vd\tau=Vt \tag{19}$$

$$Y(t)=\int_0^t\dot{Y}(\tau)d\tau \tag{20}$$

The above developed equations (17-20) will be treated as a simplified reference model of the vehicle.
In the initial reference model, the relationships (1, 2, 3) are linear and therefore can be subjected to the Laplace transformation. Then, at zero initial conditions of variables U(t) and Ω(t), an equivalent notation of the reference model can be defined in the transfer function form with the operator variable s.

$$\tilde{U}(s)=G_{U\delta}(s)\tilde{\delta}(s) \tag{21}$$

$$\tilde{\Omega}(s)=G_{\Omega\delta}(s)\tilde{\delta}(s) \tag{22}$$

$$\tilde{\psi}(s)=\frac{1}{s}\tilde{\Omega}(s) \tag{23}$$

where transfer functions have standard forms:

$$G_{U\delta}(s) = \frac{G_{U\delta 0}\left(T_{U\delta}s+1\right)}{T_0^2 s^2 + 2\xi_0 T_0 s + 1} \tag{24}$$

$$G_{\Omega\delta}(s) = \frac{G_{\Omega\delta 0}\left(T_{\Omega\delta}s+1\right)}{T_0^2 s^2 + 2\xi_0 T_0 s + 1} \tag{25}$$

The transfer function parameters can be described by the formulae:

$$T_0 = V\sqrt{\frac{mJ}{k_A k_B (a+b)^2 - MV^2\left(k_A a - k_B b\right)}} \tag{26}$$

$$\xi_0 = \frac{\left(m\left(k_A a^2 + k_B b^2\right) + J\left(k_A + k_B\right)\right)}{2\sqrt{mJ\left(k_A k_B (a+b)^2 - mV^2\left(k_A a - k_B b\right)\right)}} \tag{27}$$

$$G_{U\delta 0} = \frac{\left(k_A k_B (a+b) b - mV^2 k_A a\right)V}{k_A k_B (a+b)^2 - mV^2\left(k_A a - k_B b\right)} \tag{28}$$

$$T_{U\delta} = \frac{J k_A V}{k_A k_B (a+b) b - mV^2 k_A a} \tag{29}$$

$$G_{\Omega\delta 0} = \frac{k_A k_B (a+b) V}{k_A k_B (a+b)^2 - mV^2\left(k_A a - k_B b\right)} \tag{30}$$

$$T_{\Omega\delta} = \frac{maV}{k_B (a+b)} \tag{31}$$

Operational calculus cannot be applied to Eqs. (4) and (5) due to the presence of nonlinear terms.
All relationships in the simplified reference model are linear and therefore the Laplace transformation can be applied and appropriate transfer functions can be determined. Then, at zero initial conditions of variables $\dot{Y}(t), \psi(t), \Omega(t)$, an equivalent notation of the simplified reference model in the transfer function form can be obtained as follows:

$$Y(s) = G_{Y\delta}(s)\delta(s) \tag{32}$$

$$\psi(s) = G_{\psi\delta}(s)\delta(s) = \frac{G_{\Omega\delta}(s)}{s}\delta(s) \tag{33}$$

where

$$G_{Y\delta}(s) = \frac{G_{\Omega\delta 0} V\left(T_1^2 s^2 + 2\xi_1 T_1 s + 1\right)}{s^2\left(T_0^2 s^2 + 2\xi_0 T_0 s + 1\right)} \tag{34}$$

$$T_1 = \sqrt{\frac{J}{k_B (a+b)}} \qquad \xi_1 = \frac{b}{2V}\sqrt{\frac{k_B (a+b)}{J}} \tag{35, 36}$$

Responses to the Step Input of Wheels Rotation

$$\text{If} \quad \delta(t) = \delta_0 1(t) \quad (1(t) - \text{Heaviside function}) \tag{37}$$

$$\text{then} \quad \delta(s) = \delta_0 \frac{1}{s} \tag{38}$$

$$\lim_{t\to\infty} U(t) = \lim_{s\to 0}\left(sU(s)\right) = \lim_{s\to 0}\left(sG_{U\delta}(s)\delta(s)\right) = \lim_{s\to 0}\left(s\frac{G_{U\delta 0}\left(T_{U\delta}s+1\right)}{\left(T_0^2 s^2 + 2\xi_0 T_0 s + 1\right)}\delta_0\frac{1}{s}\right) = G_{U\delta 0}\delta_0$$

(39)

$$\lim_{t\to\infty} \Omega(t) = \lim_{s\to 0}\left(s\Omega(s)\right) = \lim_{s\to 0}\left(sG_{\Omega\delta}(s)\delta(s)\right) = \lim_{s\to 0}\left(s\frac{G_{\Omega\delta 0}\left(T_{\Omega\delta}s+1\right)}{\left(T_0^2 s^2 + 2\xi_0 T_0 s + 1\right)}\delta_0\frac{1}{s}\right) = G_{\Omega\delta 0}\delta_0$$

When the time responses to the step input are available, these formulae can be used for identification of unknown parameters of the reference model.

Steady State Responses Y(t) and ψ(t) to the Sharp Pull of the Wheels in One and Next in the Opposing Direction

The two-sided sharp pull of the steering wheel with a hold time T can be described by a combination of step functions 1(t) of wheels rotation (see Fig. 3):

$$\delta(t) = \delta_0\left(1(t) - 2*1(t-T) + 1(t-2T)\right) \tag{40}$$

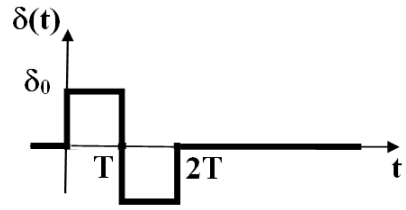


Figure 3. Two-sided sharp pull of the wheels.

An accurate analysis of the time histories of Y(t) and ψ(t) can be carried out on the basis of simulation results. The limits of ψ(t) and Y(t) at t → ∞ can be determined knowing the transform of the input function δ(t) and the appropriate transfer functions. For Y(t), due to the approximate character of the simplified reference model, this process will produce an estimated value.
The Laplace transform of δ(t) defined in formula (40) is given by:

$$\delta(s) = \delta_0\left(\frac{1}{s} - 2\frac{1}{s}e^{-sT} + \frac{1}{s}e^{-s2T}\right) = \delta_0\frac{1-2e^{-sT}+e^{-s2T}}{s} = \delta_0\frac{\left(1-e^{-sT}\right)^2}{s} \tag{41}$$

$$\lim_{t\to\infty} Y(t) = \lim_{s\to 0}\left(sY(s)\right) = \lim_{s\to 0}\left(sG_{Y\delta 0}(s)\delta(s)\right) = \lim_{s\to 0}\left(s\frac{G_{\Omega\delta 0}V\left(T_1^2s^2+2\xi_1T_1s+1\right)}{s^2\left(T_0^2s^2+2\xi_0T_0s+1\right)}\delta_0\frac{\left(1-e^{-sT}\right)^2}{s}\right) = T^2G_{\Omega\delta 0}V\delta_0 = Y_0 \tag{42}$$

$$\lim_{t\to\infty}\psi(t) = \lim_{s\to 0}\left(s\psi(s)\right) = \lim_{s\to 0}\left(sG_{\Omega\delta}(s)\delta(s)\right) = \lim_{s\to 0}\left(s\frac{G_{\Omega\delta 0}\left(T_{\Omega\delta}s+1\right)}{s\left(T_0^2s^2+2\xi_0T_0s+1\right)}\delta_0\frac{\left(1-e^{-sT}\right)^2}{s}\right) = 0 \tag{43}$$

The meaning of the above results is that vehicle steer through a sharp pull of the steering wheel in one direction, followed by another pull in the opposite direction, causes the vehicle to change the lane of travel. This conclusion is also supported by observations of real vehicle behaviour. For the development of the controller, it is crucial to note that according to the reference model on the new lane the vehicle will move with zero yaw angle. Of course, due to the presence of disturbances and imperfections of the reference model after reaching the steady state the vehicle may be moving along a straight path with nonzero yaw angle. Eliminating that error will be the subject of the corrective action of the controller.
To achieve the intended lane change represented by the lateral distance Y_0, it is necessary to appropriately choose the time duration T of the control impulse (square relationship) and its value δ_0 (linear relationship). In this process it is necessary to take into account the value of the amplification parameter $G_{\Omega\delta 0}$ and vehicle velocity V.
The reference model proposed above can be used directly in the control of the trajectory of the vehicle centre of mass (the first phase of the manoeuvre) as well as in the vehicle yaw angle control (the second phase).

Control of the Lateral Displacement of the Vehicle Mass Centre

According to the proposed control approach, in the first phase of the process, the control of the steering wheel rotation angle will be executed in the open loop – on the basis of the reference model, taking into account signal limitations and minimization of the manoeuvre duration time. At the same time, the corrective action will be carried out based on the principles of automatic regulation. Accuracy of this operation should be ensured mostly by the quality of the identified reference model. The diagram of the control system for this phase is shown in Fig. 4.

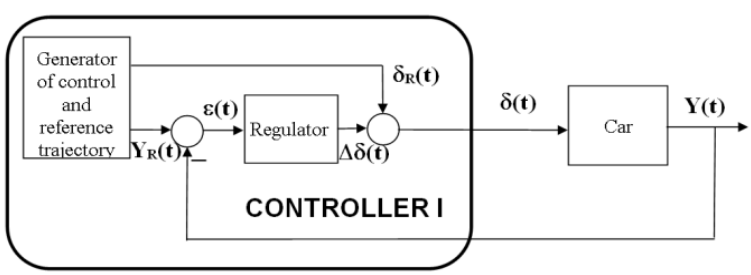


Figure 4. Block diagram of the automatic control system in Phase I.

Generator of steering wheel angle and reference trajectory Reference time profiles $\delta_R(t)$ and $Y_R(t)$ are generated.

The reference time profile of vehicle lateral displacement $Y_R(t)$ that ensures obstacle avoidance is determined by generation of the control input in the form presented in Eq. (40), with parameters δ_0 and T chosen such that the conditions $|\ddot{y}(t)| \le \ddot{y}_{dop}$ and $|\dot{\psi}(t)| \le \dot{\psi}_{dop}$ are satisfied, and the steady state is achieved within the time not exceeding the allowed value resulting from current vehicle velocity and the distance from the obstacle. For the selection of δ_0 and T, trajectory optimization can be used, for example with the objective to achieve the shortest time to reach the steady state. Such selection and representing the input function parameters in the tabular form are to be carried out off-line on the basis of simulations, for a broad range of design and operational parameters present in the initial reference model. The simplified reference model can facilitate that process.

The regulator The regulator can be developed on the basis of the classical control theory, or with the use of the optimal control theory applied to the linear-quadratic problem. As known, regulators determined from the solution of linear-quadratic problems are usually very effective and relatively simple for implementation. Such an approach is presented below.

The linear-quadratic problem is formulated as follows. For the model in the state-space matrix form

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \tag{44}$$

with initial conditions $\mathbf{x}(0) = \mathbf{0}$ find the control vector $\mathbf{u}(t)$ that minimizes the functional:

$$Q = \int_0^\infty \left(\mathbf{x}(t)^T \mathbf{P}\mathbf{x}(t) + \mathbf{u}(t)\mathbf{R}\mathbf{u}(t)\right)dt \ . \tag{45}$$

with **P** and **R** – positively defined weight matrices.

According to Kalman theorem [1] the solution

of the linear-quadratic problem is:

$$\hat{\mathbf{u}}(t) = -\mathbf{R}^{-1}\mathbf{B}^T\mathbf{K}\mathbf{x}(t) \tag{46}$$

where **K** –symmetric matrix satisfying Ricatti equation: $-\mathbf{KA} - \mathbf{A}^T\mathbf{K} + \mathbf{KBRB}^T\mathbf{K} = \mathbf{P}$ (47)

The meaning of this solution is that the control vector is computed in the closed loop system, with feedback parameters depending on the model and the objective weight matrices, and determined as the solution of the nonlinear algebraic Ricatti equation.

In order to apply the theory of linear-quadratic systems it is necessary to formulate the linear mathematical model of the object in the state-space form. The control performance index should be presented in the form of integral functional with quadratic forms. Note that the earlier determined transfer function $G_{Y\delta}(s)$ describes also the dynamics for the perturbed states:

$\Delta\delta = \delta_R(t) - \delta(t)$ and $\Delta Y = Y_R(t) - Y(t) = \varepsilon(t)$ (tracking error), and therefore one also has:

$$\Delta Y(s) = G_{Y\delta}(s)\Delta\delta(s) = \frac{G_{\Omega\delta 0}V\left(T_1^2 s^2 + 2\xi_1 T_1 s + 1\right)}{s^2\left(T_0^2 s^2 + 2\xi_0 T_0 s + 1\right)}\Delta\delta(s) \tag{48}$$

For the purpose of illustrating the method by analytical means the simplified reference model will be used together with simplified form of the transfer function:

$$G_{Y\delta}(s) = \frac{\Delta Y(s)}{\Delta\delta(s)} = \frac{G_{\Omega\delta 0}V\left(T_1^2 s^2 + 2\xi_1 T_1 s + 1\right)}{s^2\left(T_0^2 s^2 + 2\xi_0 T_0 s + 1\right)} \approx \frac{G_{\Omega\delta 0}V}{s^2} \tag{49}$$

The model that corresponds to such transfer function has the following state-space form:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix}u(t) \tag{50}$$

where

$$x_1(t) = \Delta Y(t) \quad x_2(t) = \Delta\dot{Y}(t) \quad u(t) = G_{\Omega\delta 0}V\Delta\delta(t) \tag{51}$$

The control performance index can be defined as:

$$Q = \int_0^\infty \left(p_{11}x_1^2(t) + p_{22}x_2^2(t) + ru^2(t)\right)dt \text{ which means}$$

$$Q = \int_0^\infty \left(\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}^T \begin{bmatrix} p_{11} & 0 \\ 0 & p_{22} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + uru(t)\right)dt \tag{52}$$

In the typical notation of the linear-quadratic problem one gets:

$$\mathbf{A}=\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix},\ \mathbf{B}=\begin{bmatrix}0\\ 1\end{bmatrix}\quad \mathbf{P}=\begin{bmatrix}p_{11} & 0\\ 0 & p_{12}\end{bmatrix}\quad \mathbf{R}=r \tag{53}$$

The linear-quadratic problem has a solution according to Eqs. (46) and (47). For the considered case:

$$\mathbf{R}^{-1}=\frac{1}{r} \tag{54}$$

$$\mathbf{K}=\begin{bmatrix}K_{11} & K_{12}\\ K_{21} & K_{22}\end{bmatrix}=\begin{bmatrix}K_{11} & K_{12}\\ K_{12} & K_{22}\end{bmatrix}$$

The symmetric matrix **K** satisfies the equation:

$$-\begin{bmatrix}K_{11} & K_{12}\\ K_{12} & K_{22}\end{bmatrix}\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}-\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}^T\begin{bmatrix}K_{11} & K_{12}\\ K_{12} & K_{22}\end{bmatrix}+\begin{bmatrix}K_{11} & K_{12}\\ K_{12} & K_{22}\end{bmatrix}\begin{bmatrix}0\\ 1\end{bmatrix}r\begin{bmatrix}0\\ 1\end{bmatrix}^T\begin{bmatrix}K_{11} & K_{12}\\ K_{12} & K_{22}\end{bmatrix}=\begin{bmatrix}p_{11} & 0\\ 0 & p_{22}\end{bmatrix} \tag{55}$$

Carrying matrix operations in Eq. (55) leads to the equation:

$$\begin{bmatrix}rK_{12}^2 & -K_{11}+rK_{12}K_{22}\\ -K_{11}+rK_{12}K_{22} & -2K_{12}+rK_{22}^2\end{bmatrix}=\begin{bmatrix}p_{11} & 0\\ 0 & p_{22}\end{bmatrix} \tag{56}$$

Considering stability requirements one finally gets:

$$K_{12}=\sqrt{\frac{p_{11}}{r}},\qquad K_{22}=\sqrt{\frac{p_{22}+2\sqrt{\frac{p_{11}}{r}}}{r}},\qquad K_{11}=\sqrt{p_{11}\left(p_{22}+2\sqrt{\frac{p_{11}}{r}}\right)} \tag{57}$$

Substituting calculated coefficients into Eq. (46) gives:

$$\hat{u}(t)=-\frac{1}{r}\begin{bmatrix}0\\ 1\end{bmatrix}^T\begin{bmatrix}K_{11} & K_{12}\\ K_{12} & K_{22}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix}=-\frac{1}{r}\begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}K_{11} & K_{12}\\ K_{12} & K_{22}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix}=-\frac{1}{r}\begin{bmatrix}K_{12} & K_{22}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix}=-\frac{1}{r}\left(K_{12}x_1(t)+K_{22}x_2(t)\right) \tag{58}$$

Hence

$$\hat{u}(t)=-\frac{1}{r}\left(\sqrt{\frac{p_{11}}{r}}x_1(t)+\sqrt{p_{11}\left(p_{22}+2\sqrt{\frac{p_{11}}{r}}\right)}x_2(t)\right) \tag{59}$$

$$\Delta\hat{\delta}(t)=-\frac{1}{G_{\Omega\delta 0}Vr}\left(\sqrt{\frac{p_{11}}{r}}\Delta Y(t)+\sqrt{p_{11}\left(p_{22}+2\sqrt{\frac{p_{11}}{r}}\right)}\Delta\dot{Y}(t)\right) \tag{60}$$

In the operator domain:

$$\Delta\hat{\delta}(s)=-\frac{1}{G_{\Omega\delta 0}Vr}\left(\sqrt{\frac{p_{11}}{r}}+s\sqrt{p_{11}\left(p_{22}+2\sqrt{\frac{p_{11}}{r}}\right)}\right)\Delta Y(s) \tag{61}$$

The transfer function of the proportional-plus-derivative regulator (PD):

$$G_{\Delta\delta\Delta Y}(s)=\frac{\Delta\delta(s)}{-\Delta Y(s)}=\frac{1}{G_{\Omega\delta 0}Vr}\left(\sqrt{\frac{p_{11}}{r}}+s\sqrt{p_{11}\left(p_{22}+2\sqrt{\frac{p_{11}}{r}}\right)}\right) \tag{62}$$

With the use of the vehicle lateral acceleration the controller becomes the regulator with integration.

Stabilization of the Yaw Angle of the Vehicle

Following the earlier described concept of vehicle control, in the second phase of the manoeuvre the control of the steering wheel rotation will be carried out as in the regulation system. Considering possible unification of the control system, it is useful to set the block structure of the controller in the form similar to the first phase controller. It is shown in Fig. 5.

In this case the generator of reference signals has a trivial form:

$$\psi_R(t) = 0 \qquad \delta_R(t)=0 \tag{63, 64}$$

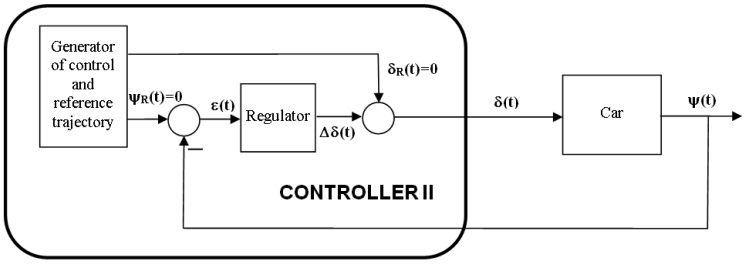


Figure 5. Block diagram of the automatic control system in Phase II.

The regulator adjusting the steering wheel rotation angle can be developed in the way similar to Phase I. Note that in this case the transfer function $G_{\Omega\delta}(s)$, determined from the initial reference model, can be also used for the description of the dynamics with angular perturbations:

$\Delta\delta(t) = \delta_R(t) - \delta(t)$ and $\Delta\psi = 0 - \psi(t) = \varepsilon(t)$ (regulation error), and thus one gets:

$$\Delta\psi(s) = \frac{1}{s} G_{\Omega\delta}(s)\Delta\delta(s) = \frac{G_{\Omega\delta 0}\left(T_{\Omega\delta} s + 1\right)}{s\left(T_0^2 s^2 + 2\xi_0 T_0 s + 1\right)}\Delta\delta(s) \tag{65}$$

Subsequent development follows an analogous path to the already presented and is omitted in this paper.

Note that due to identical structures of the controllers for the first and second phases of the manoeuvre, an universal controller device can be used, with a switchable algorithms and changing reference and feedback signals.

The developed algorithms of the controller, generating the reference signals and error feedback terms, constitute the basis of the active steering system controller. In the simplest approach, the steering wheel rotation angle $\delta_H(t)$ can be treated as a scaled version (through the steering gear ratio) of the steer angle of the wheels $\delta(t)$. In the more comprehensive solutions, additional corrective terms can be added in order to take into account the dynamics and nonlinearities of the real steering mechanism.

SIMULATION RESULTS

Verification and validation of the proposed control approach was carried out through numerical simulations in which a comprehensive model of vehicle dynamics was used. That model was treated as a "real" vehicle. The model of a commercial truck [5,6] was adapted for that purpose and used in simulations. It represents a complex, 3D model of a two-axis commercial truck of medium load capacity, having twenty degrees of freedom, and built on the basis of studies and observations of the real vehicle (STAR 1142). The active steering system included in the model takes into account its geometry, kinematics, dynamics as well as elastic and damping properties. The tire model proposed by Dugoff, Fancher, Segel [3], completed with recommendations resulting from the research conducted under the guidance of Mitschke [7], was used for the description of interaction between vehicle tires and roadway surface. An important advantage of this tire model is that in spite of relatively simple mathematical formulation it allows for an easy introduction of vehicle parameters (traction coefficient, velocity, radial loads) and makes it possible to simulate vehicle motion in the full skid condition.

The model of the truck was subjected to a broad and thorough experimental verification [5]. The results obtained during tests of the real vehicle were used for the experimental verification of the model. Typical manoeuvres included driving along a circular path in steady conditions, quick turn of the steering wheel while driving straight ahead and braking while driving along a straight road and braking while turning. In order to determine the parameters of the tire model, thorough experimental tests of dynamic characteristics of vehicle tires were carried out on a drum dyno and with a dynamometer trailer.

Effectiveness of the control approach presented in this paper has been evaluated through simulations that involved avoiding suddenly appearing obstacle through single lane change on a shortest distance possible. During numerical experiments it was necessary to tune the values of parameters p_{11}, p_{22} and r (Eq. 60). Adjusting those values was done by trial and error. A number of obstacle avoidance manoeuvres with different settings were carried out. The parameters that were changing in the consecutive tests included the initial velocity of the vehicle (in the range of V=40-80km/h), the friction coefficient between the tires and the road surface (in the range of μ=0.1-0.5) and the weight of the load in the cargo section of the truck (not loaded, partly loaded and fully loaded). The objective was to find the settings that would allow successful completion of the obstacle avoidance manoeuvre in all trials that were conducted.

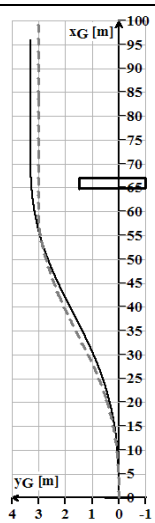
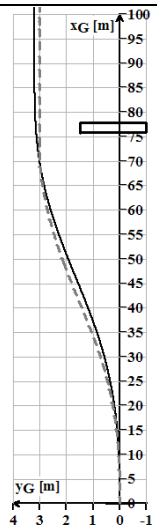
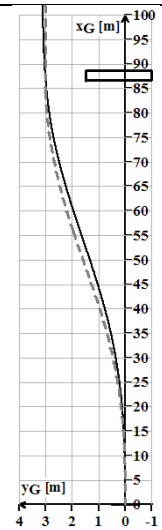
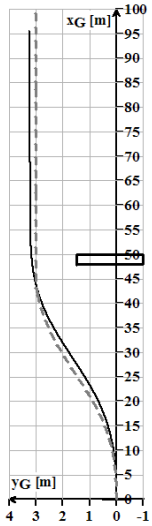
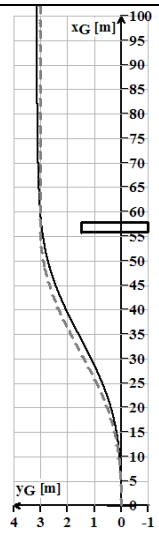
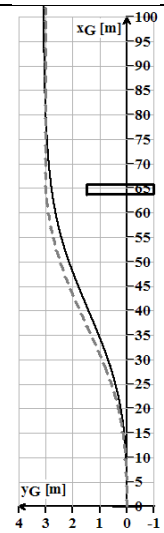
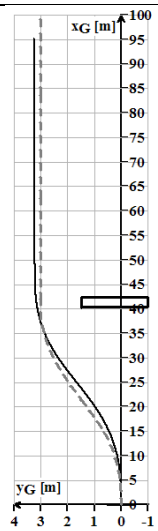
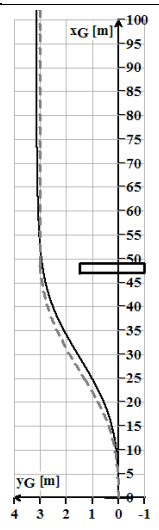
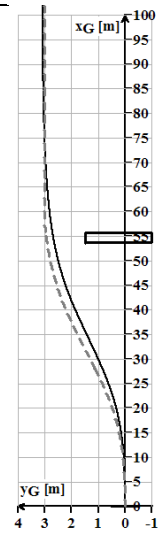
Item	V=60km/h	V=70km/h	V=80km/h
μ=0.1			
μ=0.2			
μ=0.3			

Figure 6. The results of the simulation studies – the assigned (broken line) and realized (solid line) trajectory of the car's centre of mass.

The obstacle avoidance manoeuvre, according to the earlier described approach, was implemented in two phases. The controller shown in Fig. 4 was used in the first phase. In that phase, the desired trajectories $Y_R(t)$ of the vehicle centre of mass had been generated using the bicycle model of the vehicle and Eq. (40). The time profiles of the steering wheel rotation angle $\delta_{HR}(t)$ had been determined using Eq. (40) and the mean value of the steering system ratio. For each test, the values of variables T and δ_0 (Fig. 3) were determined taking into account the limit value of the radius of the circular path on which the vehicle could move without the loss of lateral traction. The lateral displacement Y_0=3 m of vehicle's centre of mass to the target lane was used. The controller shown in Fig. 5 was used in the second phase of the manoeuvre. In that phase, the vehicle yaw angle was set to zero ($\psi(t)=0$) and the steering wheel rotation angle was assigned as $\delta_{HR}=0$. In both phases, the instantaneous value of the steering wheel rotation angle $\delta_H(t)$ taken as the sum of the assigned value $\delta_{HR}(t)$ and the value $\Delta\delta_H(t)$ computed by the regulator was limited by the allowable values of vehicle velocity and the values of steering wheel angular acceleration. In all simulations that were carried out the controller II (Fig. 5) was taking over the control of the steering wheel rotation angle after the time period of t_1=1.5T (Fig. 3).
The results of simulations have shown that in all tests that were carried out the obstacle avoidance manoeuvre was accomplished successfully. A portion of simulation results is presented in Fig. 6. They were obtained for the fully loaded truck, with the low position of the centre of mass, on slippery pavements (friction coefficient of μ =0.1-0.3), and with vehicle velocities of 60-80km/h.
The automatically controlled vehicle was able to avoid the obstacle without losing directional stability, even though the conditions of vehicle operation were changing in a broad range. Therefore, it can be stated that the proposed concept of control and the developed regulators proved to be insensitive to varying road conditions, and with that, the control approach appeared to be effective in realization of the lane change manoeuvre on the shortest path possible.

CONCLUSIONS AND CLOSING REMARKS

The adopted reference model of the lateral dynamics of the vehicle in its initial and simplified versions seems to provide an accepted basis for the development of controllers that automate the lane change manoeuvre. The proposed method of the decomposition of the control leads to two identical structures of the controller for both phases of the process. The results of simulations showing the use of such controller for the control of the commercial truck prove the correct direction of the research.
The method of automatic execution of the lane change manoeuvre presented in the paper can offer an attractive alternative for vehicle control engineers and researchers working in the fields of automatic steering systems and vehicle active safety systems. The results are especially important because they illustrate the application of the methodology for the case of a commercial truck.

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Improve Road Safety Using Combined V2V and Pre-Collision Systems

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ABSTRACT

In current vehicle to vehicle (V2V) communication systems, each vehicle broadcasts its motion status and receives information from other vehicles in order to make safety decisions and actions. State-of-the-art pre-collision systems (PCS) utilize onboard sensors to collect potential crash object information for making safety action decisions. This V2V-PCS combination enables a vehicle to not only send its own motion information, but also its PCS detected information to other vehicles. Conceptually, the additional information should help a V2V enabled vehicle make its safety related decisions more accurately and efficiently. The objective of this study is to find if a combined V2V and PCS system (V2V-PCS) can further improve the safety of not only V2V-PCS enabled vehicles but also other non V2V-PCS enabled vehicles on the road. This paper describes a process that can be used to analyze pedestrian and vehicle scenarios, and determine whether or not the safety of pedestrians could be improved by a V2V-PCS system. It also gives an analytical method for determining the benefit of using V2V-PCS. The environments set up for V2V-PCS simulation and real vehicle testing are also described.

Keyword: Pre-collision systems, V2V

1. Introduction

Based on statistics from the 2005-2008 National Automotive Sampling System (NASS) General Estimates System (GES) crash databases, V2V-based safety applications would potentially address about 4,336,000 police-reported light-vehicle crashes annually, with the 95 percent confidence interval between 3,691,000 and 4,981,000 [1]. The advancement in computation power and communication capability enables the practical implementation of vehicle to vehicle communication (V2V) systems. The advantage of V2V systems has been well discussed in many literatures. Pilot V2V implementation programs are conducted in several countries [2, 3]. The fundamental advantage of V2V is its capability of exchanging vehicle information that enables the intelligent decisions regarding road safety and efficiency. V2V-based safety applications predominantly apply to crashes that involve multi-vehicle pre-crash scenarios. This analysis is conducted with support from the Intelligent Transportation System's program for safety and mobility applications based on V2V and vehicle-to-infrastructure (V2I) communications [4]. To improve the intelligence of V2V systems, there are studies for incorporating information from traffic lights and road sensors through vehicle to infrastructure (V2I) systems, vehicle to pedestrian (V2P) systems into V2X systems. However, the current development of V2X systems is based on the concept that each participant provides its own operating information to the V2X system. There will be a long time period that V2V capable and non-V2V vehicles coexist on roads. The current design of the V2X systems does not benefit non-V2X equipped objects (vehicle and pedestrians) since the information of these objects cannot be entered into the V2X systems. To solve this problem, there should be a way to gather the information of non-V2V enabled objects on the road, transmit this information the V2X system, and use the information to improve the safety of all objects on the road.

PCS system is an active safety component in many commercially available vehicles. A PCS has sensors (video camera, radar, lidar, etc.) to detect vehicles, pedestrians and bicyclist. The sensor information is presently used for collision imminent warning, automatic braking and maneuvering. If the PCS sensor information of a vehicle can be broadcast to a V2V network, other V2V enabled vehicles may use the information to improve the safety of the sensed objects. This paper discusses the future technology development in combining V2V and PCS together to enable a V2V vehicle to broadcast its PCS detected information and use recieved information to make better crash avoidance decisions. The combined V2V-PCS can effectively extend the information gathering range of V2V vehicles and enables all V2V vehicles to get information of non-V2V enabled objects.

This paper describes a systematic process to investigate all V2V-PCS scenarios that potentially benefit the pedestrians with the adoption of the combined V2V-PCS systems. First the variables and their values relevant to V2V-PCS scenarios are identified. Then all scenarios generated from the combination of the variable values are examined to determine if they can improve pedestrian safety. The computation method for determining if the V2V-PCS improves the pedestrian safety for each scenario is described. The calculation of the first appearance location of the pedestrian to the vehicle and time to collision due to the location of the obscure object is described. The result of this study serves three purposes, (1) it provides a baseline to describe the usefulness of a V2V-PCS system, (2) it provides all pedestrian V2V-PCS simulation scenarios and crash calculation for future study and demonstration, and (3) it supports the establishment of testing scenarios for the performance evaluation of the V2V-PCS enabled vehicles.

2. Environment description and scenario categorization

It is assumed that there are three types of vehicles on the road: vehicles without V2V capability, vehicles with V2V capability but no PCS capability, vehicles with both and V2V and PCS capabilities. Each vehicle can be either moving or stationary. It is also assumed that pedestrians and stationary objects on the road do not have V2V capability. To describe V2V-PCS scenarios for pedestrian safety, the objects in the scenarios include pedestrians, vehicle potentially crashes the pedestrians (crashing vehicle), and V2V-PCS enabled vehicle that broadcast the pedestrian information and objects that obscure the view of the crashing vehicle. To describe the scenarios that a V2V-PCS system could show pedestrian safety advantage, following variables are identified:

1. *Crash Location* – The crash location variable has four relevant values: not-at-intersection, before-intersection in-intersection, after intersection.
2. *Crashing Vehicle Motion Direction*: possible values are *straight forward, turn left, turn right, merge left, and merge right*. In not-at-intersection scenarios, crashing vehicles cannot turn left or right so there are only three possible values: *straight forward, merge left, and merge right*; in intersection related scenarios, merging while turning is equivalent to turning with a different radius, so there are only three possible values: *straight forward, turn left, and turn right*.
3. *Pedestrian motion direction relative to the crashing vehicle*: Four possible values are *Left to Right, Right to Left, Along Traffic, and Against Traffic*.
4. *Obscure object*: There are seven interested values for this variable: no obscure object, stationary/moving obscure objects on left/front/right. The presence of obscure objects blocks the view of the crashing vehicle and shortens the reaction time to a potential collision.

For the convenience of describing the V2V-PCS scenarios, the notations for these variables and their values are defined in Table 1.

Table 1. Variables and values relevant for describing V2V-PCS scenarios

Crash location	**Crashing vehicle direction**	**Pedestrian direction respect to crashing vehicle**	**Obscure object- location with respect to crashing vehicle (M=motion, S=Stationary)**
IB – before intersection	VLT – left tern	PLR – left to right	OS/M – obscure obj.
IA - after intersection	VRT – right turn	PRL – right to left	OS/M – obscure obj.
II – in intersection	VST - straight	PAL – along traffic	OS/M – obscure obj.
IN – not in intersection	VLM – left merge	PAG –against traffic	ON – no object
	VRM –right merge		
	VLC – left curve		
	VRC –right curve		

168 different scenarios can be identified based on the combination of all possible values of environment variables as described in Table 1. In which 108 are intersection related and 60 are non-intersection related. 108 intersection related cases are calculated as 1(intersection)*3(Before, In, or After intersection)*3(Turn left, Turn right, Straight Forward)*4(Left to Right, Right to Left, Along Traffic, Against Traffic)*3(moving obscure objects, stationary obscure objects, no obscure object) . 60 non-intersection scenarios are calculated as 1(non-intersection)*5(Curve

left, Curve right, Straight Forward, Merge left, Merge right) *4(Left to Right, Right to Left, Along Traffic, Against Traffic)*3(moving obscure objects, stationary obscure objects, no obscure object).

Each of these 168 scenarios was studied to determine if it could benefit from the use of V2V-PCS systems. The basic idea is to check if the crashing vehicle can get potential crash information earlier when a V2V-PCS system is adopted. The crashing vehicle may not be able to see the pedestrian for various reasons. If there is another vehicle (the informing vehicle) that has the PCS capability to detect the pedestrian and send the information to the crashing vehicle, the crashing vehicle may able to take measures in advance to avoid the collision. Here it is assumed that pedestrians do not detect the potential danger and cannot send their location information to vehicles. According to the selection criteria described above, 96 scenarios (listed in Table 2) are able to benefit from V2V-PCS systems and 72 Scenarios will not benefit from V2V-PCS systems.

Table 2. 96 scenarios that the V2V-PCS system can improve the pedestrian safety

Location	Vehicle	Pedestrian and the Obscure object
IB	VLT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VRT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VST	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
IA	VLT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VRT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VST	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
II		None
IN	VST	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VLC	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VRC	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VLM	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON
	VRM	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON

Table 3. 72 Scenarios that the V2V-PCS cannot improve the pedestrian safety

Location	Vehicle	Pedestrian and the Obscure object
IB	VLT	PAL_OS; PAL_OM; PAG_OS; PAG_OM
	VRT	PAL_OS; PAL_OM; PAG_OS; PAG_OM
	VST	PAL_OS; PAL_OM; PAG_OS; PAG_OM
IA	VLT	PAL_OS; PAL_OM; PAG_OS; PAG_OM
	VRT	PAL_OS; PAL_OM; PAG_OS; PAG_OM
	VST	PAL_OS; PAL_OM; PAG_OS; PAG_OM
II	VLT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON
	VRT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON
	VST	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON
IN	VST	PAL_OS; PAG_OS; PAL_OM; PAG_OM
	VLC	PAL_OS; PAG_OS; PAL_OM; PAG_OM
	VRC	PAL_OS; PAG_OS; PAL_OM; PAG_OM
	VLM	None
	VRM	None

To make the graphical description easier, following icons are used in figures:

The pedestrian sign represents the pedestrian without the capability to communicate with vehicles.

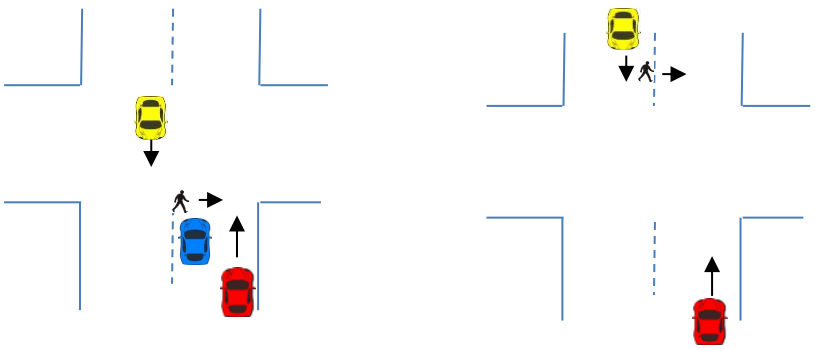
The red vehicle represents the crashing vehicle equipped with V2V (may have PCS capability).

The yellow vehicle represents the informing vehicle equipped with both PCS and V2V.

The blue vehicle represents the stationary vehicle equipped with both PCS and V2V

The hexagon represents the obscure object.

Figure 1A demonstrates a situation that the use of a V2V-PCS system could improve the safety of a pedestrian. The red car (crashing vehicle) is going straight forward. The stationary blue car is waiting for a left turn signal and obscures the view of the red car. The pedestrian is walking across the road from left to right. The red car may not be able to stop due to the short reaction time. If the yellow car (the informing vehicle) coming from the other side or the blue car has pedestrian PCS and V2V capability, they can detect the pedestrian and send the pedestrian motion information to the red car so that the red car can take measures in advance to avoid potential crash to the pedestrian. If the red car is equipped with V2V but no PCS, it can generate warning to the driver, and or generate pre-braking command to the brake system to be ready for real brake. If the red car has both PCS and V2V capabilities, it can pay special attention to the location where the pedestrian is expected to appear and make quicker and better decisions. The V2V-PCS is useful even if the obscure blue car is not present (Figure 1B). If the pedestrian is far from the fast moving red car, the sensors in the red car may not be able to detect the pedestrian so the PCS on the red car may not be able to make effective braking decision. Since the pedestrian is much closer to yellow car, the V2V-PCS of the yellow car can provide pedestrian information before the red car can recognize the pedestrian.



(A) IB-VST-PLR-OS *(B) IA-VST-PLR-ON*

Figure 1. Example scenarios showing that the V2V-PCS system may prevent a crash to the pedestrian.

Figure 2 demonstrates a scenario that the V2V-PCS system cannot improve the safety of a pedestrian. The red car (crashing vehicle) is going straight forward. The obscure blue car is in front of the red car. The pedestrian is walking along the road. Even the pedestrian information sent by the blue car and received by the red car, there is not a situation that the red car can crash to the pedestrian.

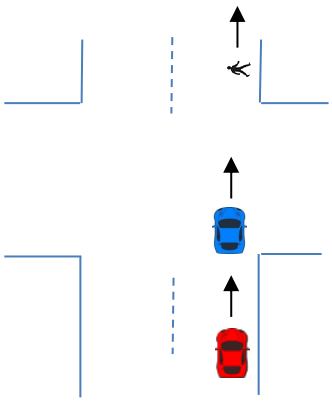


Figure 2. A scenario IA-VST-PAL-OM showing the scenarios at the V2V-PCS system does not help pedestrian safety.

3. Analysis of scenarios

All scenarios that V2V-PCS systems improve the safety of the pedestrians are identified in last section. The next step is to answer two practical questions quantitatively,

A. Given any scenario as described in Table 2 with detailed motion information of all objects, how do we know if there is a crash or not? The answer to this question is useful for developing a V2V-PCS warning/braking strategy.

B. Given any scenario as described in Table 2 with the positions and speeds of all objects except the initial position of the crashing vehicle, what is the initial position of the crashing vehicle so that there is a crash to the pedestrian at a specific location of the vehicle? The answer to this question is useful for setting up the test scenario for evaluating the effectiveness of the V2V-PCS systems.

To answer these questions, scenarios in Table 2 are reorganized into three categories based on the vehicle motion direction: vehicle move straight, vehicle change/merge lanes, and vehicle move in a curved lane.

3.1. The straight moving vehicle crashes a pedestrian crossing a street

This subsection provides a method to check if there will be a crash when a pedestrian is crossing the road and vehicle is moving straight. This method is essential for evaluating whether or not a V2V-PCS system is capable of improving a pedestrian's safety. Figure 3 depicts a situation where a straight moving vehicle crashes into a pedestrian crossing the street. The red car is moving straight forward with center at the y-axis, while a pedestrian crosses the road from left to right with an angle of Θ to x-axis. Assuming the crash location is at the origin of the coordinate system, the following equations can answer the aforementioned two questions.

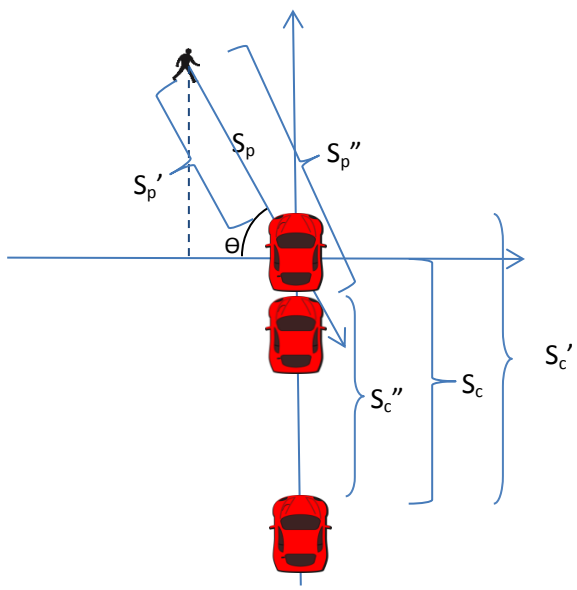


Figure 3. The straight moving vehicle crashes a pedestrian crossing a street.

Definition of notations in Figure 3:

Θ: The angle of the pedestrian's motion with respect to x axis

L_c: The length of the vehicle

W_c: The width of the vehicle

S_c: The distance between the vehicle's initial position (front center) and the potential collision point

S_c': The distance between vehicle's initial position (front left corner) and the potential collision point

$$S_c' = S_c + 0.5W_c \tan \Theta$$

S_c'': The distance between vehicle's initial position (front right corner) and the potential collision

$$S_c'' = S_c - 0.5W_c \tan \Theta$$

S_p: The distance between pedestrian's initial position (front center) and the collision point

S_p': The distance between the pedestrian's initial position and the collision point with vehicle's front left corner

$$S_p' = S_p - 0.5W_c/\cos \Theta$$

S_p'': The distance between pedestrian's initial position and the collision point with vehicle's front right corner

$$S_p'' = S_p + 0.5W_c/\cos \Theta$$

v_p: The velocity of the pedestrian (Assume the pedestrian is moving at a constant speed)
v_c: The initial velocity of the vehicle
a_c: The acceleration of the vehicle

A. Determine if there is a collision between the vehicle and the pedestrian

According to Figure 3, potential crash time t_c is bounded by two conditions, one where the pedestrian is struck at the left front corner of the vehicle and one where the pedestrian is struck at the right front corner of the vehicle. The time interval for the pedestrian to move between these two points can be expressed as [t_p', t_p"], and the time interval for the vehicle to move between these two points can be shown as [t_c', t_c"]. Vc crashes to the pedestrian when [t_c', t_c"] overlaps [t_p', t_p"].

t_p' and t_p" can be calculated as S_p'/v_p and S_p''/v_p, respectively.
t_c' and t_c" can be calculated using Newton's laws of motion: $t = (-v_c \pm sqrt(v_c^2 + 2a_cS_c)) / a_c$,
If $a_c > 0$, If $sqrt(v_c^2 + 2\, a_cS_c) \geq v_c > 0$, Then $t = (-v_c + sqrt(v_c^2 + 2a_cS_c)) / a_c$
If $v_c > sqrt(v_c^2 + 2a_cS_c') > 0$, Then no positive t, invalid for this application.
If $a_c < 0$, If $v_c \geq sqrt(v_c^2 + 2a_cS_c') > 0$, Then $t = (-v_c + sqrt(v_c^2 + 2a_cS_c')) / a_c$
If $0 < v_c < sqrt(v_c^2 + 2a_cS_c')$, Then $t = (-v_c + sqrt(v_c^2 + 2a_cS_c')) / a_c$
If $a_c = 0$, $t = S_c/v_c$

Example 3.1.A:

Given the situation in Figure 2 and the variable values in the following table

a_c	v_c	v_p	Θ	L_c	W_c	S_p	S_p'	S_p"	S_c	S_c'	S_c"
$5m/s^2$	13.5m/s	1.5 m/s	60°	4.8m	1.8m	7.5m	5.7m	9.3m	55m	56.56m	53.44m

The calculation of (t_p', t_p") is (3.8 sec, 6.2sec), and (t_c', t_c") is (3.96 sec, 4.18 sec). Since there is an overlap time range which is [3.96 sec, 4.18 sec], it there is collision between the pedestrian and the crashing vehicle during this time interval.

B. Determine the initial positions of Vc and the pedestrian that guarantee a crash

According to Figure 3, the crashing vehicle is on y-axis and the crash point is at the origin, so the initial position of the vehicle is (0, $-S_c$) and the initial position of pedestrian is ($-S_p\cos\Theta$, $S_p\sin\Theta$). To guarantee a crash for vehicle testing, the initial position of the vehicle can be decided according to the initial position of the pedestrian and vice versa. In other word, the travel time for the pedestrian to reach origin should be the same as that for the vehicle. If the desired crash point is not at the middle front of the vehicle, the path of vehicle in the y-direction can be shifted along the-x axis accordingly.

3.2 The vehicle crashes a pedestrian crossing a street while change lanes

This section provides the method to check if there is a crash when a pedestrian is crossing the road and vehicle is changing lanes. Figure 4 depicts the situation that a vehicle crashes into a pedestrian crossing the street while changing lanes. The red car Vc is changing to the left lane centered at y-axis while a pedestrian crosses the road from left to right with an angle of Θ to x-axis. The definitions of the notations in Figure 4 are the same as that in Section 3.1. The additional notation α is the angle between y-axis and the line from the vehicles initial position to origin.

A. Determine if there is a crash between Vc and the pedestrian

Practically, in the vehicle changing lanes cases, the distance that the vehicle moves forward is much longer than the distance that the vehicle moves laterally (equals the width of a lane). Thus the width of the lane that the vehicle merges can be ignored so that these cases can be regarded as the vehicle moving straight forward as described in Section 3.1. So the method described in Section 3.1 can be used for these change lanes cases.

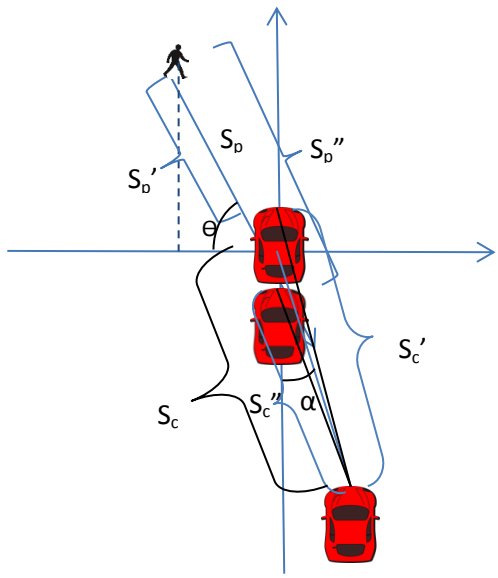


Figure 4. The vehicle changes lanes and crashes a pedestrian crossing a street.

B. Determine the initial positions of Vc and the pedestrian for vehicle V2V-PCS performance evaluation

According to Figure 3, the initial position of Vc is ($S_c\sin\alpha$, $-S_c\cos\alpha$) and the initial position of the pedestrian is ($-S_p\cos\Theta$, $S_p\sin\Theta$). To guarantee a crash in V2V-PCS evaluation, the initial position of the vehicle needs to be decided according to the initial position of the pedestrian and vice versa. In other words, the travel time for the pedestrian to reach origin should be the same as that for the vehicle. If the desired crash point is not at the middle front of the vehicle, the path of vehicle in the y-direction can be shifted along the-x axis accordingly.

3.3 The vehicle crashes the pedestrian while following a curved road

This subsection provides the method to check if there will be a crash when a pedestrian is crossing the road and vehicle is moving along a curved road (depicted in Figure 5). The red car is curving with center at y-axis while a pedestrian crosses the road from left to right with an angle of Θ to x-axis. It is assumed that the crash location will be at the origin of the coordinate. The curved lane in a non-intersection location can be considered as a straight lane in terms of traveling distance and time. Therefore, the method described in section 3.1 for determining if there is a collision between the vehicle and the pedestrian can be directly applied is this case. The method described in Section 3.2 for determining the initial positions of Vc and the pedestrian that guarantee a crash also can be directly applied is this case.

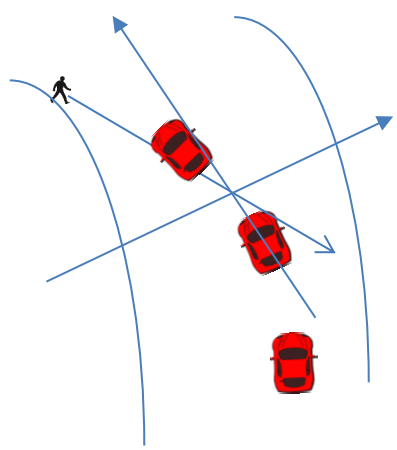


Figure 5. The vehicle crashes a pedestrian crossing a street while curving.

4 Add obscuring objects to the scenarios

The presence of obscuring objects does not change the collision time. However, they would delay a vehicles ability to recognize the pedestrian, which leads to less time for the vehicle to react to imminent crash to the pedestrian. To analyze the effect of the obscuring objects, the following question needs to be answered:

> *Given the path of the pedestrian and the location of the obscuring objects, how could the locations of the obscuring objects be determined so that the object obscures the vehicles view of the pedestrian?*

By answering this question, the time between the first appearance point of the pedestrian and a collision, or time to collision (TTC), can be calculated. If PCS systems are obscured then vehicles must rely more on V2V systems. Figure 6 will be used to describe the effect of the location of obscuring objects on potential crashes. For the simplicity of explanation, it is assumed that the camera is located at the front center of each vehicle. Notations in Figure 6 are defined as follows

Lvs & Wvs: The length and width of the blocking vehicle Vs.
Pp: The coordinates of the pedestrian.
Pvc: The front center position of Vc.
Pvc'& Pvc": The initial position and the final position that Vc is blocked by Vs.
Pvs-fr: The coordinates of the front right corner of Vs
Pvs-rl: The coordinates of the rear left corner of Vs

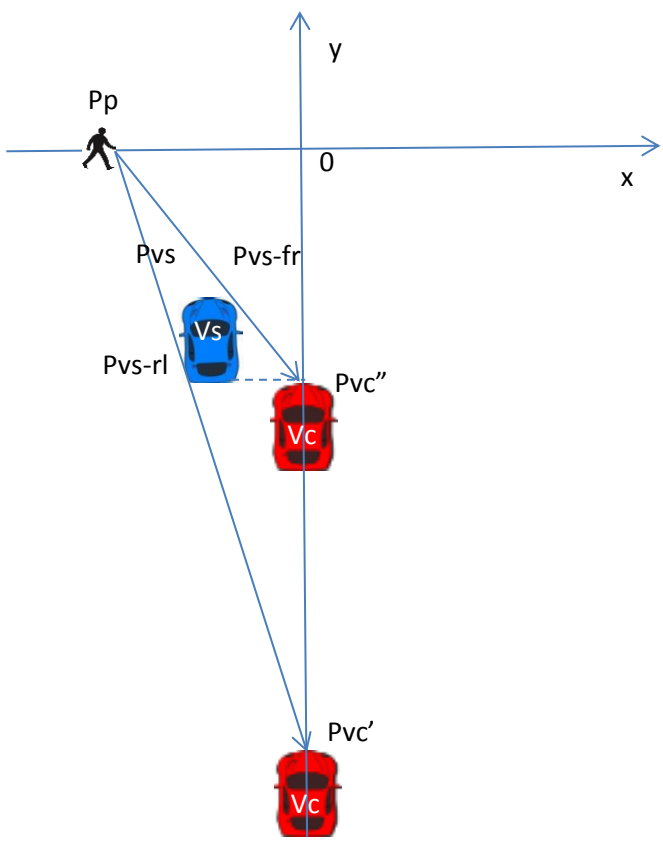


Figure 6. Add obscure vehicle Vs to scenarios

According to Figure 6, the range of positions that the blocking vehicle Vs blocks the crashing vehicle Vc's view of the pedestrian is from Pvc' to Pvc". For a given Pvs, Lvs and Wvs, Pvs-fr and vs-rl can be calculated. If Pp is given, Pvc' can be calculated as the point on y-axis and on the line of PpPvs-rl, and Pvc" can be calculated as the point on y-axis and on the line of PpPvs-fr. If Pvc is between Pvc'and Pvc", Vc cannot see the pedestrian.

5 Conclusion

This paper used an exhaustive analysis method to identify the scenarios that a combined PCS and V2V system can improve the pedestrian safety theoretically. 96 out of 168 pedestrian related scenarios can benefit from V2V-PCS system. The method for determining if there is a potential crash for all 96 cases for given vehicle and pedestrian motion parameters is described. The method for creating a crash condition for V2V-PCS system evaluation is also described. The calculation of the first appearance location of the pedestrian to the vehicle and time to collision due to the location of the obscure object is described. These results lay a good foundation for further V2V-PCS system studies.

Acknowledgement

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SAFETY LAYER for INTELLIGENT TRANSPORT SYSTEMS

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ABSTRACT

Intelligent Transport Systems are currently being developed in many different industry sectors.
These developments range from highly automated land vehicles, robots for mail delivery, agricultural drones up to ships automating vehicle ferry operations or automating the transportation of oil from the corresponding platforms.
Virtual drivers are a big challenge for implementation of these systems, and there is currently much activity in this area. But this is not the major challenge; which is making those systems safe and reliable. The following article shows an approach to realize safety and reliability of Intelligent Transport Systems by separating the functional components into a driver model with limited safety and reliability, and an additional safety layer.
In this approach, the driver model takes care of putting the required application case into practice and tries, similarly to a human driver, to continuously optimize the driving task. It is also possible to use training programs in productive operations for such driver models.
The driver model is supported by a static safety layer. This safety layer implements all safety targets that have been defined in the development phase and ensures that all safety targets are continuously being adhered to during the operation. This article shows an overview of the relevant safety targets for Intelligent Transport Systems and demonstrates strategies for implementing the security layer.

INTRODUCTION

Intelligent Transport Systems in combination with Highly Automated Driving are a frequent topic for research and development. IAV GmbH showed different use-cases with different speed levels of highly automated driving at the ITS World Congress in Detroit [1]. In Las Vegas the BMW Group presented technologies up to fully automated driving with the Remote Valet Parking Assistant [2]. Daimler AG introduced “The Truck of the Future”, an autonomously driving truck with the “Highway Pilot” system [3]. In Europe the first autonomous delivery flights of parcelcopters have been authorized for Deutsche Post DHL AG [4]. So compared to highly automated driving in Intelligent Transport Systems, there are also many similar technologies for automation and autonomous enabling of mechatronic systems in this area.
The objective of this technology is to provide a comfortable and safe future in all situations and numerous companies and institutions are putting a big effort into this [5]. But instead the big issue is to make these systems reliable and safe. The public acceptance of such high technology in their environment can only be achieved by a policy such as that aimed for in the “Vision Zero” initiative [6].
The goal of “Vision Zero”, introduced by the European Commission in 2011, aims for no fatalities or serious injuries by the year 2050. To accomplish a full acceptance it is necessary to put these goals into practice and familiarize the public with these technologies by continuous exhibiting [7].
Currently available assistance systems have a high level of safety, while their main features can be identified by availability and performance. These systems are primarily the basis of future highly automated or autonomous systems in Intelligent Transport Systems. The following article shows an approach to realize safety and reliability of Intelligent Transport Systems by separating the functional components into the comfort function with the main focus on availability and performance (i.e. assistance functions) and an additional safety layer as the safety function. (See Figure 1)

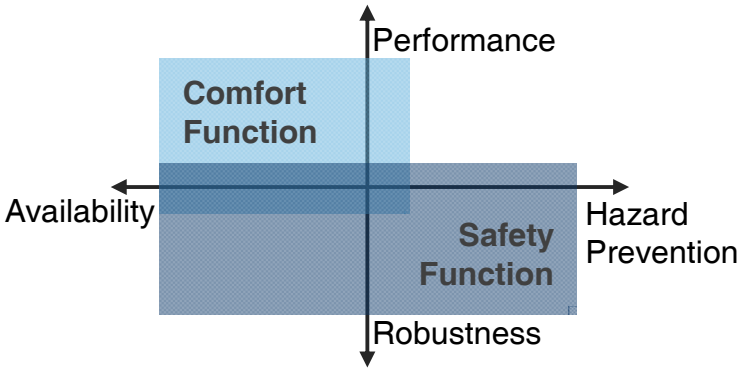

Figure 1: Characteristics of Comfort and Safety functions

CURRENT STATE OF ART

For a better comprehension of Intelligent Transport Systems (Abbr. ITS) and their safety issues, it is necessary to determine all essential system elements within the scope of this article. Starting in the lowest layer with assistance systems, followed by the Highly Automated Driving Systems (Abbr. HAD) and finally showing their part in ITS.
The "autonomous" character of driver assisting functions can be defined as decisions made by the car without the intervention of the driver [7].

Assistance Systems

Current driver assistance systems help drivers by way of a comfort function in standard situations as well as a safety function in critical situations [8]. Normally their function is limited to one problem and independent of other assistance systems [9]. There are two main types of systems: passive and active, not to be confused with categories of safety engineering. While the passive system works in background and the driver won't notice their assistance except for signaling, i.e. the Electronic Stability Control (ESC). The active system has to be turned on and/or adjusted by the driver. Situations the assistance function can't handle, the driver has to take over in around one to two seconds [11][15].
Input data can come from function-exclusive sensors. Shared input sources are a common way to distribute sensor data to the relevant functions. Objects already compiled from different input sources, e.g sensor data fusion, is also an increasingly popular method.
The function can be implemented as part of several functions on a control unit or alone on a control unit [10].

Highly Automated Driving

In contrast to assistance systems, here the car mostly operates by itself. The car controls the longitudinal and lateral directions. In first developments the driver sits in the loop with the automated system to intervene in situations the system can't handle. This take over action should have 8-10s to guarantee a smooth handover to the driver. With further research and development fully automated systems should be able to handle most situations. Then drivers won't be required and the handover request should give them several minutes time. The goal is an autonomous system which can handle every situation and where no drivers are necessary (See Figure 2) [5][11][15].

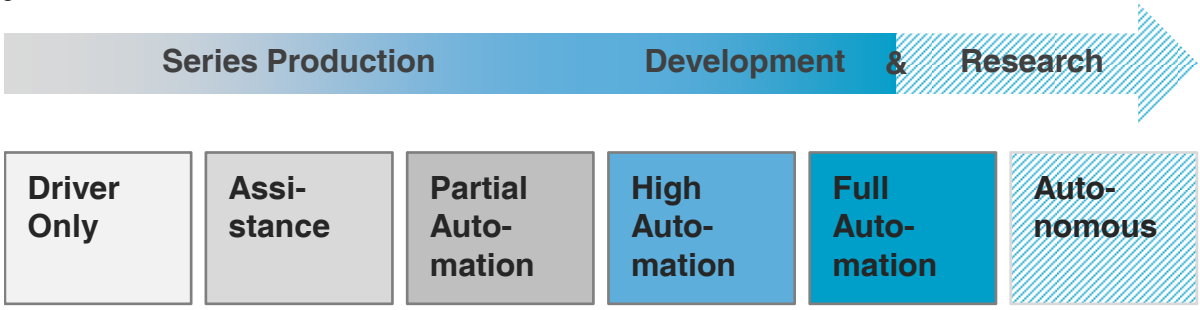

Figure 2: Levels of Automated Driving

Highly automated or autonomous systems require detailed environmental information, which can be achieved by data fusion of different sensor's data and information by communication between all participants. A verification of the presence of objects is possible with different sources of data.

Safety Functions & System Restrictions

Actual HAD Systems include state-of-the-art safety functions like redundancy, watchdogs etc. In addition the driver is sitting every time in the loop of the system [9]. When the automatic system fails, the driver has to take over. In emergency situations safety systems can support the driver or try by them self to bring the car into a safe state [8].

Moreover the German regulatory body doesn't support highly or fully automated driving systems, because the driver has to pay permanent attention to the traffic situation [12].

Fully Automated & Autonomous Systems

Furthermore highly automated or autonomous systems are more and more being introduced into ITS. They range from autonomous multicopters for parcel delivery [4] to fully automated public services [13] and unmanned cargo ships [14].

ANALYSIS OF APPLICATION

In the following illustration a scheme of different ITS participants and their interactions are characterized. It shows a possible example of a future application. Afterwards the limitations of highly automated and autonomous systems are demonstrated for the example with special focus on safety matters. The example also serves as the basis for practical application of the proposed safety concept.

Scheme of an ITS Interaction

The example is shown in Figure 3. It describes situations in an urban area with several participants such as pedestrians, cyclists, cars, public services and delivery services. The description is situation based. All cars are equipped with Highly Automated Driving. The public service and delivery service are also capable of autonomous or highly automated acting. Communication between most participants is possible.

Situation 1 Two cars are reaching an intersection at the same time. There is no direct visual contact between them. Because of car-to-car communications, the vehicles know each other's position, direction and velocity. The HAD System can handle this situation by cooperative actions, e.g. based on the most energy-efficient decision or the traffic rules.

Situation 2 A careless cyclist isn't paying attention to the traffic and just wants to reach the cycle path on the other side of the road. A car, equipped with HAD, is approaching the virtual crash point between these two participants. Even with the knowledge of the cyclist the car can't avoid a crash just by using emergency braking.

Situation 3 A car is approaching a crash site. The crash happened seconds before, so the car is entering a critical phase. Left of the car is a lane of oncoming traffic. On the other side is the sidewalk. The HAD System decides to brake and change to another lane.

Situation 4 A full autonomous delivery service distributes parcels by car and for the last meters to the house by multicopter. The multicopter drops off the parcel in a parcel box next to the house. On the way all sensors for obstacle detection fail.

Situation 5 A fully automated public bus is reaching a bus stop. Sensing an approaching passenger, the bus wants to pull over and stop, but a subsystem fails and is in danger of suffering damage.

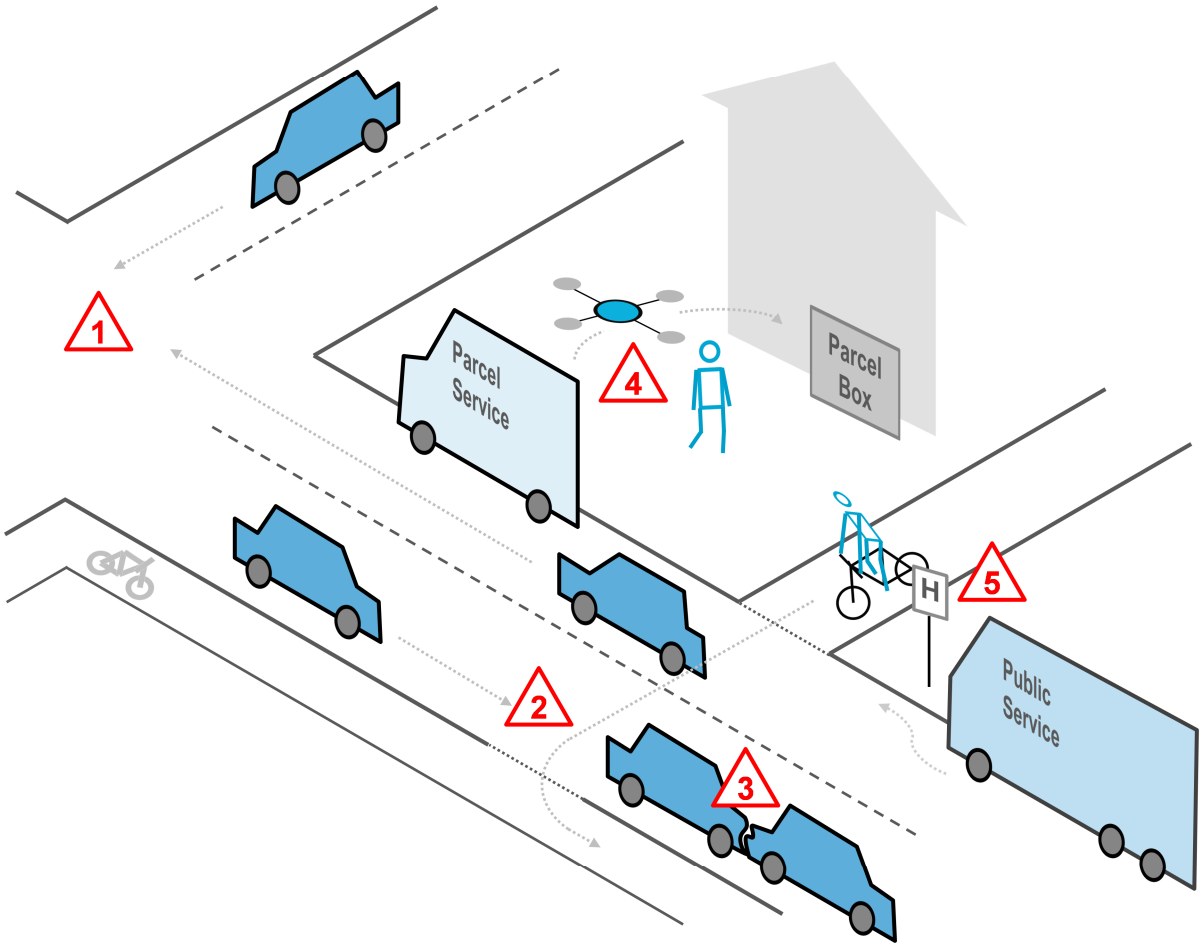

Figure 3: Scheme of danger situations in Intelligent Transport Systems

Limitations to Highly Automated Systems

To point out the limitations of highly automated systems, problems are explained for each proposed situations.

Situation 1 It might use a special implementation to detect other cars, their trajectory and a possible collision point. So for every unique situation like intersection crossing, turning or driving on the highway, there's a corresponding unique detection function for such problems.

Situation 2 The HAD System has to make a tough decision. The first objective is to avoid the crash or in the case it is unavoidable, to minimize the consequences of the accident. The HAD System chooses a process of avoidance, but can't guarantee a successful outcome with regard to the time-critical situation.

Situation 3 The car decides to change to another lane to avoid the crash. The system requests a steering angle, which exceeds the actual possible steering angle of the car. The HAD System thinks it's avoiding the crash, but actually it is not.

Situation 4 The multicopter's autonomous system still wants to deliver the package. It's actually possible, because of the knowledge of the position of the drop-off zone. But it is not safe to go there, because of the failure of the detection sensors.

Situation 5 The fully autonomous bus' system tries to reach the bus stop, but it doesn't recognize the failing system. If it keeps going, it may result in damaged subsystems.

CONCEPT PROPOSAL

This section introduces the Safety Layer Concept. This includes a theoretical explanation of the concept and a detailed description of all components. The concept is then applied to the proposed situations from the above section and the advantages are pointed out.

Safety Layer Concept

If assistance, automated and autonomous systems have a system failure, there is a probability for human or object damage. The concept aim is making these systems safer by separating the functions or subsystems in a comfort part and a safety part as fallback layers (See Figure 1). These fallback layers serve as basis to transfer the system with the failure condition into a safe state. The fallback layer initiates a plan of actions to achieve the safe state.

The procedure can be applied to different assistance functions and automated or autonomous systems, especially in situations where the function or system leads to undefined states, guides into accidents or where components and functions aren't executable. Furthermore the multiple variants of applied applications will be summed up as *functions*.

So the main purpose of monitoring the *functions* is to evaluate their output for regularity, check for possible hazard outcomes and verify for operability of relevant components. The input data can contain condition parameters of the vehicle and environment parameters, which may include information of mobile and stationary objects. The output contains the original output of the *function* or the corrected output in the case that one or more safety functions take control.

Plausibility Layer The first layer of the concept evaluates the output data of the *function* for their plausibility. If the output data exceed a defined interval, the plausibility of the data is not fulfilled.

If the plausibility of the data is not performed, plausible or none data will be forwarded. The check for plausibility can be performed on the basis of defined faults, tables, characteristic diagrams, functional relations, look-up tables or similar methods. The usage of more than one method is also possible.

A feedback to the *function* allows a recalculation for the next period or the deactivation of the *function*. If the *function* is deactivated, a notification to the driver can be given to take over, or another assistance function tries to bring the system into a safe state.

Accident Layer The second layer checks for possible hazard outcomes of the performed action of the *function*. This layer calculates on the basis of the new trajectory of the car and all objects in the environment, a value of accident risk. If the value exceeds a threshold, measures will be initiated to prevent or to reduce the consequences of the accident. This layer can be used for the whole system, even when there is no *function* in use.

Objects can be all other transport systems and users as well as infrastructure elements. So hazard outcomes are defined as damages to people and inanimate objects. Along with the calculated value of accident risk, it is also possible to include the expected hazard or the criticality of the accident in the calculation.

Function Layer The third layer verifies the operability of all relevant components, which are used in context with the *function*. If components are not functional, the layer tries to replace them or deactivates the relevant one.

Relevant components are sensors, actuators, control units, computing resources and algorithms which are used by the *function*. The replacement can be an adequate component or a substituted function by emulation or simulation, where the output data of the component is determined by other components data. If the component is deactivated, the driver should be informed to take over.

Complete Concept All layers are displayed in Figure 4. They are working constantly and monitor the *function* the whole time. It is possible to prioritize all layers differently, but to release output data all layers have to consent. The advantage of this concept is the provision of three independent layers to localize all cause-specific failure sources and eliminate them. All layers can adjust the output data of the function or execute a special action plan to reach a safe state.

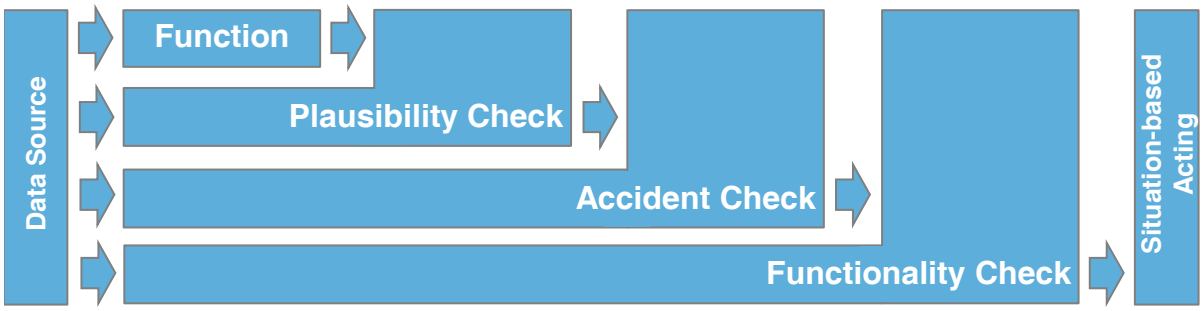

Figure 4: Scheme of Safety Layer Concept

To apply the concept to multiple systems, it is advisable to develop a configurable variant to adapt the layers to a specific system. So the development effort covers several systems and the costs can be divided between them. Also the development effort on the *functions* is a far less, because failures originating from systems, algorithms, undefined conditions or correlation of *functions* don't have any hazard-relevant effects. Further tests on the *functions* and defined threshold values are not necessary. So *functions* can be developed as platform-independent. With an already developed Safety Layer Concept it is easier to test *functions* and re-fit them in running systems.
It is possible to deactivate all relevant components which are associated with a failed component, to suppress false system activity and the usage of unnecessary system resources. After substituting a component, the system should assign a lower confidence value to it, maybe because of inaccuracy, to accomplish a higher safety in the system by adding additional safety tests based on this value.

Implementation in Scheme
In the following, the capabilities of the Safety Layer Concept are shown by applying it to the proposed situations. Application possibilities and advantages are presented.

Situation 1 The *Accident Layer* can operate as the detection function for external objects like other cars. So there is no need for multiple functions to detect outside objects. The HAD System can handle the longitudinal and lateral direction. If the *Accident Layer* detects a possible accident, it handles the specific situation on the basis of regulations and cooperative acting, and reports the takeover to the HAD System.

Situation 2 The HAD System has to handle a time-critical situation. The *Plausibility* and *Accident Layer* work in parallel with it. The layers can support the HAD System, which can only work as a comfort function, by monitoring steering angle and braking force plus adding more braking force. It is also possible to let the layers control the mechanical system, while the HAD System has more system resources to calculate the best avoidance procedure.

Situation 3 The *Plausibility Layer* detects a limit exceedance of the steering angle by the subsystem "Lane Change". By overwriting it to the maximum value, the *Accident Layer* detects a possible crash and decides to steer into the other lane, which is reachable with the maximum steering angle and also free of objects. The layers initiate an action plan to bring the car to a safe state by avoiding a crash with the cyclist.

Situation 4 The *Function Layer* detects the failing sensors. The layer decides to bring the multicopter into a safe state, because it is not safe for the environment to continue the flight. It initiates an action plan and overrules the autonomous system.

Situation 5 The system may end up with damaged parts. Instead the *Function Layer* also detects the failing subsystem and the consequences of its breakdown. The layer executes an action plan to reach a safe state with no further usage of the failing subsystem. The system can call another bus for exchange and a service to make repairs.

CONCLUSIONS

Assistance functions as well as highly automated and autonomous systems may contain possible failure effects like exceeding limit values, going into unknown states, guiding into accident situations or experiencing function losses and suchlike. By introducing the Safety Layer Concept it is possible to counteract these failures based on several layers to evaluate the output of functions for regularity, check for possible hazard outcomes and verify for operability of relevant components. These three layers are designated as *Plausibility Layer*, *Accident Layer* and *Function Layer*.
The concept can be applied to every level of a system, to monitor and control functions, subsystems or the whole system. With the possibility of feedback to the monitored element, overruling and deactivating, the layer concept includes several opportunities to act. By paralleling the layers themselves and to the *function*, it has high potential in time-critical situation to solve complex tasks by distributing the work between different methods. Also the concept can and should be used in every ITS participant, regardless to a possible superior functional unit, to improve the safety of all systems.
The introduction of highly automated and autonomous systems in daily life can only be achieved when these systems are totally reliable and do not present any hazards to people or objects. These goals are equal to the ones of the "Vision Zero" policy. Also the regulations in European States will only be adapted to this technology if sufficient activity on these features will be made. To fulfil such high standards in Intelligent Transport Systems, the use of the Safety Layer Concept is absolutely recommended.

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