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.

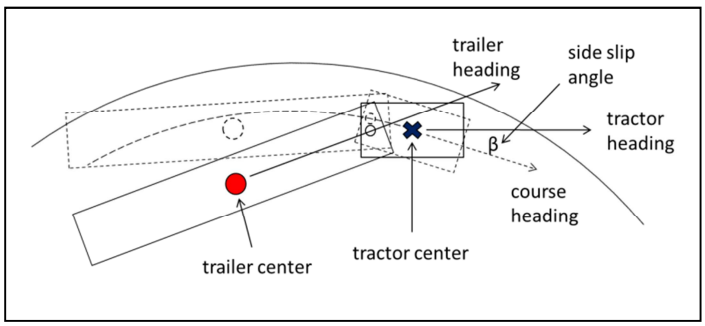


Figure 1. Articulated Vehicle Terminology.

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.

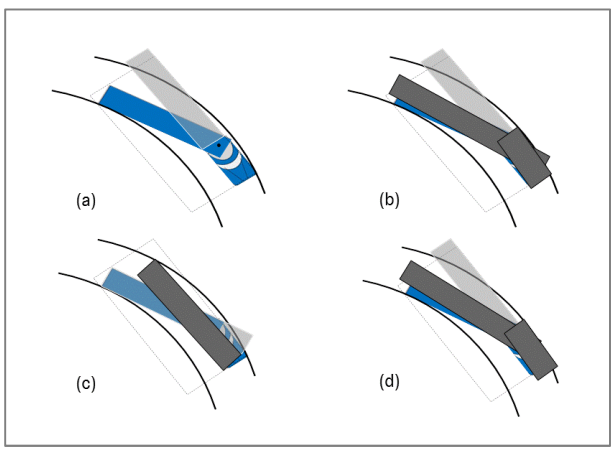


Figure 2. TT-BSM Project Solution Set.

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.

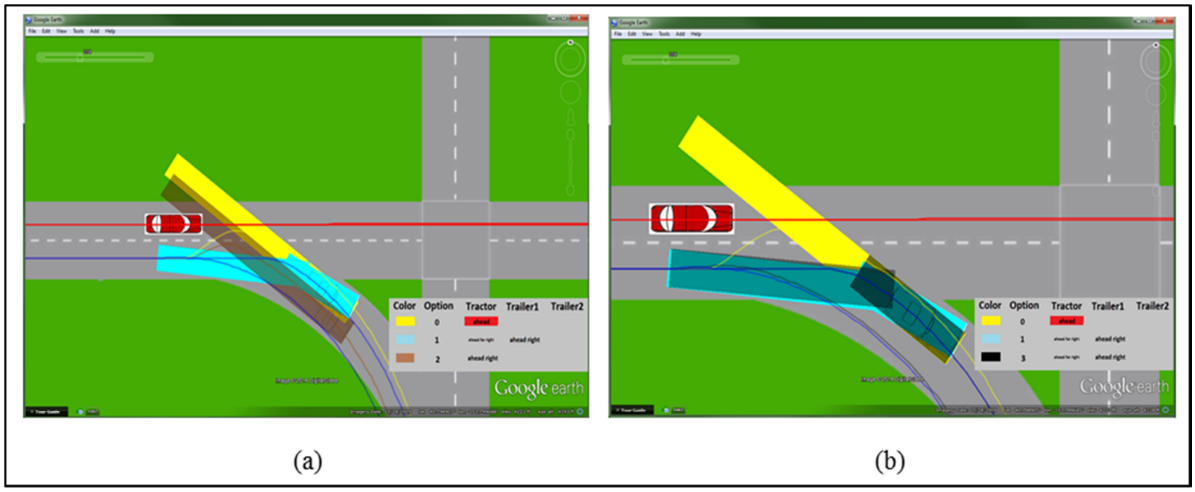
TruckSim was used in a co-simulation environment with Matlab/Simulink, as noted previously. A constant velocity target was sent from Simulink to TruckSim for each vehicle in each scenario. TruckSim then simulated the dynamics of the vehicle in the specific run case of the scenario. In all cases, the 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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