DEVELOPMENT OF TRAILER IDENTIFICATION SYSTEM FOR IMPLEMENTATION OF VEHICLE SAFETY COMMUNICATIONS IN ARTICULATED TRACTOR-TRAILERS

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ABSTRACT
Develop and demonstrate methods by which a vehicle safety communications system on a heavy vehicle tractor can automatically determine the geometric parameters of the trailer being towed. This information is required to assemble a Basic Safety Message (BSM) that conveys the dynamically changing position of an articulated tractor-trailer combination vehicle to surrounding vehicles. A review of existing object-detection technologies and the means to extract the trailer parameters from these technologies was conducted. The classes of trailers with highest market penetration were identified and used in the development process of the trailer detection system so as to maximize the applicability to a majority of trailers on the road today. Using the required trailer descriptive parameters defined in the previous study, accuracy requirements were developed. These were derived based on the light vehicle requirements for Vehicle-to-Vehicle (V2V) communication specified in SAE J2945/1. Trailer-identification related data were collected using LiDAR (2D and 3D), radar, camera (monocular, stereo and thermal), and ultrasonic sensors. Subsequent evaluation of the data resulted in the selection of a subset of these technologies for development into a prototype system. The final system technologies included: camera (stereo and monocular), LiDAR (2D and 3D), and ultrasonic. The 3D LiDAR based measurement system developed was able to accurately detect and measure the trailer parameters for box and tanker style trailers which accounts for nearly 90 percent of the trailers in use on roadways in the United States. Also demonstrated were trailer identification solutions based on other technologies. The camera-based solution provided a less robust means than the 3D LiDAR while the ultrasonic and 2D LiDAR was found to be applicable for fixed axle trailers only. The system designs did not require any special trailer markings or input from the driver. In addition, a simpler alternative solution for some fleet applications was developed that utilized markings (AprilTags) placed on the trailer for identification. This research demonstrated that there were methods to determine trailer parameters automatically for use in vehicle safety communications systems on articulated heavy vehicles. The system developed in this study allowed for a sufficiently accurate representation of the position of tractor-trailers during turning maneuvers in the BSM. This is important for effective implementation of safety applications based on vehicle safety communications.

RESEARCH QUESTION / OBJECTIVES

Figure 1 shows a typical turning scenario. The solid purple represents the actual path of the truck and trailer and the grey shadowed area shows the position for the trailer in the light vehicle BSM. For the car in the left lane with no traffic ahead, this representation would communicate a vehicle ahead, resulting in a possible warning (false positive). The car in the right lane would be told there was greater distance between them and the trailer than actually exists and therefore may not receive a warning that should have been issued (false negative).

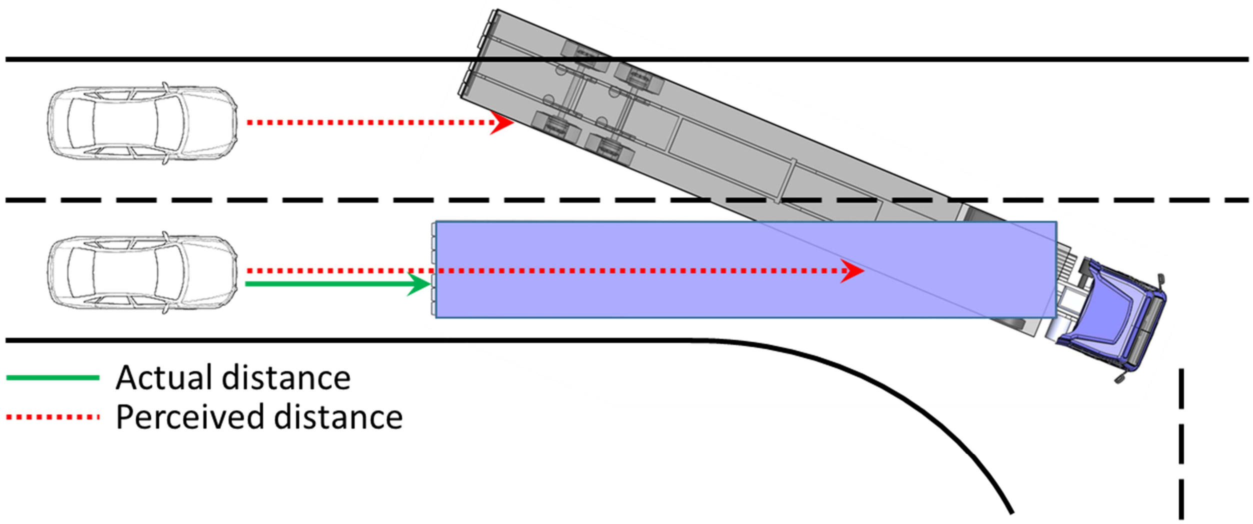

Figure 1. Single-body BSM Challenge for Articulated Vehicles During Low-Speed, Cornering

Previous research [1] showed that representing the trailer as a second vehicle was the most effective means of accurately representing the trailer to surrounding vehicles. Position and heading of the trailer was calculated based on the trailer geometry (length and pivot locations) and the kinematics of the tractor. A new data frame was proposed to transmit the information associated with the trailer.

The objective of this research was to develop and demonstrate methods by which a vehicle safety communications system on a heavy vehicle could automatically determine the trailer parameters needed to populate the content of the proposed Basic Safety Message (BSM).

METHOD

This project built on prior research which resulted in a proposed two-part BSM for heavy vehicle tractor-trailers [1]. The BSM developed in that study treats the trailer as a unique vehicle on the road during low-speed turning maneuvers. During these conditions, the system uses the trailer length and the two pivot locations (fifth-wheel and axle positions) along with the kinematics of the tractor to solve for the position and orientation of the trailer.

In order to develop a system to identify these three parameters, this research defined the scope of the project including the vehicle configurations and the target performance parameters the system needed to obtain. Then a technology survey was performed to identify applicable technologies for the system. These technologies were tested to determine which ones were most likely to meet the system requirements and then integrated into a test bed for evaluation. Based on this initial evaluation, the best performing sensors were selected for integration, testing, and demonstration.

CONSTRAINTS

Scope

One of the guiding principles of this research was that the final system was practicable for the trucking industry. Consequently, the scope of the project focused on the market segment that would impact the largest number of the tractor-trailers on the road. This kept the primary investigation to single trailer trucks, though the potential efficacy of the methods developed to work with multi-trailer heavy vehicles was included in the evaluation. Similarly, rather than trying to develop a solution that would work for all single-trailer truck configurations, including all the variations of load and trailer types, this research surveyed focused on the truck tractor market segment in the U.S. to ensure the development effort was applied toward the largest number of trailers currently on the road.

To accomplish this, annual trailer sales [2] were reviewed to provide an estimate of the trailers on the road. Functional categories were defined consistent with extracting the parameters pertinent to the project from sensor data. For example, box van presents a rectangular feature with straight lines that fall in a common plane. Similarly, container chassis and dump trailers present similar features. Consequently, these trailer types were grouped into the same class. The following list presents the categories shown in Table 1, which group types of trailers based on similarities in how the trailer parameters would be extracted from sensor data.

- Box = dry van + reefer + container chassis + dump
- Flatbed = flatbed + platform + low bed
- Tanker = tanks + dry bulk
- Other = those not included above

Table 1.
Distribution of Trailers Based on Annual Sales

Class	Box	Flatbed	Tanker (round)	Other
Number	285952	36787	15062	2147
Percent	84%	11%	4.5%	0.5%

Performance requirements
To set the performance requirements for the system, the operational conditions were considered along with the performance requirements of the V2V system as a whole. In particular, accuracy targets for length, axle position and 5th wheel or hitch position as they relate to the BSM elements of vehicles size, position and heading were determined.

SAE J2945/1 [3] provides system requirements for light vehicle, on-board V2V systems. This is currently the only published standard that provides function and performance requirements. It was therefore used as a starting place to identify minimum performance criteria for the trailer measurement system. Table 2 provides the requirements from SAE J2945/1 that were relevant to the trailer parameters.

Table 2.
Relevant SAE J2945/1 Requirements for Light Vehicles

Parameter	Value	Description	Primary Mapping to Heavy Vehicle
vPosAccuracy	1.5 m	2D position accuracy* of vehicle reference point	Axle location
vHeadAccuracyB	3 deg.	Heading accuracy* when speed is less than vHeadingSpeedThresh	Heading used to calculate other parameters
vHeadingSpeedThresh	45 km/h	Speed threshold for heading accuracy requirement	Relevant speed
vSizeAccuracy	0.2 m	Length and width accuracy requirements	Length

* Must be accurate to within the value of the vehicle's actual position or heading (respectively) for over 68 percent of the test measurements in open sky conditions.

However, as these specifications are for light vehicles, they had to be translated into values that were pertinent for a heavy vehicle and specifically to the trailer parameters necessary for populating the values for the two-part BSM. For example, vPosAccuracy is the accuracy requirement for the positioning subsystem, which includes at a minimum a GNSS (Global Navigation Satellite System). The average light vehicle width is around 1.8 m (6 ft.) which, for a standard 3.7 m (12 ft.) lane width, provides lane level accuracy. To get lane level accuracy for a 2.6 m (8.5 ft.) wide tractor-trailer (TT) would require a positional accuracy closer to 1.1 m (3.6 ft.). Note that this is trying to meet the intent of the current standard for lane level accuracy and is not under the constraints of the GNSS performance. The 1.1 m value was then used as one of the parameters in the simulation model to determine the required accuracy for the pivot location. Table 3 provides a summary of the accuracy requirements for the measurement system.

Table 3.
Summary of Measurement Requirements

Parameter	Value	Comments
Length	$\leq$ 0.5 m (20 in.)	Most common trailer lengths are > 2 ft. (0.61 m) different so the practical requirement is 1–2 ft. (0.3 - 0.61 m).
Axle position/ trailer wheelbase	1.3 m (52 in.)	Primarily effects lateral position of trailer during turning maneuvers.
5^{th} wheel/hitch location	< 1.1 m (43 in.)	Primarily effects longitude position but since this moves the pivot point on the tractor, it also changes the directional input for the trailer.
Angle	< 3 deg.	Used to derive pivot locations rather than provide heading.

SYSTEM DESIGN

Figure 2 shows a block diagram of the entire measurement system, including the components independent of the measurement subsystem being developed. On the left of the figure, different trailer types are listed. Those not greyed out were evaluated during the course of the study. The information path between the trailer and sensors is filtered through the environmental conditions that occur during normal operation of heavy vehicles. These include lighting conditions, weather (e.g., rain, snow, fog), road grime, site impurities (e.g., oil, grain dust), and anything else that could influence the quality of the data.

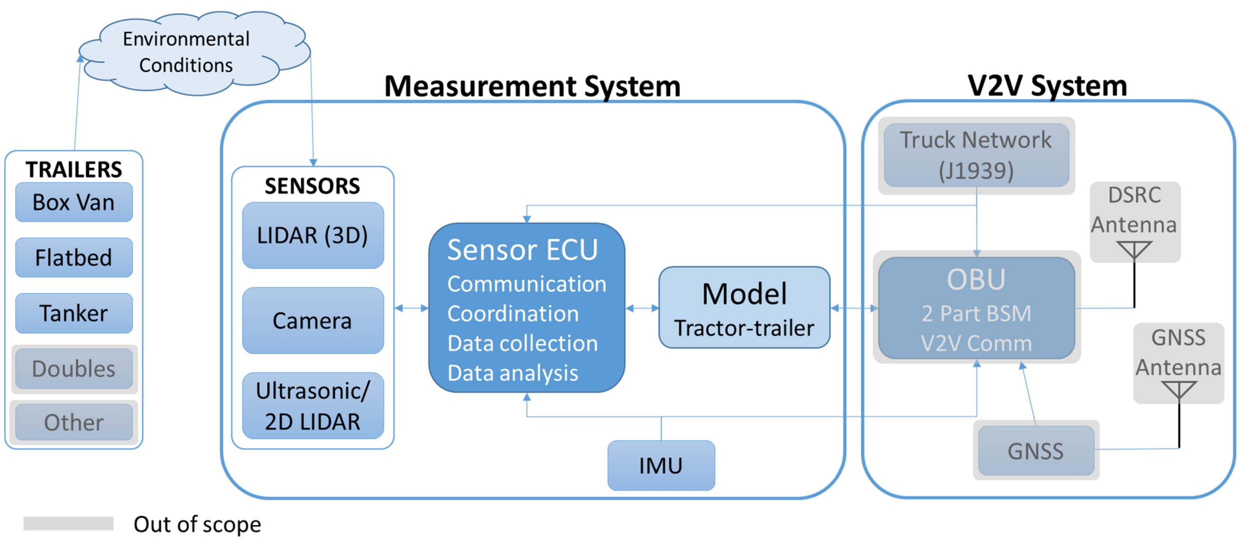

Figure 2. System Block Diagram

The effort for the system design focused on three primary components: the system software, sensors, and data processing. The system software resides on the sensor ECU and is responsible for the communication and coordination with the different system components, data collection from the different sensors, data storage, analysis of the data to extract the trailer parameters, and display of the information. System software and analysis methods will be discussed later in separate sections.

The sensors used in the study were evaluated on their ability to successfully address the different trailers and environmental conditions. For the initial evaluation, a wide array of sensors beyond what is shown in Figure 2 were examined. In addition to those that could measure the three trailer parameters, sensors that provided two or more distance measurements to the front of the trailer were evaluated. While this does not provide a measure of trailer length, for trailers with fixed axles at the rear of the trailer (e.g., tankers, bulk, dump), distance measurements along with tractor data required for the BSM allows calculation of the pivot locations (5th wheel and axle location). Trailer length could then be estimated by adding additional length to the effective axle location determined from trailer angle. This type of system could provide an alternative for trucking fleets that only haul fixed axle trailers and may be more appropriate for some environments. It may also require an additional step to tune the length factor based on the typical trailer within a fleet (e.g., fuel tankers). In addition to the trailer sensors, an IMU was included to provide truck data, in particular yaw.

Sensor Evaluation

In addition to collecting data with a heavy truck tractor and trailer, data were collected with a sensor suite at the Troutville weigh station on U.S. Interstate Route 88 (I-88) just east of Roanoke, VA. Data collection at different times of day starting at dawn and going to dusk was conducted to ensure a broad selection of lighting conditions. In addition to a stereo camera and LiDAR, two high-resolution digital SLR cameras were used to capture images at an angle and perpendicular to the trucks. Images from the latter provided a means to measure trailer length. A light gate was used to trigger the sensors as a truck entered the weigh station. This resulted in the collection of approximately 6,000 images on 2,000 different trucks. Of these, 5,000 were used in developing machine learning algorithms.

These data, along with the data collected on the tractor and trailer, were used in the sensor selection prior to the implementation. The following summarizes the results from the data collection performed during the system design effort. After that follows a description of the criteria used in creating the evaluation matrix that was assembled to help determine which sensor(s) would be used during implementation of the system concept.

<u>Cameras</u> The camera configurations tested during the system design performed as expected in most instances. Cameras are inherently sensitive to low light and low contrast conditions and this bore itself out in running classical machine vision techniques on the data. The trailer used in testing was white except at the rear where there was a collage of different images. This varied background often blended in with the surroundings. To address this fundamental challenge, optical flow was used to isolate pixels based on the motion of the trailer. Optical flow works by looking at consecutive frames and calculating the movement of pixels from one frame to the next. This provides an indication of the rear of the trailer as well as a means to identify pixels in the image associated with the trailer. These pixels can then be segmented into a single entity.

Figure 3 provides an example where the dark section of the end of the trailer looks like the yard and the building on the other side of the street and the street looks similar to the light portion of the trailer (first frame). Consequently, when a simple clustering is performed, the algorithm gets confused and lumps the street and the landscape in with the trailer (second frame). However, when the results from optical flow are used in conjunction with the clustering, the trailer is easily segmented out from the rest of the image (third frame).

Figure 3. Example of Trailer Blending in with Background

While this does not solve the problem of determining the trailer parameters, it does provide a means to extract the parameters.

In addition to having a relative motion that is different from the background, the trailer also has a predictable procession in the image through the turn. Figure 4 shows a sample of images taken during a turn. During the first half of the turn, the trailer moves from right to left in the image. Once it reaches the apex of the corner (lower left), the trailer starts to move left to right.

Figure 4. Procession of Trailer in Image during a Turn

By looking at the pixel velocities throughout the turn, the rear of the trailer can be identified. Figure 5 shows an example of this. In this analysis, the horizontal components of the pixel velocities were used. Red indicates pixels moving to the right and blue indicates pixels moving to the left in the image. The truck is past the apex of the corner so the trailer is moving back in line with the tractor, and thus is moving to the left. The black area above the trailer shows the boundaries of areas with different pixel velocities. The top of the trailer and the back of the trailer both appear as boundaries; however, the correct boundary is easy to identify given the relative strength of the lines and the fact there is only one vertical line.

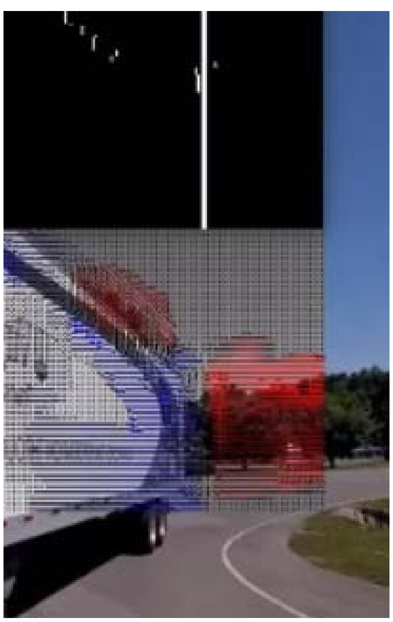

Figure 5. Identification of the End of the Trailer Using Optical Flow

As discussed previously, knowing the lateral position of the end of the trailer does not provide sufficient information to determine the length. However, with additional kinematic data from the truck or a sensor to measure angle, the length can be determined.

LiDAR The 3D LiDAR provided the most consistent results during the evaluation stage. The primary weakness was the cost. However, due to the push from automated vehicle development, the development of new, low cost units helped neutralize some of the cost considerations. 2D LiDAR provides a low cost alternative but does not provide sufficient data density to accurately determine length. The application of 2D LiDAR is therefore limited to trailer heading measurements.

Radar Two radar systems were evaluated. The first system was evaluated by the manufacturer of a light vehicle trailer length detection system. This system was designed to extend the functionality of a blind spot warning system when pulling a trailer, and automatically determines the length of the trailer rather than requiring the user to input the length. The system worked by picking up the motion of features of the trailer during a “significant/dynamic turning maneuver.” This information was then used to calculate the hitch to axle length of the trailer. The manufacturer performed additional testing to evaluate the effectiveness for heavy vehicles which revealed potential challenges to extending the technology to heavy vehicles. First, the motion of the trailer was slower with small trailers, making it more difficult to see the relative motion in the radar signature. Second, a large, flat, rectangular box van provided a poor reflective target for the radar. The expected outcome for the axle length measurement was < 1m standard deviation or 68 percent of the measurements would be within ±1 m (±3.3 ft.). Unfortunately, this was outside the acceptable accuracy for the BSM.

The second radar evaluation was set up to determine if a radar could identify the tires on the trailer. The hypothesis was that since the top and bottom of the tires are moving at equal but opposite directions, the relative velocity may be sufficient to be seen apart from the trailer. The first test performed was with the radar stationary as the truck drove past. With this configuration, the radar was able to pick up the tires on the trailer. However, when the radar was mounted to the tractor, the tires were no longer distinguishable.

While it may be possible to tune the signal processing of the radar data to extract trailer parameters, the amount of development that would be required was outside of the scope of the project.

IMPLEMENTATION

The primary sensors selected were 3D LiDAR, with the goal to improve the point cloud analysis and the single camera solution. For the latter, the stereo camera was used to collect the data so that both image sources were available for future development. Secondary sensors were the 2D sensor options of single plane LiDAR and ultrasonic sensors. Figure 6 shows the placement of the sensors on the tractor. The graphic is a simplified representation of the truck that was created to aid in the visualization of the real time data display. The sensor locations were based on the physical measurements of the actual tractor. The LiDAR was mounted at the top of the doorframe, the camera on the bottom of the passenger mirror, and the ultrasonic sensors and 2D LiDAR on the back of the cab.

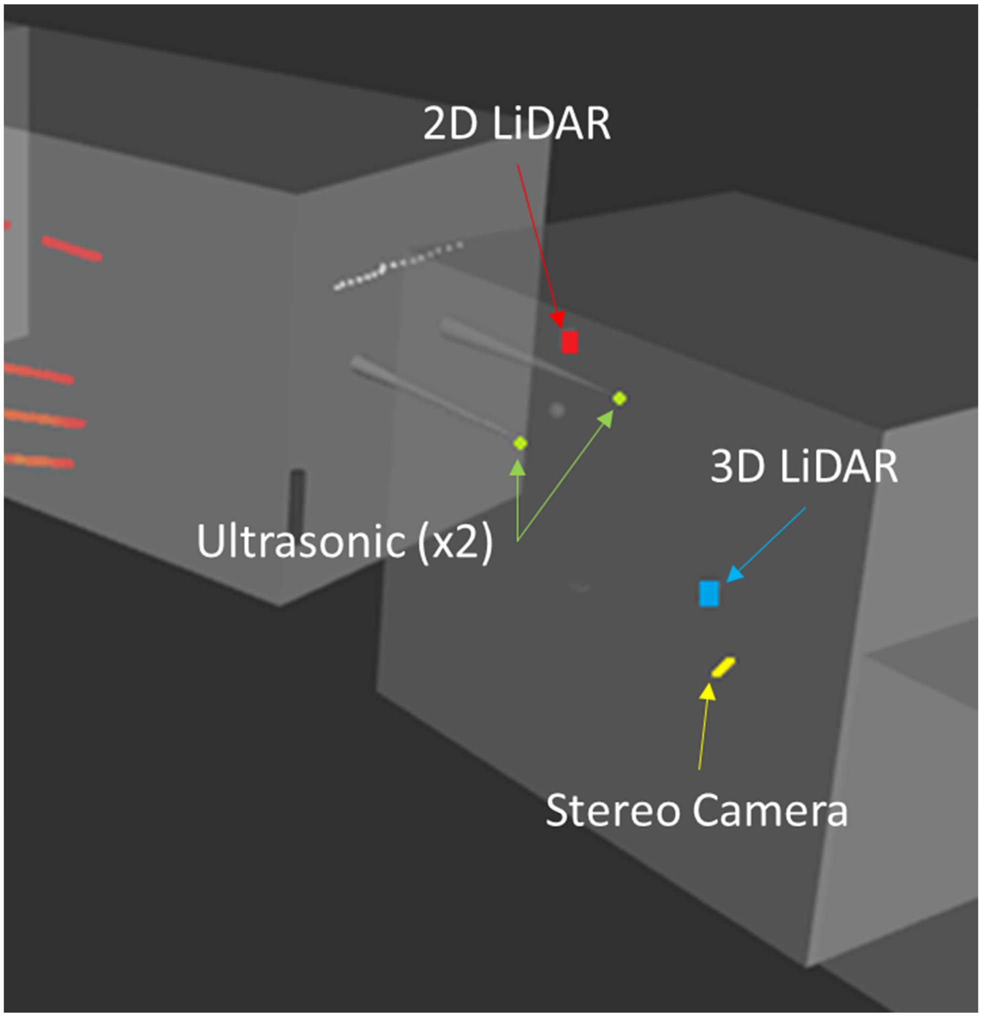

Figure 6. Sensor Placements on Tractor

All sensor data were displayed in real time. The 2D LiDAR output appeared as white dots on the front of the trailer, with each dot representing the output of one of the beams. Similarly, for the ultrasonic sensors, the output appeared as cones, which changed in length based on their returned values. For the stereo camera, both channels were recorded but only one of the video channels was displayed.

To demonstrate the functionality of the system as well as provide context to discuss specific development efforts, the flow diagram in Figure 7 shows the operation of the system and describes the solutions that were implemented. It should be noted that the system was designed as a proof of concept rather than a prototype of a commercial product. Consequently, some of the details were intentionally left out of the development. For instance, the first decision block evaluates whether the trailer is new or not. The most simplistic solution to this step is to assume a new trailer on start up. However, a more robust method might be to monitor the acceleration of the cab to identify the signature impulse that occurs when a tractor connects to a trailer. However, as this step does not preclude the demonstration of the measurement of the trailer parameters, the system was set to default to a new trailer on startup.

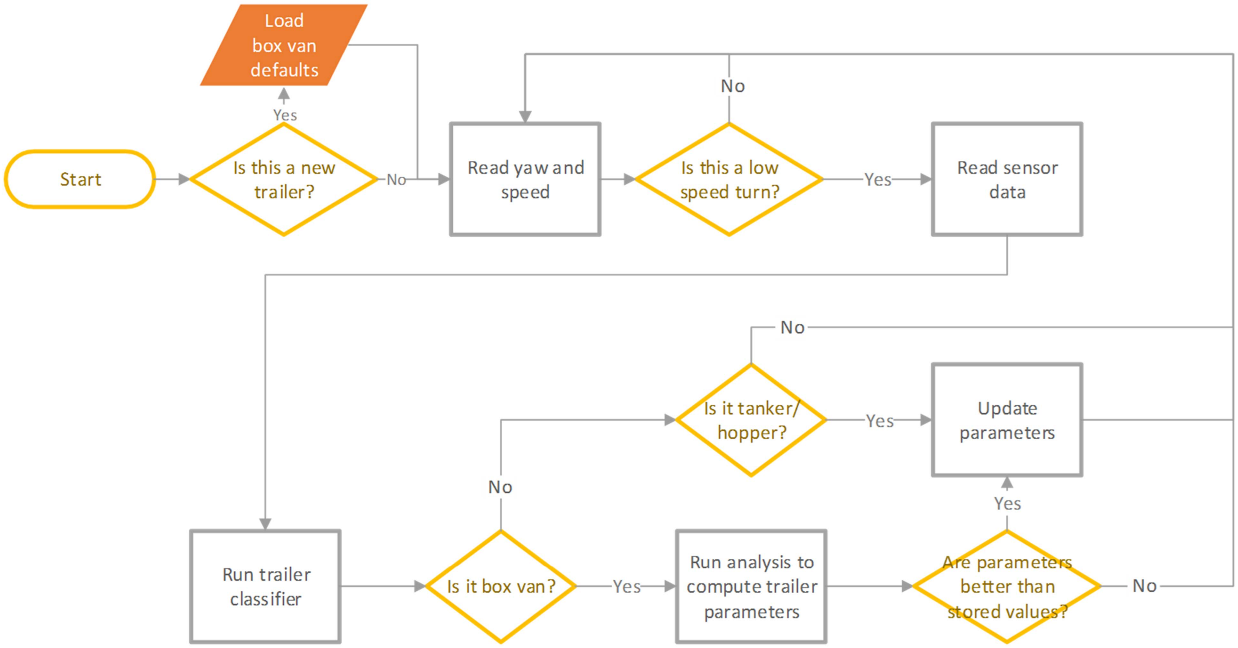

Figure 7. System Flow Diagram

Initialization

The first step in the algorithm is to initialize the system. As stated before, the default condition for this step is that the trailer is new. Therefore, the system initializes the trailer parameters with the following default values (Table 4) for a box van, as this is the most common type of trailer on the road.

Table 4.
Default Trailer Parameters

Trailer Parameter	Default Value	Comment
Length	53 ft.	The most common length of box van used is 53 ft., which is also the longest standard size. If this value is wrong, false rather than missed warnings will occur.
Axle position	0 ft. forward	This gives the trailer the longest wheel base possible, resulting in greater off-tracking.
5th wheel position	0 ft. (middle)	The midpoint minimizes the likelihood of exceeding the 1.1 m position error.

The system then monitors the yaw and speed of the tractor to determine if it is performing a low speed maneuver. Since the ECU was not tied into a V2V system nor the vehicle network, yaw was used. If yaw exceeds a threshold (0.2 rad), the next step was to read the data from the sensor suite.

The data from a single camera were used to run a trailer classifier to classify the trailer into one of four types: box van, tanker/hopper, double, or flat/other. The classifier was based on a convolutional neural network developed using the images from the data collection.

The output from the classifier directs the sensor data to the associated analysis module to extract the trailer parameters. The analysis for the other two trailer classes were not developed in this study, but the structure is in place to accommodate additional classes and associated techniques.

Figure 8 provides a snapshot of the real time display collected during testing with different length trailers. The trailer in this example is a 45 ft. box van. The length displayed, which was extracted from the LiDAR data, is 44.81 ft. (13.66 m)

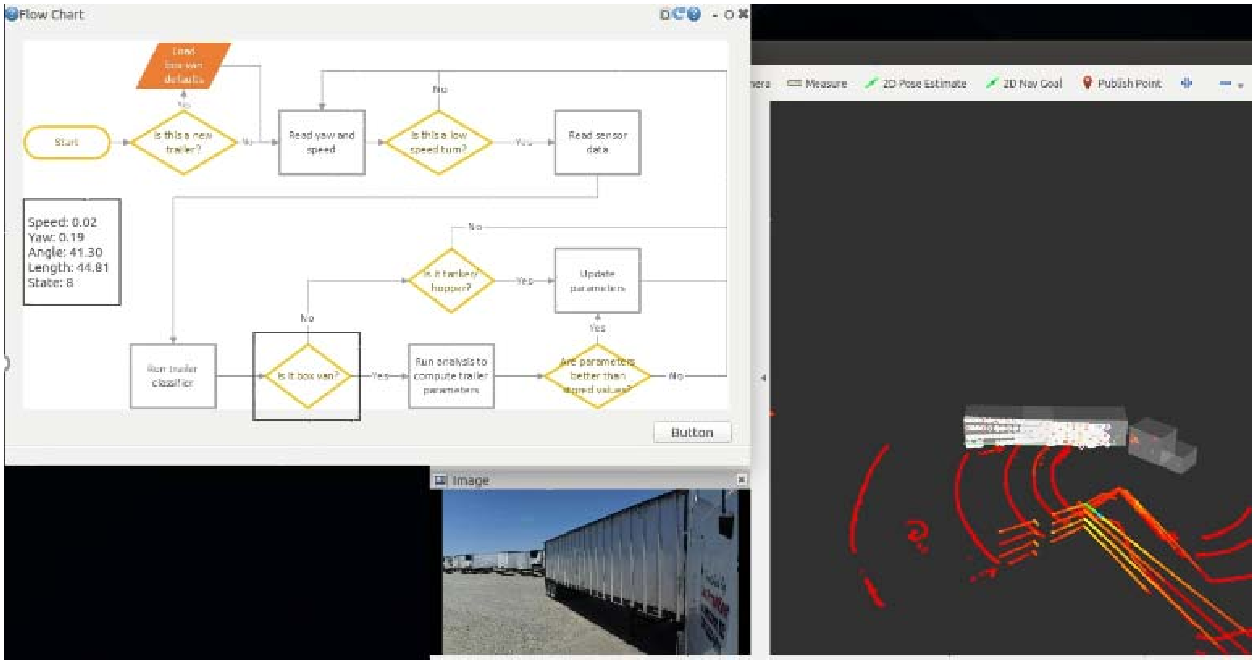

Figure 8. Example Output for 45 ft. Box Van

While the system collected the five sensor channels, the trailer parameter estimation for real time display was based on the point cloud data from the LiDAR. While the stereo vision camera can also produce point cloud data, the LiDAR provided cleaner data that yields better results. The single camera data were processed offline. While identification of the trailer is robust, determination of the trailer length consistently, turn after turn at the accuracy requirements identified, was a challenge. However, each turn provided an opportunity to collect more data and refine the trailer parameters if deemed appropriate.

Marked trailer Implementation

In order to demonstrate more than one solution, an alternative was developed that used special markings on the trailer. This option was included to determine the cost and benefit of this type of system over the type of non-contact system described previously.

One direct method evaluated for detecting the angle of the trailer used unique visual fiducial called AprilTags. Commonly used in augmented reality and robotics, these two-dimensional bar codes were easily detected by a camera system and directly provided pose. The pose information collected by the AprilTags included the X, Y, Z position and roll, pitch, yaw orientation parameters for each tag. Multiple AprilTags could be detected by a single camera because they each contained a unique pattern that corresponded to an identification number.

To track the pose of the trailer, a camera system was mounted on the rear of a heavy truck to observe the front of the attached trailer. An AprilTag fiducial was placed on the front of the trailer so that it could be continuously observed by the camera system during straight and turning maneuvers. A coordinate frame was established to correlate the camera's position to the detected fiducial at every timestamp. As the truck traversed straight paths and turns, the detected fiducial provided the pose information as an output. The most important pose parameter is the yaw angle, which directly correlates to the angle of the trailer relative to the camera. A more accurate measure of the trailer's angle from this extracted yaw angle required further transformations to the truck's axle or other defined coordinate frame. The tracked fiducial output was demonstrated on a closed test loop showing constant updates of the trailer's angle. The AprilTags were used due to their simplicity and existing software tools, but any picture or pattern can be converted and calibrated into a fiducial for tracking by a camera system. Figure 9 provides an example of the application of the AprilTag, including the position of the tag and the results of the tag tracking.

Figure 9. Example of Output from AprilTags

The camera requirements were relatively low, so an inexpensive camera solution could be used. In addition, the method was robust in terms of placement of both the camera and the tags. One embodiment of this solution could be for a fleet to place these markers on their trailers. The code itself could be associated with a given length so that in addition to measuring the angle of the trailer, which provided heading as well as a means to determine pivot locations, the system would also know the length of the trailer from the marker. Another embodiment would provide drivers with a selection of tags that they would then place on the front of a trailer during hook up. They would be responsible for selecting the tag with the correct associated length.

While still being subject to the same weaknesses of other camera systems, this system provided a lower cost alternative to the fully automated system. The tradeoff is that it required more operator interaction to ensure the proper tag was on the trailer and that the tag was clean of debris. However, for small fleets or owner-operators, this tradeoff may allow these fleets to implement a more economical V2V solution.

RESULTS

Figure 10 shows a single frame of the output for 33 ft., 45 ft., and 53 ft. trailers. The return from the LiDAR data turned white when it identified the side of the trailer. The length of the trailer was then updated to reflect the length calculated from the data. The system was able to identify the trailer and extract its length and angle.

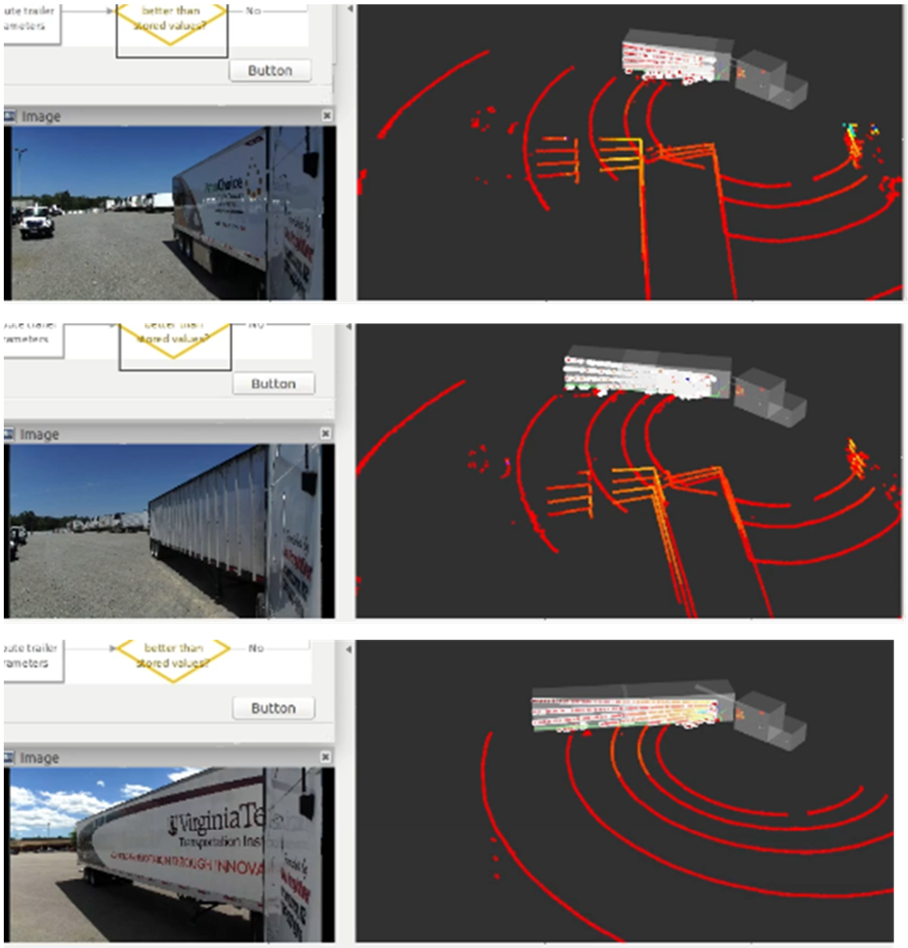

Figure 10. Display of Single Frame from System Output for 33 ft., 45 ft., and 53 ft. Trailers

The plots in Figure 11 show the results for a simple turn with a 53 ft. trailer. The lower value on the left plot, approximately 10 degrees, indicates the minimum angle that the system was able to extract from the trailer measurement data. The right plot shows the time for the measurement to settle in to its final value.

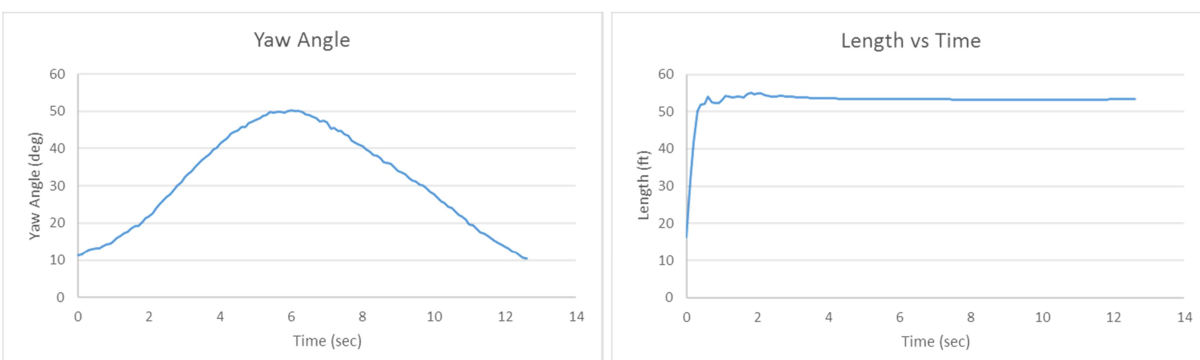

Figure 11. Length as a Function of Yaw Angle

Within a few seconds of a turn with a high enough trailer angle, the trailer length settles into the final value within a few seconds.

Figure 12 shows the results from the tanker trailer. In addition to the angle and length, the system state is shown below as an indication of when the system is and is not reading data from the sensor suite. The red lines indicate the length requirement from Table 3 as applied to this trailer.

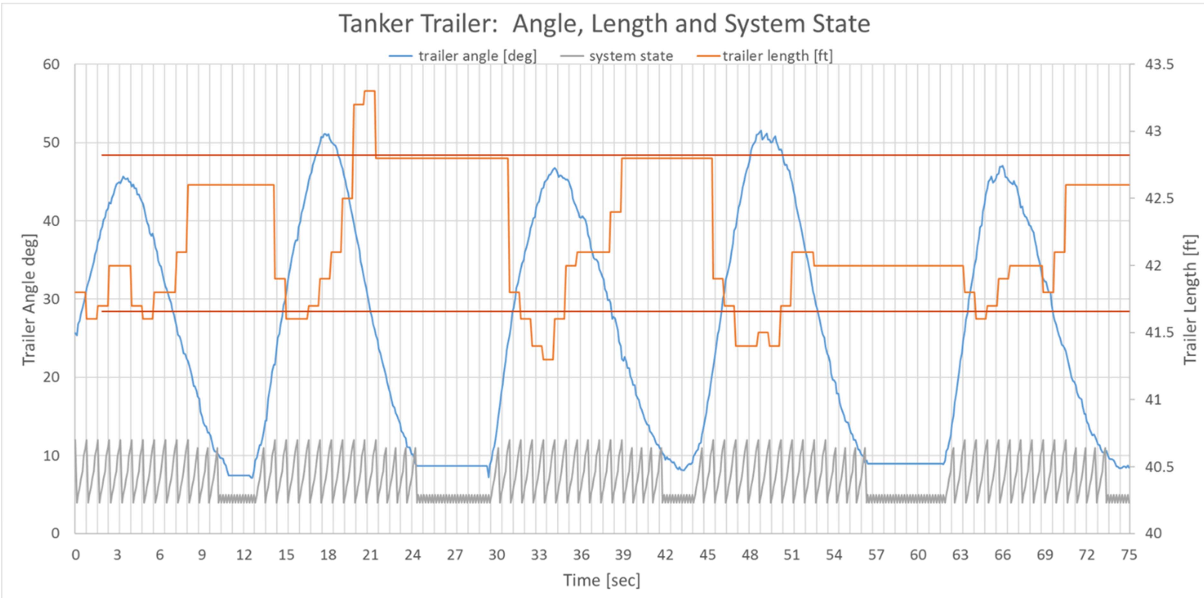

Figure 12. Trailer Length and Yaw Angle for Tanker Trailer

As expected, the tanker trailer results are noisier than for the box van. However, the system still provides adequate results for the BSM.

Results from the camera proved more challenging. The primary factors affecting the results were identification of the edges of the trailer, which were affected by lighting (e.g., shadows, low contrast, occlusions).

Based on a single frame from 45 turning events, with three different trailer lengths, approximately 50 percent of edge detections were within 2 ft. (0.61 m), 30 percent of edges were incorrectly identified, and 20 percent of detections were outside of the acceptable range. Applying the analysis to the entire video sequence during the turn and applying statistical analysis to reject outliers and provide an indication of the quality of the measurements would improve the performance of the method. In addition, given the method’s sensitivity to changing light, it would provide a sample across a wider variety of lighting and backgrounds and therefore not be dependent on a single sample.

The ultrasonic, 2D LiDAR and the marked trailer solution (AprilTags) demonstrate solutions that can provide trailer heading information. However, trailer length would have to be obtained through a secondary method. For AprilTags or similar defined tag, trailer length can be associated with a given tag design. For flat trailer surfaces, the ultrasonic and 2D LiDAR perform similarly. While 2D LiDAR is more expensive than ultrasonic, the additional measurement points give additional data from which to calculate the heading. This allows for application with a variety of trailer types and over a large heading range. AprilTags require a human to mark the trailer prior to operation but does provide lower cost solution compared to 2D LiDAR that could be applied to many trailer categories.

DISCUSSION AND LIMITATIONS

While the 3D LiDAR sensors provided the best performing solution tested, they are currently comparatively high in cost. However, with the focus on future automated driving systems, the rapid development of new lower cost sensor solutions is occurring. Consequently, it is expected that cost effective LiDAR sensors could soon be available for use in heavy vehicle V2X applications.

The 2D sensors (ultrasonic and 2D LiDAR) and the marked trailer method provide three different potential solutions to provide trailer heading information. If trailer length is known through some other means, these lower cost alternatives demonstrated provided the opportunity to broaden the adoption of vehicle safety communications by trucking fleets that may otherwise choose not to integrate the technology. However, the lower cost AprilTags have the limitation that they require a human to mark the trailer prior to operation.

CONCLUSIONS

The study described in this paper developed a system that detected and measured the trailer parameters required for populating the elements of the 2-body BSM for box type trailers (dry vans, refrigerated, intermodal trailers, and other enclosed trailers) which account for over 80 percent of the trailers on U.S. roads. Table 5 provides a brief summary of the primary concepts developed and demonstrated.

Table 5.
Overview of Results for Primary System Concepts

Concept	Strengths	Weaknesses
3D LiDAR	• Provides all three trailer parameters • Robust measurements • Works in low/no-light conditions • Provides for other safety functionality (e.g. blind-spot warning)	• Requires significant turning maneuver (>10 degrees) • Cost currently higher than other sensors
Camera (no trailer modification)	• Provides all three trailer parameters • Low cost • Provides for other safety functionality (e.g. blind-spot warning)	• Requires significant turning maneuver (>10 degrees) • Increased processing requirements • Accuracy sensitive to lighting
Camera (with trailer modification)	• Provides all three trailer parameters • Low cost • Results for low turning angles • Robust measurements	• Requires modification of trailer • Sensitive to lighting • No additional safety functionality

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