

## **SINGLE UNIT TRUCK AND BUS CONSIDERATIONS FOR V2V IMPLEMENTATION**

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### **ABSTRACT**

The objective of this analysis was to identify if selected classes (or categories) of single-unit heavy vehicles require additional information beyond the standard elements in the Basic Safety Message (BSM) as defined in SAE J2945/1, and to make recommendations for the requirements for any such BSM modifications. This study relied on existing literature from pilot testing programs, such as the U.S. Department of Transportation (DOT) Safety Pilot, and other foundational research studies into the slow speed maneuvers of heavy vehicles. Heavy vehicle manufacturing partners including Kenworth, MCI, Navistar, and New Flyer provided vehicle configuration data covering a range of trucks, motorcoach buses, school buses, and transit buses. Heavy vehicle-to-vehicle (V2V) interaction scenarios were identified from among safety-critical events derived from existing naturalistic vehicle data. Dynamic vehicle parameters such as GPS coordinates, heading, lateral accelerations, vehicle yaw, and vehicle speed were exported and applied to path-tracing models of heavy vehicles. The data analysis demonstrates that properties of some long, single-unit heavy vehicles cause them to operate outside of the tolerance range specified for light vehicles' V2V safety applications. Heavy vehicles with wheelbase lengths greater than 20 ft. (6.1 m), which also have tire track widths of 8 ft. (2.4 m) and higher, track differently from light vehicles, especially at low speeds. Some of these vehicles also have large body overhangs forward and rearward of the axles due to the differences between their overall vehicle length and wheelbase length. These parameters affect heavy vehicle maneuverability performance such as turning radius and lane keeping. The position of the vehicle is defined as the center of a rectangle projected onto the roadway that encompassed the outer limits of the vehicle. Given the variability in lengths, length to wheelbase ratios, and configurations of single-unit heavy vehicles (including fixed length, articulating transit buses), reporting vehicle position with the simple light vehicle approach does not accurately capture the positive and negative off-tracking that occurs. The need to account for this is well documented in roadway geometry design specifications and shows the wide array of configurations. The findings suggest that there are additional elements that should be included when communicating the BSM during turn maneuvers, either as additional position information within the heavy vehicle's BSM Part 2 or by simply flagging the heavy vehicle host as an "oversize" vehicle in the BSM. These solutions are consistent with to the conclusions of the TT-BSM project conducted by the U.S. DOT and the Crash Avoidance Metrics Partnership (CAMP). This research will provide guidance to the developers of future V2V systems in heavy vehicles, as well as the developers of safety applications that will use the BSM to enhance connected and automated vehicle safety.

## INTRODUCTION

This investigation was completed during one task within the Heavy Vehicle – Vehicle-to-Vehicle (HV-V2V) Basic Safety Message and Implementation Issues for Deployment Project. Virginia Tech Transportation Institute (VTTI) conducted the HV-V2V Project under sponsorship from the National Highway Traffic Safety Administration (NHTSA).

### Purpose

The design goal for V2V safety communications is to exchange basic safety information among vehicles to aid in the detection of imminent collision threats. Safety information is contained and transmitted between vehicles within the Society of Automotive Engineers (SAE) J2735 defined Basic Safety Message (BSM). Currently, the only standard for safety applications performance requirements (SAE J2945/1) is limited to light vehicles. While this may be acceptable, given the variety of vehicle types and configurations within the single-unit truck (SUT) and bus class, NHTSA sought to investigate and identify exceptions to the applicability of the current BSM and determine possible solutions for when it does not apply.

### Background

In the late 1990s, the Federal Communications Commission allocated a band at 5.9 GHz for Dedicated Short Range Communications (DSRC) for vehicle communication. Starting in 2002, NHTSA and the Crash Avoidance Metrics Partnership (CAMP) began V2V research to investigate the applicability of DSRC communications for safety applications. This early research led the U.S. Department of Transportation (USDOT) to expand the research into the public domain, first through the Safety Pilot program (2012–2013) which was designed to evaluate the efficacy of the safety application and provide insight into consumers' responses to the technology in their vehicles. The primary focus was light vehicles, but also included medium and heavy duty trucks and transit vehicles.

**Prior Studies on HV-V2V Communication** The application of V2V communication in heavy vehicles has been under study in recent years and has been predicted to provide significant safety enhancements to heavy vehicle operations. One project sponsored by NHTSA, entitled Development of Performance Requirements for Commercial Vehicle Safety Applications, sought to investigate the performance requirements for V2V safety applications among heavy vehicles (Bowman et al., 2013). The approach included a literature review; interviews with representatives from heavy and light vehicle

manufacturers, suppliers, and heavy vehicle fleet operators; and development of high-level performance requirements. As a result of that project, current and future safety applications were identified for which V2V communications hold great potential. Additionally, the project identified light vehicle performance requirements that may require modification for heavy vehicles. The primary differences identified between vehicle classes were size, variety of configurations, and loads.

Regarding size, the research team concluded first that the height of heavy vehicles could block message transmission between vehicles, and second, that the outer boundary of the vehicle length among heavy vehicles can be significantly larger than the length of light vehicles. This study suggested that signal blockage due to heavy vehicle heights required a non-line-of-sight solution, which is generally recognized to be outside the capability of DSRC standard communication requirements. Other studies and solutions to vertical blockage are discussed in LeBlanc et al., (2012) below. Second, this research suggested that larger heavy vehicle length might lead to error in the offset value, as defined in SAE J2735, which designates the position of the heavy vehicle relative to the DSRC/GPS antenna(e).

Recommendations were given regarding additional information that should be identified on heavy tractor-trailer (TT) vehicles, such as the number of trailers and the length of trailers.

These findings are similar to those determined in another study sponsored by NHTSA, entitled Interoperability Issues for Commercial Vehicle Safety Applications (LeBlanc et al., 2012). In this study, the following two areas of concern were highlighted by 90 percent or more of interview respondents: 1) DSRC performance and commercial vehicle physical factors, and 2) SAE J2735 BSMs related to articulated vehicles. Also referenced in the study, Gallagher et al. (2006) demonstrates error rates of communication for signal powers of 20 dBm and 29 dBm for tall, heavy vehicles. Although the height of these vehicles can create line-of-sight blockages, messages sent at the 29 dBm signal power were provided at error rates low enough to meet the BSM performance requirements. Furthermore, the study suggested the height of the vehicle can provide an advantage by elevating the line-of-sight path of the signal to surrounding vehicles. However, a full discussion regarding the positioning of the DSRC antenna(s) on tall heavy vehicles is a topic beyond the scope of the applicability of the standard BSM on SUTs.

The Tractor-Trailer Basic Safety Message (TT-BSM) Development project (Svenson et. al., 2016) analyzed heavy vehicle path accuracy when using the standard BSM. The study started with the BSM applied in the USDOT Safety Pilot project where a TT vehicle is represented as a single rigid body model (rectangle). The TT-BSM project then sought to determine the most accurate way to enhance the BSM's communication of the trailer when articulating separately from the tractor while meeting the following goals:

- Accurately represent the position of articulated vehicle bodies in vehicle-to-everything (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

Based on simulation and physical vehicle validation, the TT-BSM project team determined that the best method was to transform the yaw rate of the tractor to the trailer king pin and thus determine the articulation angle of the trailer. Four scenarios were developed: one-lane turn, two-lane turn, highway ramp, and highway lane change. Based on simulation alone, the project team determined that the highway lane change was a low priority due to the limited amount of articulation that occurs during the maneuver. In fact, the trailer articulates to the opposite side of the lane change direction at moderate and high speeds, whereas in low-speed maneuvers in the other three scenarios, the trailer axles and wheels will off-track inside of the tractor's radius.

The result of the physical vehicle communication testing led the team to determine that additional information about the combination vehicle was necessary. It was deemed best to communicate that an additional vehicle(s), one or more trailers, was attached to the original vehicle in the BSM Part II, and the team specifically recommended that the optional data frame *DF\_TrailerInfo* be broadcast at the same priority as the regular BSM Part I. The recommendation also suggested that the *DF\_TrailerInfo* data frame should include *DE\_TrailerCount* and *DF\_TrailerDetailOne*. The following points summarize the project team's conclusions for the addition of that message information:

- The additional information about the trailer can be included in a single DSRC packet,

and TTs make up a small fraction of the number of vehicles on the roadway.

- Information about the position of the trailer in the BSM Part II is only necessary during slow-speed turn maneuvers. During the remaining limited-angle turning maneuvers and straight articulation operations, the Part I message can sufficiently communicate combined tractor and trailer length.
- The vehicle size of the TT is similar to at least two light vehicles moving in close sequence, which would make the TT Part I and Part II messages of the TT similar to the channel load of two smaller vehicles.

Recommendations to further investigate TT HV-V2V communication are underway as a result of this study. However, elements of the findings of the TT-BSM study apply to this investigation, which focuses on the effects of single-unit truck and bus heavy vehicle configuration and size.

### Approach

VTTI compiled a list of representative SUTs and buses along with non-standard single unit heavy vehicles (SUHVs). The team also considered existing research involving connected vehicles as well as other areas that could shed light on the challenges SUHVs pose (e.g., roadway design). Some of the existing research reviewed included naturalistic data collected by VTTI on heavy vehicles, including motorcoach buses. This allowed the team to gain insight into the scenarios that caused safety-critical events to arise with vehicles in proximity to the instrumented heavy vehicle.

For the identified scenarios, an analysis was made of the motion of the vehicle types to evaluate the standard bounding box model. Where the model was insufficient, the team identified the characteristics of the SUHV that were different from a light vehicle. In the evaluation, the importance of minimizing changes to the existing standards and applications was kept as criteria as well. These data were then analyzed to determine which vehicle types would benefit from a modified BSM and what modifications would be needed to ensure the accurate transmission of information to surrounding vehicles. All of this information drove the recommended modifications to the current BSM. Finally, the team established objective criteria to evaluate which vehicles need a modified BSM.

### REVIEW OF EXISTING RESEARCH AND DATA

The team reviewed existing research to help identify relevant input and system parameters to consider in the evaluation of a BSM for SUHVs. This included physical characteristics and design parameters, vehicle performance, naturalistic data collections and existing V2V research and standards.

### Heavy Vehicle Characteristics

A review of the literature regarding heavy vehicle characteristics and performance focused on vehicle parameters and the maneuverability performance of single-unit trucks and buses. Heavy vehicles are defined as trucks and buses with a gross vehicle weight rating of 10,000 pounds (4,536 kg) or more. The Federal Highway Administration (FHWA) categorizes vehicles into classes by application, axle number, and vehicle frame unit number. The project scope for this task included evaluation of single-unit heavy vehicles. Based on the FHWA’s descriptions of vehicles, this includes Class 4 (buses) through Class 7 single-unit trucks with four or more axles (shown in bold in Table 1).

**Table 1.**  
**FHWA vehicle classes**

FHWA Class	Definition
1	Motorcycles
2	Passenger cars (including pulling light trailers)
3	Other two-axle, four-tire single-unit vehicles
<b>4</b>	<b>Buses (two axles or three or more axles)</b>
<b>5</b>	<b>Two-axle, six-tire, single-unit trucks</b>
<b>6</b>	<b>Three-axle, single-unit trucks</b>
<b>7</b>	<b>Four or more axle, single-unit trucks</b>
8-13	Single and multi-trailer trucks or tractors

The definition of single-unit vehicles may be understood to include vehicles that carry an articulation joint between two frame units, where the vehicle length cannot be modified by the operator. This is a common vehicle configuration among the transit intercity bus application. Heavy vehicle parameters and performance characteristics were provided by vehicle manufacturing stakeholders. The dimensions and parameters and turning radius performance of those for-sale products were compared to the SUHV design vehicles provided for roadway design in the American Association of State Highways and Transportation Officials (AASHTO) *Policy on Geometric Design of Highways and Streets*

(*Sixth Edition, 2011*), also known as the “Green Book.”

**Heavy Vehicle Design Parameters** The weight of a vehicle and its distribution of weight, especially front to back, play an important role in its operating characteristics at high speeds, but not at low speeds. However, it is worth noting that the weight of the vehicle, or more precisely, the total weight of a vehicle as designed, requires other characteristics, such as width and length, to be present in its design. It is the width and length characteristics of heavy vehicles that lead to their most significant differences from light vehicles in terms of maneuverability. The height of heavy vehicles, which provides for an increase in cargo carrying capabilities, also varies significantly from light vehicles, though this characteristic affects moderate and high speed roll stability rather than maneuverability. For more information on the topic, publications by both Fancher et al. (1984) and Fancher and Winkler (2007) provide expanded discussions on the characteristics and factors affecting heavy vehicle performance.

**Body and Tire Width** The differences in heavy vehicle and light vehicle width have a direct effect on the ability of heavy vehicles to operate within the same lane widths as light vehicles. A typical passenger vehicle has a body width of 6.0 ft. (e.g., Toyota Camry), and a long passenger sport utility vehicle has a body width of 6.7 ft. (e.g., Chevrolet Suburban), while heavy vehicles have widths between 8.0 ft. and 8.5 ft. Accordingly, the margin for operating heavy vehicles within the same lanes as light vehicles is typically one to two feet narrower. National Cooperative Highway Research Program (NCHRP) Report 505 (Harwood et al. 2003) references older studies that investigated the performance of heavy vehicle widths within 11 and 12-ft. lane widths. One joint study completed by the FHWA and NHTSA found no difference in lane-keeping performance between heavy vehicles that were 8 versus 8.5 ft. wide, which suggests that existing lane widths are satisfactory for heavy vehicles. However, this study did find that wide heavy vehicles influenced the lateral position of surrounding light vehicles, creating a 12–18-inch shift around 8 or 8.5-ft.-wide buses (Weir and Schilling, 1972). This finding suggests that single-unit heavy vehicle size at least influences the lane keeping behavior of drivers of narrower light vehicles.

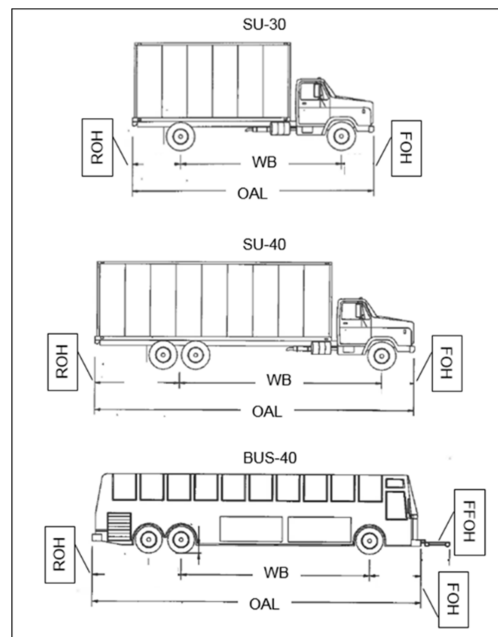
Tire widths are measured at the outermost tire sidewall. The rear axles are typically spread for high

cargo or passenger capacities to provide for maximum load support. The front axles can be narrower than the rear axles, which assists with improving turning radius. Tire track widths define the path that a heavy vehicle will tend to follow. The track width of rear dual axles is measured to the center of the two tires on each side (i.e., at the tire gap). The track width of front axles, which are not dual, are measured similarly to standard single tire axles on heavy and light vehicles (Fancher et al., 1986). However, the variety of tire width options available, especially on trucks, can lead to a measurable difference in turning radius performance. Dimensions of one particular Class 7 truck model provided by a truck original equipment manufacturer stakeholder lists an overall width range of 94.9 inches to 103.9 inches for the rear dual axle and from 91.0 inches to 102.7 inches for the front axle.

**Body Length and Wheelbase** The differences in heavy and light vehicle length are more extreme and carry with them a greater impact on heavy vehicles' performance than does vehicle width. A typical passenger vehicle sedan is 15.9 ft. long (e.g., Toyota Camry), and a long passenger sport utility vehicle is 18.7 ft. long (e.g., Chevrolet Suburban). The wheelbases of these vehicles are 9.1 ft. and 10.8 ft., respectively. Typically, single-unit heavy vehicles have bodies that are at least 30 ft. long with wheelbases of approximately 20 ft. (AASHTO, 2011). The economic pressures on cargo transportation encourage the use of long vehicles, which then require long wheelbases to satisfy the balancing of load front to rear. A representation of overall vehicle lengths (OAL) is provided in Figure 1 for multiple single-unit vehicle types, including a single rear axle truck (SU-30), tandem rear axles truck (SU-40), and tandem rear axles bus (BUS-40).

The position of wheelbase relative to body length is intentionally balanced on light vehicles, mainly to control for stability and maneuverability of those vehicles at moderate and high speeds (Weigand, 2011). However, that is not the primary design focus among heavy vehicles. A substantial proportion of the weight of heavy vehicles is positioned toward the rear axles, which leads to the common configuration of rear dual wheels and tandem axles (Fancher and Winkler, 2007). Wheelbase is traditionally measured on tandem-axle single-unit trucks to be the distance from the front steering axle to the geometric midpoint of the rear non-steering axles, as demonstrated in SU-40. A representation of wheelbase lengths (WB) is provided in Figure 1 for multiple single-unit vehicle types. However, single-unit tandem-axle buses wheelbases are traditionally measured from the front

axle to the drive axle center, which is typically the forward-rear axle, as demonstrated in BUS-40. This can be because some single-unit motorcoach buses have a floating, caster steering axle on their rear most axle, which follows the forward-rear axle at slow speeds, typically only floating when speeds are below 20 mph. As discussed in the Heavy Vehicle Maneuverability Performance section below, as wheelbase length increases, vehicle maneuverability performance characteristics — minimum turning radius, off-tracking, and swept path width — decrease. This performance can be moderated by higher steering angles and assisted to some degree with caster steer rear axles on motorcoach bus models.



**Figure 1. Heavy vehicle length parameters (adapted from AASHTO, 2011).**

**Body Overhang** The body overhang in front of the front axle and rearward of the rear-most axle exists on all vehicles and is typically measured from the outer-most axle wheel center to the bumper on the front or rear of the vehicle. A representation of front and rear overhang lengths (FOH, ROH) is provided in Figure 1 for multiple single-unit vehicle types. Gattis and Howard (1998) observed that the rear overhang exceeds the wheel path at the beginning of the turn at slow speeds. School bus rear body overhangs on sampled manufacturer vehicles are described by Gattis and Howard (1998) to be 11.70 ft. on a conventional bus (i.e., engine over front axle) and similarly, the AASHTO “Green Book” (2011) lists the same vehicle configuration with a rear body

overhang of 12.0 ft. Additionally, some buses carry bike racks that extend the far front overhang (FFOH) beyond the body, as demonstrated in BUS-40.

**Steering Angle** Heavy vehicle maneuverability performance is primarily influenced by wheelbase and steering angle. Steering angle is defined as the average of the angles made by the left and right steering wheels with the longitudinal axis of the vehicle when the wheels are turned to their maximum angle (AASHTO, 2011). Off-tracking, which will be discussed further in the next section, is a function of wheelbase and steering angle and increases exponentially with increased steering angle (Stevens et al., 1965). The maximum steering wheel angle, or cramp angle, is based on the limits of this assembly. Thus the steering angle of the vehicle is set by the driver's input until the assembly meets its limits.

**SUVs' Configuration Classification** Standard heavy vehicle configurations have been identified to define design vehicles, which are used for roadway design. These design vehicles provide a common reference point for the evaluation of the light vehicle BSM relative to SUVs. Table 2 (See Appendix) provides a list of standard reference dimensions published by AASHTO (2011) unless otherwise noted.

### **Heavy Vehicle Maneuverability Performance**

These primary and secondary vehicle design parameters described above create a range of vehicle performance variables that affect heavy vehicle maneuverability. This is true to the extent that the parameters are commonly referenced on configured design vehicles in the application of roadway design. The resulting vehicle performance parameters are as follows: minimum turning radius, off-tracking, and swept path width.

**Turning Radius** The turning radius is a general term that can be applied to the specification of vehicle performance, as measured from a center reference point to a part on the vehicle (e.g., center axle, rear-inside wheel/tire, and front outside body). The minimum turning radius is typically used to describe vehicle performance specifications at the front, within which a vehicle can turn when steering is extended to the maximum steering angle input. The minimum turning radius may vary by object clearance. Generally, a so-called curb height turning radius requires that the tires clear a curb at ground height and thus references the front outside tire track (i.e., curb-to-curb turning radius). A wall height turning radius requires that the vehicle body (i.e.,

bumper) clear obstructions above ground (i.e., wall-to-wall turning radius).

The minimum turning radius performance for low speed steady state cornering of any vehicle configuration is fundamentally a result of two vehicle parameters: the vehicle wheelbase and steering angle. The chosen turning radius path can, however, be larger than the minimum. The vehicle wheelbase is a fixed parameter that cannot be adjusted by the driver to change the vehicle radius path; however, the steering angle can be adjusted. It is beneficial to keep some real-world operational factors in mind. For instance, the minimum or best-case performance is not always applied or available to drivers. Drivers must choose the best path, by varying the steering angle, that will allow them to navigate through the lanes, as well as around curbs, other vehicles, bicyclists, and pedestrians present on or near the roadway. Furthermore, as noted in the AASHTO "Green Book" (2011, p. 2-9), the turning radii performance of vehicles described in critical and scientific publications presumes that the vehicle is operating per manufacturer specifications, for example with perfect front-end alignment. However, many vehicles operating on the roadways do not have such alignment, leading to inconsistent turning radius performance.

When applying vehicle performance variables to the design of roadways and, specifically, intersections, it is most important to recognize that the turning radius variable of interest is measured at the rear inside wheel for clearance to curbs and lane keeping. The turning radius performance at the front of the vehicle, as measured on other parts, will be treated in this discussion as a measurement of swept path width—which is fundamentally a result of vehicle off-tracking.

**Off-Tracking** Off-tracking can be simply understood to be the difference in path of any following axle/wheel from the front axle/wheel. This can happen even for very narrow vehicles, such as bicycles. In fact, only vehicles that operate on fixed paths, such as light or heavy rail, will avoid off-tracking (Harwood et al., 2003). Off-tracking is the natural result of the separation of axles on a vehicle frame and is closely related to the vehicle performance parameter of turning radius. Typically, articulated heavy vehicles are the focus of off-tracking study. However, off-tracking can refer to the difference in path of any single-unit following wheel from a front wheel.

Off-tracking can be described as positive or negative value, meaning as either inside of the turn path taken by the front wheels or outside, depending on the vehicle maneuver at low or high speed and depending on the part that is being tracked, meaning chassis or body components. Off-tracking tends to be the focus of articulated combination vehicle performance at low speed, when a trailer is said to be cheating the path of the tractor, and is usually managed carefully by drivers at intersections to avoid running over curbs or other objects. However, it is worth noting that the off-tracking of an articulated TT combination at a given overall length can be seen as improving the performance of the combination's turning radius and area of roadway covered by the vehicle (i.e., swept path widths) as compared to a single-unit vehicle of the same length.

Like turning radius, off-tracking is dependent on the vehicle wheelbase and steering angle. Rather than being a trace of one single vehicle reference, off-tracking refers to the difference between two radii on two similar vehicle reference points (e.g., axle centers, inside wheels, outside wheels, or body corners). Similar to minimum turning radius, which is dependent on the driver's steering input, fully developed low speed off-tracking occurs when the steering angle input is at its maximum and the rear axle/wheel has reached the point of maximum delta from the front axle/wheel.

**Swept Path Width** Another important heavy vehicle performance variable is the swept path width, which is the area covered by the vehicle throughout the turning maneuver. It can be understood as the trace of the inner rear wheel to the front body corner throughout the turning maneuver (AASHTO, 2011). A combination of the previously defined vehicle performance variables should be considered to determine when this path is at its largest width, including the minimum turning radius on the inside to the opposite vehicle outside body corner at the fully developed low-speed off-tracking. The overhang of the body at the front and rear of the vehicle affect swept path width performance.

Rear overhang has only a minor effect on the swept path and only at the beginning of the turn. Gattis and Howard (1998) highlighted the effect of the rear overhang on swept path in a study on school bus vehicle characteristics. Since then, the swept path of the rear overhang has been included in design standards such as the AASHTO "Green Book." However, the front body overhang has the most significant effect on swept path. As clearly demonstrated in the design vehicle turning radii

performance graphics (AASHTO, 2011), the rear overhang translates into the swept path area early in the turn, while the front overhang creates a prominent outward trace during most single-unit vehicles' turns. When accounting for the maximum swept path width on a range of single-unit vehicle bodies, the most outboard components should always be included. These include variable components, such as bike racks, that are commonly present on transit buses.

**SUHVs' Performance Classification** The design vehicles selected by AASHTO represent each category of vehicle to provide national guidance on roadway design. The VTTI team therefore chose these design vehicles to evaluate common design dimensions and the general applicability of the BSM and standardized comparison of SUHV maneuverability performance characteristics. As stated previously, the scenarios that are most likely to require special consideration are those involving low speed turning maneuvers. Accordingly, the performance characteristics of these design vehicles affecting turning maneuvers were considered in Table 3 (See Appendix).

#### **Dynamic Heavy Vehicle Scenarios**

Based on the conclusions drawn from the TT-BSM project (Svenson, 2016) — that articulated heavy vehicles were sufficiently represented by a single body BSM except for low-speed maneuvers — the team focused on the same criteria in assessing scenarios for SUTs and bus heavy vehicles among pre-existing safety-critical events collected during Year 1 of the On-Board Monitoring System (OBMS) Field Operational Test (FOT) project.

**Naturalistic Data Collection** VTTI has compiled a large quantity of naturalistic data on heavy vehicles. Of special interest to this investigation was the video, vehicle network, and GPS tracing data (e.g. speed, heading, latitude, longitude, yaw rate, and lateral acceleration) collected from motorcoach buses during the aforementioned OBMS FOT project. The project's objective was to determine whether an OBMS would reduce at-risk behavior among commercial drivers and improve driver safety performance. A large quantity of motorcoach data across multiple years was collected and one year was processed through reduction software to identify safety-critical events prior to application in this HV-V2V investigation. The collection analyzed for application in this study was based on Year 1 of the OBMS project (May 2013 through July 2014), and included 43 motorcoaches, 65 drivers, and approximately 600,000 miles of vehicle data. The safety-critical events processed from that one-year

period included crashes, near crashes, crash-relevant conflicts, tire strikes, and unintentional lane deviations.

The list of safety-critical events was filtered to find scenarios that would be most applicable to V2V communication issues. The filters for the data included all pre-incident maneuvers (e.g., merging, changing lanes, turning right, and turning left), with a few maneuvers removed (e.g., going straight-accelerating). Events were also filtered to focus on conflicts with other vehicles — all types — and filtered for crash, near-crash, or crash-relevant conflicts. After this sorting, the remaining list was sampled by observing the video of these events based on incident descriptions. A subset of safety-critical events was selected as containing likely scenarios that could provide guidance on typical heavy vehicle operations and interactions with other vehicles.

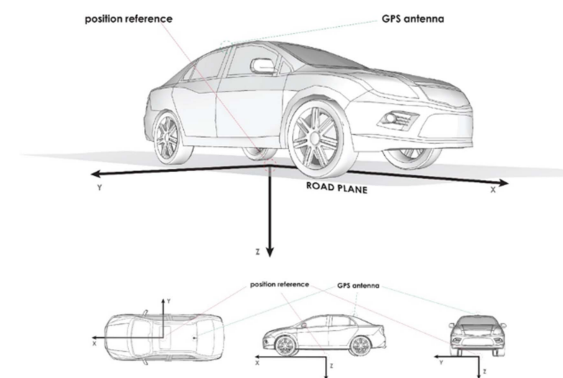
**Naturalistic Scenario Observations** After careful review of the events, one event was found to be particularly interesting in relation to this investigation. This event involved a motorcoach turning left on the inside lane while other vehicles, mostly cars, tried to maintain the same path on the outside turning lane. The driver of the motorcoach made every effort to keep the bus close to the inside curb and stay within the lane. However, at the middle of the turn, the motorcoach bus could not avoid crossing the dotted white lane-separation line, while a small car in the outside lane paused and swerved out of the way as the motorcoach driver applied the brakes until both lanes were clear to proceed.

These events were exported for application in the investigative model. The variables exported for application included the following: timestamp, speed, longitudinal acceleration (accel X), lateral acceleration (accel Y), yaw (gyro Z), latitude, longitude, and heading at a rate of approximately 10 Hz. This data was applied to a path tracing model proposed as one method for determining the sufficiency of the V2V BSM for SUHVs

The large overhang of the motorcoach bus made it necessary for the driver to encroach on adjacent lanes occupied by other vehicles. For situations involving high speed maneuvers and/or straight or nearly straight driving conditions, even those with safety-critical events, the bounding box model can adequately reflect the actual motion of the vehicle. Consequently, the team focused on low speed turning maneuvers where large overhangs can create a scenario in which the front or rear of the SUHV can encroach on adjacent lanes.

## BSM Standards

Heavy vehicles, and even large light vehicles, pose challenges to lane keeping tasks. However, if this behavior is captured with the light vehicle BSM, then the BSM is sufficient for heavy vehicles. Therefore, in evaluating the applicability of the light vehicle BSM, it is first necessary to review the related assumptions as defined. There are two published standards associated with the BSM: SAE J2735 and SAE 2945/1. The former provides a data dictionary for the contents of messages, while the latter provides the minimum performance requirements for a V2V safety system for light vehicles that utilize 5.9 GHz DSRC. A light vehicle is a Class 2 or Class 3 vehicle as defined by FHWA (excluding emergency and construction vehicles). The vehicle position is a point projected onto the ground that is the center of a bounding box that encompasses the extents of the vehicle fore, aft, and side-to-side, including all original equipment, as seen in Figure 2 (SAE J2945/1 [March, 2016]).



**Figure 2. BSM position reference (source: SAE J2945/1 [March, 2016]).**

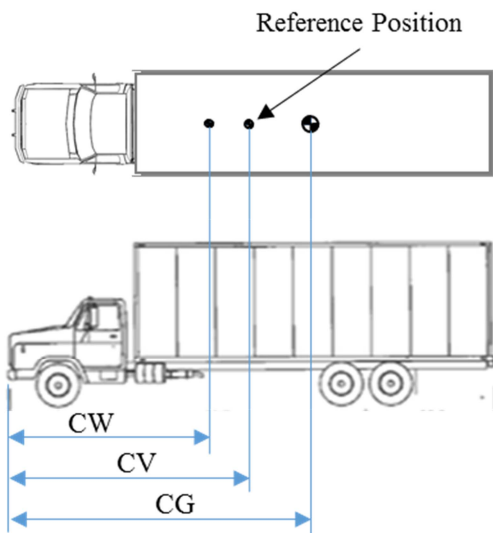
The position reference and bounding box provide the basis for the communication regarding the vehicle's position and motion. As such, they were a primary part of the evaluation for the SUHVs. The parameter settings specified in J2945/1 were used to try to provide a quantitative assessment of the position and motion requirements. The standard specifies a position accuracy of 1.5 m and speed accuracy of 1 km/h (SAE J2945/1 [March 2016]), which serve as the basis for the evaluation.

## ANALYSIS

The typical V2X equipped vehicle is represented by a rectangle that bounds the outside of the vehicle to identify its position during V2X communication. The center of this rectangle is projected onto the ground plane and is the reference for the position and motion



information for the vehicle. For light vehicles, the center of gravity and wheelbase are both near the geometric center of the vehicle. This aids in stability and handling performance, as well as ride quality. For heavy vehicles, this is not necessarily the case, since utility is a primary design constraint. Consider the commercially available 40-foot long SUT with a 23-foot wheelbase and a 9-ft. cab with 4 ft. of front overhang and 12 ft. of rear overhang. This configuration is depicted in Figure 3 and shows the center of the vehicle (CV) (corresponding to the reference point in J2945/1) and the center of the wheelbase (CW). For this vehicle, the CW is 15.5 ft., 4.5 ft. forward of the CV. For the standard AASHTO design vehicle SU-40, the CW is 16.5 percent ahead of the CV. For reference, the CG is also shown for a vehicle configured with a 10,000-lb. front axle and a 40,000-lb. rear tandem axle. As the vehicle is loaded, the center of gravity (CG) will move towards the rear axle where 80 percent of the load carrying capacity resides.



**Figure 3. BSM reference position for single unit heavy vehicle.**

**Light Vehicle and SUHV Reference Ratios**

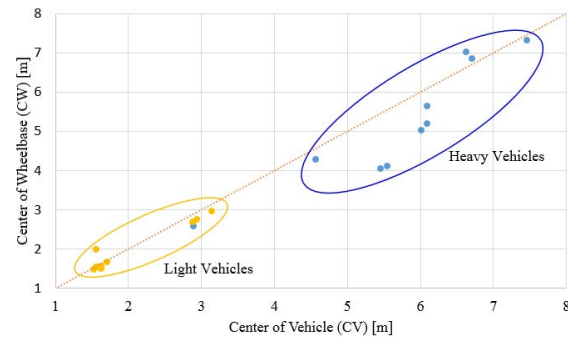
To compare the similarity and therefore, the adequacy of the light vehicle BSM to support the bounding box reference of SUHVs, an arrangement of the CV positions to the CW positions is instructive. The CV and CW positions are determined from common references at the front-most body reference, the vehicle bumper. The CV is directly determined from the outer-most vehicle body dimension, as shown in Equation 1. The CW is a dimension between axles, and therefore, must be

determined relative to a body dimension (i.e., front over-hang), as shown in Equation 2.

$$CV = \frac{OAL}{2} \quad (1)$$

$$CW = \frac{WB}{2} + FOH \quad (2)$$

In Figure 4, a selection of light vehicles, ranging from small hatchbacks to full size pickups, were added to provide a baseline. The line in Figure 4 provides a reference where the body is centered on the wheelbase. Vehicles below the line have a CW in front of the BSM reference point and vehicles above the line have a CW to the rear of it. The light vehicles generally fall below the line as do the heavy vehicles. The two vehicles furthest from the line are the school buses, labeled SB-C and S-BUS-36.



**Figure 4. BSM reference point (CV) vs. CW.**

**SUHV Wheelbase Turning Radius Effects**

Looking at the turning radii for these two vehicles (SB-C and S-BUS-36), we see the turning paths highlighted in Figure 7 (See Appendix) with outer front body turning radii of 40.1 ft. and 39.7 ft., respectively. As expected, these have nearly the same path through the corner. To study the impact of bodies that are not centered on the chassis, the front and rear overhang values were reversed. The effect of shifting the body relative to the chassis is shown in Figure 8 (See Appendix). As evidenced from the figures from left to right, when the standard rear body overhang is moved forward over the axles to match the wheelbase center and then in front of the wheelbase center, the outer front body turning radii increases even though the rear-inside axle follows the same turning path (i.e., 23.8 feet).

The black dot shows the geometric center (reference position). The red plus is the center of the wheel base, which defines the path around the corner. As can be plainly seen in this extreme case, a bounding

box centered at the reference point would not accurately represent the position of the body of the vehicle during slow speed cornering.

Table 4 (See Appendix) provides a comparison of the three configurations. As expected, the tire paths are the same for all configurations since the chassis remains the same. The paths the body sweeps are significantly different. Comparing the swept path of the vehicles, the standard configuration takes just under twice the width of the vehicle. On the other extreme, the body forward design takes 40 percent more space than the standard, body back configuration.

For the light vehicle BSM, SAE J2945/1 specifies accuracies that must be met to comply with the standard. The most relevant for this evaluation are for position (1.5 m) and size (0.2 m). For the positional constraint, the BSM expects a configuration similar to S\_BUS\_36a in Figure 8 (See Appendix). As shown in Table 4 (See Appendix), the maximum error in path radius is less than the 1.5 m accuracy constraint. The constraint attempts to ensure that the V2V system can confidently determine if the vehicle is within its lane. For the front corner, to honor that intent, the positional accuracy would need to be a quarter of the required accuracy. The greater challenge is the size accuracy since, during a low speed turn, the shift in the body is akin to an error in the length measurement.

While the body forward configuration with the large forward overhang is a greater issue both in terms of the extent and duration of the subsequent intrusion into traffic, from the vehicle data presented, it is apparent that this configuration would be an anomaly. The only vehicles that are above the line in Figure 4 are the buses with bike rack included on the front (these fall below the line if the rack is folded up) and, among the light vehicles, a small fastback. Consequently, the focus was on identifying a metric to quantify how much shift in the body relative to the chassis was too far for the BSM.

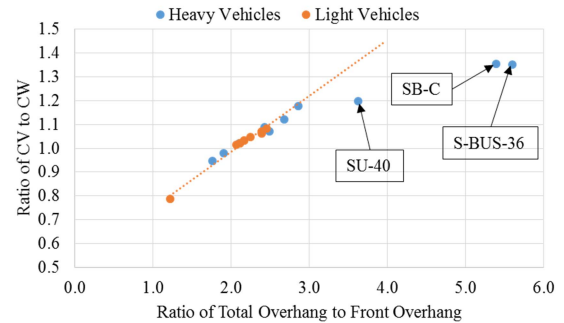
#### SUHV Body Overhang Turning Radius Effects

Vehicles that have a large overall length compared to the wheelbase have more room to shift the body relative to the chassis. Consequently, this metric was selected. However, it does not provide an indication of how far the center of the two measures may be shifted. To try to capture that, the ratio of the total overhang compared with the front overhang was selected. Front overhang was selected to be

consistent with the measure of CV (Equation 1) and CW (Equation 2). The following equations (Equation 3 and Equation 4) are defined and produce the front overhang ratio and the ratio of body to chassis (i.e., wheelbase) center positions, as arranged in Figure 5.

$$\text{Front Overhang Ratio (FOR)} = \frac{OAL-WB}{FOH} \quad (3)$$

$$\text{Ratio of CV to CW (ROC)} = \frac{CV}{CW} \quad (4)$$



**Figure 5. Metric to identify problematic vehicle configurations.**

Similar to Figure 4, additional light vehicle configurations were included to establish a baseline. A simple linear regression was used to identify possible outliers from the baseline. Most of the heavy vehicles lie within the range of the light vehicles. As expected, S-BUS-36 and SB-C are outliers. Similarly, SU-40, a 40 ft. SUT, is also an outlier. Running a turning path simulation and analysis on the 40-foot truck (SU-40) where the body is centered on the wheelbase in the left figure compared to the standard truck configuration on the right, yields the result demonstrated in Figure 9 (See Appendix).

As expected, the standard configuration with the body back relative to the chassis has a smaller swept path. Table 5 (See Appendix) provides a summary of the results. The deltas show that the rear corner moves outside the expected path by the allowed accuracy for size. The front corner is greater than the 0.3 m tolerance specified, but remains inside the predicted path. While this might cause a false alert, it would not pose a safety threat.

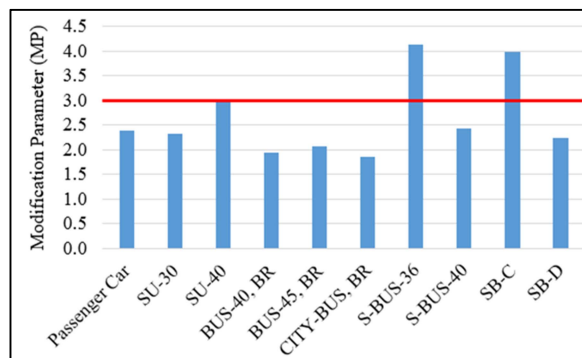
#### SUHV Configuration Metric for BSM Modification

The 40-foot truck (SU-40) vehicle is used as the threshold for the recommendation to include an augmented BSM. Dividing the front overhang ratio (Equation 3) by the ratio of the centers (Equation 4) leads to Equation 5. This ratio of front-overhang to

the ratio of vehicle/wheelbase centers provides a metric to highlight vehicle configurations that may require additional elements in Part II of the BSM during turning maneuvers.

$$BSM \text{ Metric} = \frac{FOR}{ROC} \quad (5)$$

The list of vehicles in Figure 6 illustrates the threshold modification parameter (MP) value of “3” that provides guidance on which vehicles may require additional elements to communicate that their body and wheelbase configuration do not sufficiently align to operate within the tolerance allowable for the standard light vehicle BSM.



**Figure 6. Threshold for recommended BSM modification parameter (MP).**

## CONCLUSIONS

As stated, the two primary goals were to accurately represent the position and motion of SUHVs and to minimize false warnings. This includes both false positives (nuisance alerts) and false negatives (failure to warn for true threat).

For most driving scenarios, the SUHV tracks similarly to a light vehicle and therefore the BSM as defined adequately represents the position and motion of SUHVs and therefore provides accurate information to minimize false warnings. The primary exception is for low speed cornering maneuvers. For these maneuvers, the difference in vehicle configurations can cause the paths of the front and rear of the vehicle to be misrepresented. This is particularly true when the center position of the wheelbase differs significantly from that of the center of the bounding box of the body. For vehicles that have this characteristic, additional information is necessary to capture the position of the wheelbase relative to the body.

One way to capture this is by adding an element to Part 2 of the BSM as defined in J2735 for the

wheelbase and the overhang. These two elements, *DE\_VehicleWheelbase* and *DE\_FrontOverhang* can be combined into a single data frame *DF\_VehicleWheelbase* and follow the same specifications for *DF\_VehicleSize* made up of *DE\_VehicleLength* and *DE\_VehicleWidth* that currently exist in J2735.

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**APPENDIX: TABLES AND FIGURES**

**Table 2.**  
**Single unit heavy vehicles dimensions for design vehicles**

Application	Model	Body Width		Overall Length		Wheelbase		Rear Overhang		Front Overhang	
		m	ft.	m	ft.	m	ft.	m	ft.	m	ft.
General	Passenger Car	2.1	7.0	5.8	19.0	3.4	11.0	1.5	5.0	0.9	3.0
Dry Van	SU-30	2.4	8.0	9.1	30.0	6.1	20.0	1.8	6.0	1.2	4.0
Dry Van	SU-40	2.4	8.0	12.0	39.5	7.6	25.0	3.2	10.5	1.2	4.0
Intercity Bus	BUS-40	2.6	8.5	13.4	44.1	7.1	23.3	2.7	9.0	3.0	9.8
Intercity Bus	BUS-45	2.6	8.5	14.9	49.0	8.1	26.6	3.3	10.8	3.0	9.7
City Transit	CITY-BUS	2.6	8.5	13.3	43.5	7.6	25.0	2.4	8.0	3.2	10.5
School Type C	S-BUS-36	2.4	8.0	10.9	35.8	6.5	21.3	3.7	12.0	0.8	2.6
School Type D	S-BUS-40	2.4	8.0	12.2	40.0	6.1	20.0	4.0	13.0	2.1	7.0
School Type C <sup>1</sup>	SB-C	2.4	8.0	11.1	36.4	6.5	21.3	3.7	12.0	0.9	2.8
School Type D <sup>1</sup>	SB-D	2.4	8.0	12.2	40.0	7.0	23.0	2.9	9.7	2.1	7.0

<sup>1</sup> Proposed by Gattis et. al. (1998) as alternates to AASHTO school bus configurations

**Table 3.**  
**Radii of turning paths for AASHTO design vehicles**

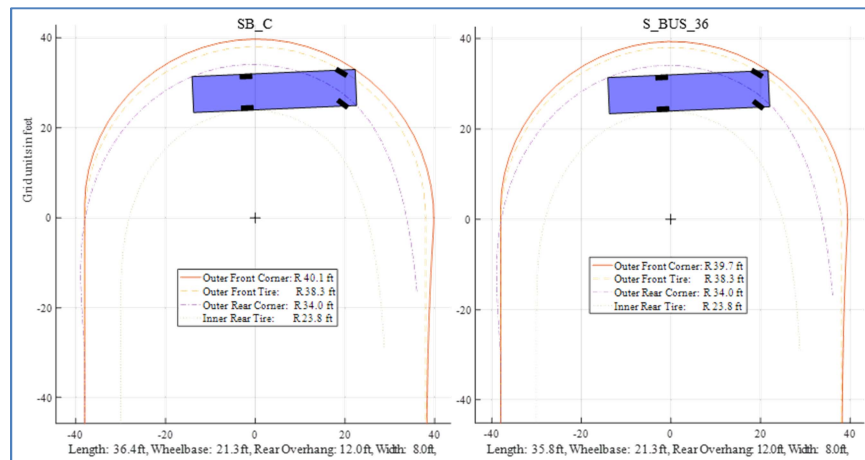
Application	Model	Inside Rear Tire		Outside Front Tire		Front Overhang		Swept Path	
		m	ft.	m	ft.	m	ft.	m	ft.
General	Passenger Car	4.4	14.4	7.3	23.8	7.8	25.4	3.4	11.0
Dry Van	SU-30	8.6	28.3	12.7	41.8	13.2	43.3	4.6	15.0
Dry Van	SU-40	11.1	36.4	15.6	51.2	16.1	52.8	5.0	16.4
Intercity Bus	BUS-40	7.4	24.3	12.7	41.7	14.2	46.5	6.8	22.2
Intercity Bus	BUS-45	7.5	24.7	13.4	44.0	14.9	48.9	7.4	24.2
City Transit	CITY-BUS	7.5	24.4	12.8	42.0	14.3	46.8	6.8	22.4
School Type C	S-BUS-36	7.3	23.8	11.8	38.5	12.1	39.6	4.8	15.8
School Type D	S-BUS-40	7.7	25.3	11.9	39.1	12.9	42.2	5.2	16.9
School Type C <sup>1</sup>	SB-C	7.7	25.2	11.8	38.9	12.4	40.8	4.7	15.4
School Type D <sup>1</sup>	SB-D	7.7	25.2	12.2	40.0	13.4	44.1	5.7	18.7

**Table 4.**  
**Turning path variations for 36-foot school bus (S-BUS-36) body shifted on chassis**

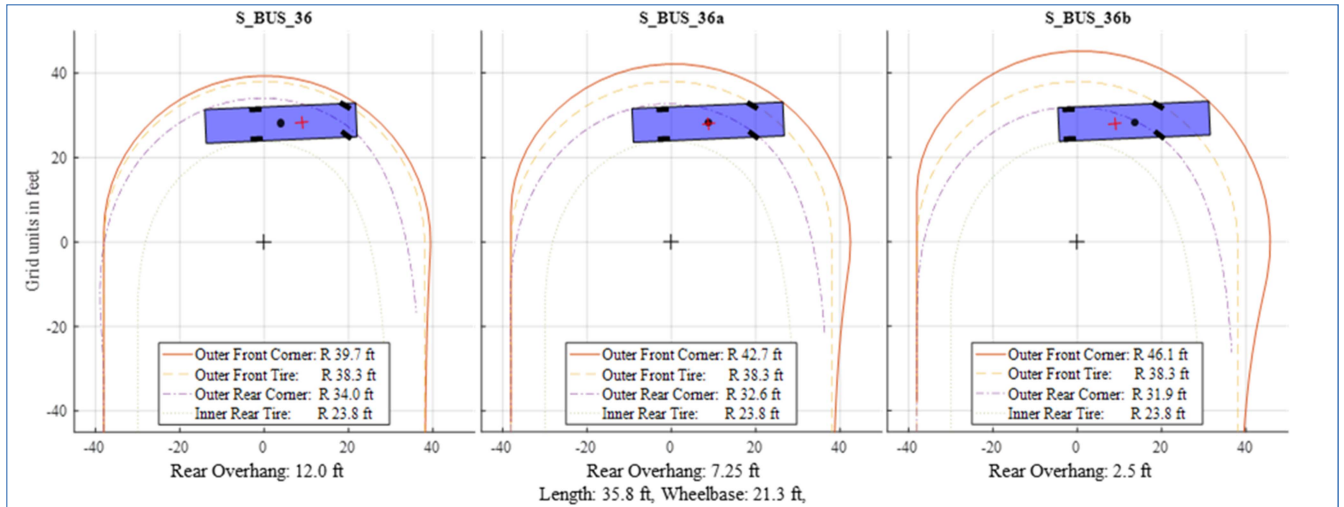
S-BUS-36	Inside Rear Tire		Rear Corner		Front Tire		Front Corner		Swept Path		Rear Over-swing	
	m	ft.	m	ft.	m	ft.	m	ft.	m	ft.	m	ft.
Standard (Body Back on Chassis)	7.3	23.8	10.4	34.0	11.7	38.3	12.1	39.7	4.8	15.9	0.28	0.91
Body Centered on Chassis	7.3	23.8	9.9	32.6	11.7	38.3	13.0	42.7	5.8	18.9	0.08	0.25
Body Forward on Chassis	7.3	23.8	9.7	31.9	11.7	38.3	14.1	46.1	6.8	22.3	0.0	0.0
Delta: Centered – Standard			-0.5	-1.4			0.9	3.0			0.2	0.66
Delta: Centered - Forward			0.2	0.7			-1.1	-3.4			0.08	0.25

**Table 5.**  
**Turning path variations for 40-foot truck (SU-40) body shifted on chassis**

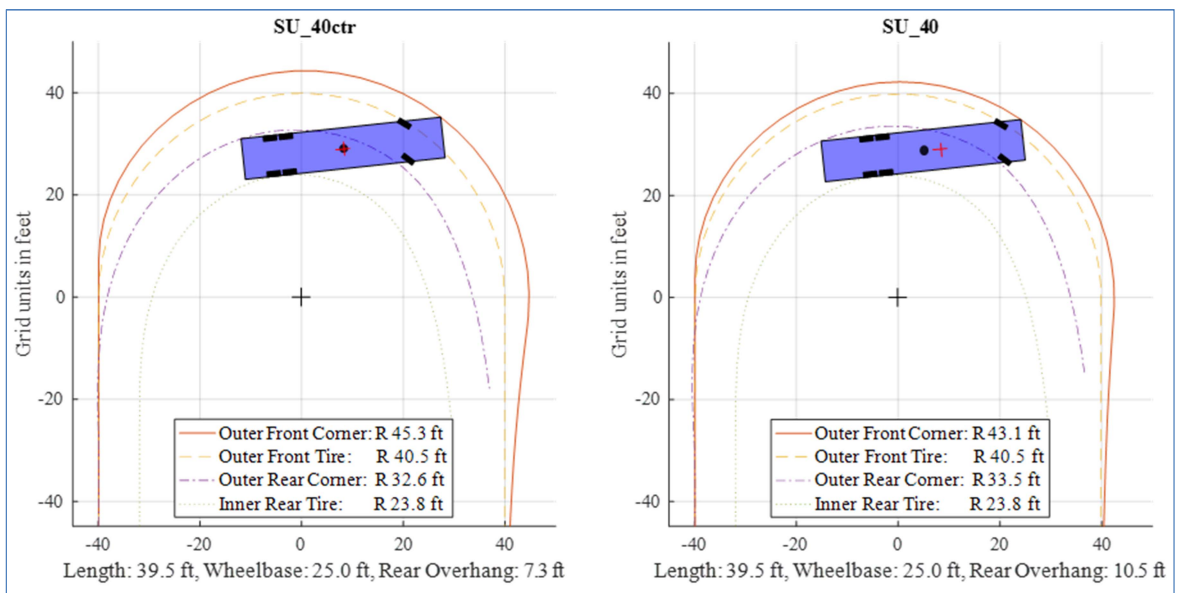
SU-40	Inside Rear Tire		Rear Corner		Front Tire		Front Corner		Swept Path		Rear Over-swing	
	m	ft.	m	ft.	m	ft.	m	ft.	m	ft.	m	ft.
Standard (Body Back on Chassis)	7.3	23.8	10.2	33.5	12.3	40.5	13.1	43.1	5.9	19.3	0.2	0.51
Body Centered on Chassis	7.3	23.8	9.9	32.6	12.3	40.5	13.8	45.3	6.6	21.5	0.0	0.0
Delta: Centered – Standard			-0.3	-0.9			0.7	2.2			0.2	0.51



**Figure 7. 36-foot school bus (S-BUS-36) turning paths.**



**Figure 8. Effect of shifting 36-foot school bus (S-BUS-36) body on chassis.**



**Figure 9. Effect of shifting 40-foot truck (SU-40) body on chassis.**