FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

Transit Bus Automation Project: Transferability of Automation Technologies

Final Report

SEPTEMBER 2018

FTA Report No. 0125
Federal Transit Administration

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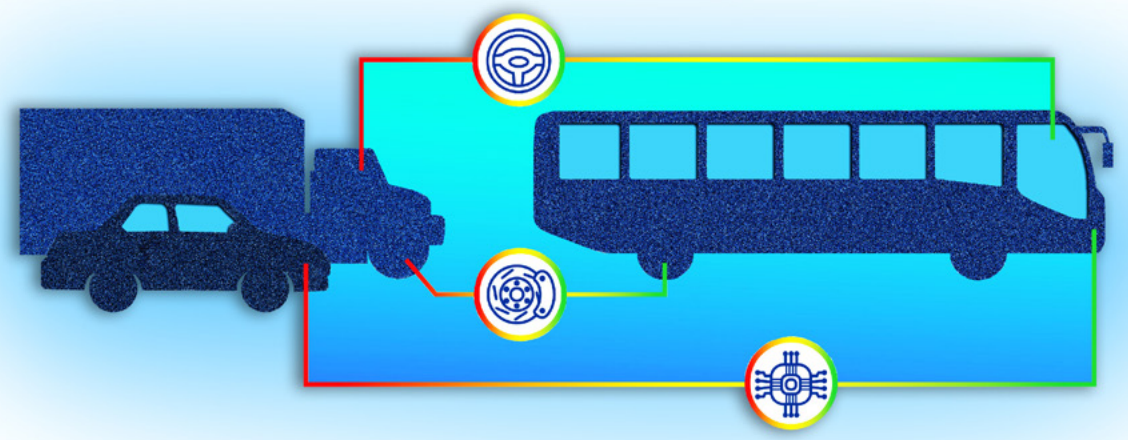

U.S. Department of Transportation
Federal Transit Administration

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY	2. REPORT DATE September 2018	3. REPORT TYPE AND DATES COVERED Final Report, October 2017-June 2018

4. TITLE AND SUBTITLE Transit Bus Automation Project: Transferability of Automation Technologies Final Report	5. FUNDING NUMBERS
6. AUTHOR(S) Ahmad Nasser, John Brewer, Wassim Najm, Joshua Cregger	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSE(ES) John A. Volpe National Transportation Systems Center U.S. Department of Transportation 55 Broadway Cambridge MA 02142	8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-FTA-18-02
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Transit Administration Office of Research, Demonstration and Innovation East Building 1200 New Jersey Avenue, SE Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER FTA Report No. 0125

11. SUPPLEMENTARY NOTES [https://www.transit.dot.gov/about/research-innovation]

12A. DISTRIBUTION/AVAILABILITY STATEMENT Available from: National Technical Information Service (NTIS), Springfield, VA 22161. Phone 703.605.6000, Fax 703.605.6900, email [orders@ntis.gov]	12B. DISTRIBUTION CODE TRI

13. ABSTRACT

This report examines the feasibility of transferring 13 current automated systems technologies from light-duty vehicles and commercial trucks to 40-ft diesel transit buses. It explores the associated technical and safety challenges of implementing those systems in transit buses and ways to overcome some of the identified barriers to implementation. The transferability of each systems was given a grade of Red, Yellow, or Green, with Green indicating most ready to be transferred.

Transferring existing automation systems from other vehicle formats will generally require modification, replacement, or redesign of components and systems on the bus. Sensors are relatively mature and should be able to be adapted to buses without modification. To enable other automation systems, however, the transit bus industry will need to implement foundational and interfacing systems that can support electronic actuation. Modifications to propulsion systems should be more easily made than modifications to other foundational systems (i.e., steering and braking). Steering systems may require more modification, but heavy-duty vehicle steering solutions that enable automation exist and may not require extensive changes. Implementation of electronic control of a transit bus brake system appears to be a major challenge, as pneumatic brakes found in buses are less conducive to automation and more extensive design changes may be needed. Automated applications may require a new communication system architecture with bandwidth to carry numerous complex signals reliably. Finally, buses will require new human-machine interfaces to control automation systems, although these should be relatively easy to design and implement.

14. SUBJECT TERMS

Transferability, automation, human machine interface, sensors, actuators, transit buses, communication, heavy duty truck, light duty vehicle, electronic control unit, Object Detection and Collision Avoidance, Lane Keeping/Lane Centering, Steering Assist, Docking, Park Assist, Park Out, Yard Park, Automatic Emergency Braking, Reverse Brake Assist, Full Park Assist, Valet Parking (Bus Yard), Adaptive Cruise Control with/without Stop and Go, Traffic Jam Assist with Lane Keeping/Lane Centering

16. PRICE CODE	15. NUMBER OF PAGES 100

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

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ABSTRACT

This report examines the feasibility of transferring 13 current automated systems technologies from light-duty vehicles and commercial trucks to 40-ft diesel transit buses. It explores the associated technical and safety challenges of implementing those systems in transit buses and ways to overcome some of the identified barriers to implementation. The transferability of each systems was given a grade of Red, Yellow, or Green, with Green indicating most ready to be transferred.

Transferring existing automation systems from other vehicle formats will generally require modification, replacement, or redesign of components and systems on the bus. Sensors are relatively mature and should be able to be adapted to buses without modification. To enable other automation systems, however, the transit bus industry will need to implement foundational and interfacing systems that can support electronic actuation. Modifications to propulsion systems should be more easily made than modifications to other foundational systems (i.e., steering and braking). Steering systems may require more modification, but heavy-duty vehicle steering solutions that enable automation exist and may not require extensive changes. Implementation of electronic control of a transit bus brake system appears to be a major challenge, as pneumatic brakes found in buses are less conducive to automation and more extensive design changes may be needed. Automated applications may require a new communication system architecture with bandwidth to carry numerous complex signals reliably. Finally, buses will require new human-machine interfaces to control automation systems, although these should be relatively easy to design and implement.

EXECUTIVE SUMMARY

Automation capabilities have advanced rapidly in recent years and have changed the dialogue around all aspects of the surface transportation system. Although automation systems for light-duty vehicles and commercial trucks are increasingly available, these systems have yet to appear in transit buses.

This report examines the state of the industry and the feasibility of implementing automated systems in 40-foot diesel transit buses. It explores commercially-available automation systems in light-duty vehicles and commercial trucks, technical and safety challenges of transferring those systems to transit buses, and ways to overcome some of the identified barriers to implementation.

The scope of the report is limited to SAE Level 2 and lower automation systems currently in production for light-duty vehicles and commercial trucks with potential applicability to transit buses. This report considers 13 relevant automation systems, assesses their potential transferability to transit vehicles, and assigns each system a grade (Green, Yellow, or Red, as shown in Table ES-1) based on an analysis of the extent of modifications required and the severity of safety concerns:

- A grade of **Green** suggests that for the introduction of the automation system, minor modifications to foundational bus systems may be required and that safety issues or concerns are few and of low severity.
- A grade of **Yellow** suggests that major modifications to the foundational bus systems may be required for the implementation of the automated system and that safety issues or concerns are considered low to moderate.
- A grade of **Red** suggests that significantly new technology may be required for one or more foundational bus systems to accommodate the automated systems and that safety issues or concerns may be relatively high.

Table ES-1

Relevant Automation Systems and Modification Classifications

Green – Minor Modifications	Yellow – Major Modifications	Red – New Technology Required
• Object Detection and Collision Avoidance	• Lane Keeping/Lane Centering • Steering Assist • Docking • Park Assist • Park Out • Yard Park	• Automatic Emergency Braking • Reverse Brake Assist • Full Park Assist • Valet Parking (Bus Yard) • Adaptive Cruise Control with/without Stop-and-Go • Traffic Jam Assist with Lane Keeping/Lane Centering

Object Detection and Collision Avoidance (ODCA) systems are most ready for transfer and are graded as Green. It should be noted that ODCA systems can be component inputs to automation systems that are graded as Yellow or Red. Applications using only automated steering were graded as Yellow due to the modification required. Automation of current transit bus brake systems, particularly electronic actuation of braking, is more challenging. Consequently, applications using automated braking or a combination of automated braking paired with automated steering were graded as Red.

The analysis contained in this report is directly relevant for Federal Transit Administration (FTA) strategic decisions regarding research programming. Similarly, the findings have strategic implications for industry research and development. Key findings from the report include the following:

- Transferring existing automation systems from other vehicle formats is not straightforward. Beyond the minor adjustments that would be needed to install an automation system on a new vehicle model (e.g., modifying the number and placement of sensors to accommodate a new vehicle footprint), transferring these systems to buses requires modification, replacement, or redesign of components and systems on the bus.
- To enable automation systems, the transit bus industry will need to implement foundational and interfacing systems that can support electronic actuation.
- Modifications to powertrain systems in support of automation should be made more easily than modifications to other foundational systems (i.e., steering and braking).
- Bus steering systems may require more modification, but heavy-duty vehicle steering solutions exist to enable automation and may not require extensive changes.
- With respect to technologies currently found in light-duty vehicles and commercial trucks, automated steering applications may be easier to transfer to transit buses than automated braking applications.
- Implementation of electronic control of a transit bus brake system appears to be a major challenge, as pneumatic brakes found in buses are less conducive to automation and more extensive design changes may be needed.
- Automated applications, especially those requiring a braking component, may require a new communication system architecture with bandwidth to carry numerous complex signals reliably.
- Buses will require new human-machine interfaces to control automation systems, although these should be relatively easy to design and implement.
- Sensors are relatively mature and should be able to be adapted to buses without modification.

A significant part of the FTA research mission is to fund demonstration of transit technologies, with the goal of improving system performance throughout the industry. When considering research and demonstration priorities, FTA should consider not only the relative transferability of an application but also the objectives that federally-supported research and demonstration can serve.

There are other factors to consider beyond the ease and safety of transferring a technology. Transit agencies have particular issues that are conducive to automation solutions (e.g., eliminating gaps at boarding platforms or keeping buses centered in narrow lanes or road shoulders). FTA should consider the importance and value of the problem to be addressed when prioritizing research and demonstration projects. Similarly, some technologies may help reduce operational or other costs (e.g., maintenance and repair or insurance liability) more than others and, hence, may be more valuable to transit agencies than applications that may be more readily transferable.

SECTION 1

Introduction

Automation capabilities have advanced rapidly in recent years and have changed the dialogue around all aspects of the surface transportation system. Automation systems for light-duty vehicles and commercial trucks are increasingly available but have yet to appear in transit buses. Transit bus automation could deliver many potential benefits, but transit agencies need additional research and policy guidance to make informed deployment decisions. The U.S. transit industry often is slow to adopt new technologies, services, and business models. Although funding and policy constraints play a role, a full understanding of the approach and appropriate federal leadership and guidance is necessary to support transit agencies as they undertake new operational models.

To support the development and deployment of automated bus transit services, the Federal Transit Administration (FTA) has developed a draft five-year Strategic Transit Automation Research (STAR) Plan that outlines FTA's research agenda on automation technologies.[1] As part of the research outlined in the STAR Plan, this report discusses the state of the industry and feasibility of certain automation technologies for transit buses. It explores potential applications of automation technologies from the light and commercial vehicle areas to bus transit. It examines transferability and delineates gaps of automated technology applications from light-duty vehicles and heavy-duty trucks to transit bus operations and considers opportunities to bridge those gaps.

This report considers automation with respect to the SAE Level 2 Automation and lower.[2] The scope includes human-operated buses with automation technologies such as collision-avoidance, lane centering, and precision docking. The scope does not include driver assistance systems without an automation aspect (e.g., driver warnings and alerts), but does include those with automated actuation (e.g., automatic emergency braking [AEB]).

For the purposes of FTA's Strategic Transit Automation Research Plan, "bus" is defined broadly to consider a range of passenger capacities and both traditional and novel vehicle designs, although for this report, the emphasis is on applicability to transit buses (i.e., a 40-foot bus with front and center doors, low-back seating, and without luggage compartments or restroom facilities for use in frequent-stop, fixed-route service.) The choice of a 40-foot diesel bus as

[1] For more information on this work and access to a draft of the Strategic Transit Automation Research Plan document, visit https://www.transit.dot.gov/automation-research.

[2] For an explanation of SAE Automation Levels, see Appendix A.

the unit of analysis for this report is based on its popularity; of the 4,230 transit buses reported in the National Transit Database (NTD) that were manufactured in 2015, nearly 70% were 40-foot buses and nearly 60% had standard diesel powertrains.[3] Of the buses reported in the NTD, nearly 30% of those produced in 2015 had compressed natural gas (CNG) powertrains, 5% had liquefied petroleum gas (LPG) (a mixture of propane and butane) powertrains, and nearly 5% had hybrid diesel powertrains. Battery electric buses represent approximately 0.5% of the buses produced in 2015.

Section 2 of this report discusses automation requirements and provides a literature review of research projects and demonstrations involving transit bus automation. Section 3 provides background on the foundational actuation systems for non-automated vehicles, including brake systems, steering systems, and powertrain systems. Section 4 compares automation systems for light-duty vehicles, commercial trucks, and transit buses, looking at use cases, sensors, algorithm strategies, system control strategies, and safety. The methodology of assessing the transferability of the identified automation systems is discussed in Section 5, and Section 6 provides in-depth analysis of the transferability of automation systems, including system descriptions, assessment of feasibility, assessment of safety, and a grade (overall rating) of transferability. Section 7 provides concluding remarks, including key takeaways and potential implications for FTA.

[3] Federal Transit Administration, 2018, "2011–2016 Annual Database Revenue Vehicle Inventory," National Transit Database, https://www.transit.dot.gov/ntd. Note that this analysis reflects buses produced in 2015 as reported by public transit agencies for 2016 NTD collection.

SECTION

2

Literature Review

The literature review for this report included a content analysis of previous work to identify functional objectives and examples of pilot studies and demonstrations of automation and driver assistance systems in transit buses.

Functional Objectives

Through the analysis of the previously-conducted literature review on transit automation,[4] the research team identified functional objectives for bus automation, including system performance (i.e., functions and use cases), costs, and safety.

Automated vehicle functions identified include Automatic Emergency Braking (AEB), Lane Keeping/Lane Centering (LK/LC), Steering Assist, Reverse Brake Assist, Docking, Park Assist, Park Out, Full Park Assist, Valet Parking (Bus Yard), Yard Park, Adaptive Cruise Control (ACC) with/without Stop-and-Go, Traffic Jam Assist (TJA) with LK/LC, and Object Detection and Collision Avoidance (ODCA). These functions are at the core of the analysis of this report and are described in detail in Section 6.

Use cases considered include service type (e.g., fixed route, paratransit, on-demand shared ride), road type (e.g., controlled lanes, highways, expressways, urban, rural), road geometry (e.g., straight, curved, hilly, intersections), road conditions (e.g., degraded lane markings, presence of leaf or snow cover), environmental conditions (e.g., lighting, precipitation, temperatures, visibility), special zones (e.g., school or construction), presence of other road users (e.g., vehicles, bicyclists, pedestrians), and transit-specific locations (e.g., bus yard, maintenance facility, bus stops, fueling stations). These conditions and locations were considered in conjunction with the vehicle functions in the analysis included in Section 6.

Cost factors considered included aspects related to engineering development, standardization, and ease of retrofit into existing systems. Development costs on a per-unit basis may be high, considering the low volume of bus applications, although use of existing sensor technologies and control algorithms can help minimize development costs for transit applications. Partnering with system manufacturers with cross applications between transit buses, heavy-duty trucks, and light-duty vehicles may help leverage cost benefits from

[4] See "FTA Strategic Transit Automation Research Plan (2018)," Appendix F: Technology Literature Review and Analysis, https://www.transit.dot.gov/research-innovation/strategic-transit-automation-research-plan.

economies of scale, transfer lessons learned (e.g., for function, safety, packaging, reliability, and robustness), and allow for reuse of system validation techniques. Standardization would establish a minimum set of design requirements for system architecture, interfaces, and components, allowing parts to be sourced from many competitors and reducing storage space required for replacement parts. If minimal design changes are required to adapt the existing foundational systems (e.g., steering and braking) in buses to automation systems, it will eliminate the need to re-design existing in-use systems.

As a safety requirement, automated systems in transit buses must meet the functional safety requirements for all identified use cases. If situations outside the design intent are encountered during bus operation, the system must be able to warn the driver with enough notice that the driver will be able to take control of the vehicle. The system may need to provide the driver with the location of the bus within the lane and the location of objects that may interfere with the bus operation, making it easier for the driver to take control of the bus when required. The system must identify pedestrians and may need to provide their location (relative to the bus) to the driver. The system must avoid collision with pedestrians under all operating conditions. The system must avoid collision with other vehicles or objects under all operating conditions.

System override must be simple and intuitive (e.g., applying a low steering torque or depressing the accelerator or brake pedals). System activation and deactivation must not distract the driver. When reverting to manual driving, the system must use a method (e.g., an escalating driver warning strategy) that ensures that the driver can assume full control of the system when required. The system must prevent malicious cyber intrusions from unauthorized parties and must comply with the state-of-the-art safety standards in the industry.

Domestic and International Examples

As part of the literature review, researchers examined examples of related transit demonstrations and pilot projects, such as the Vehicle Assist and Automation (VAA) project in Oregon, the Driver Assist System (DAS) in Minnesota, and the Active Safety-Collision Warning Pilot in Washington. International examples considered included the Mercedes-Benz Future Bus with CityPilot in the Netherlands and automated bus testing in China and Singapore.

Vehicle Assist and Automation Pilot in Oregon

FTA identified automation as a topic of interest more than a decade ago, leading to the development of the VAA project, which was active between 2009 and 2016 with testing in revenue service between 2013 and 2015.[5] The

[5] For more information, see https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/65486/ftareportno0113-002.pdf.

California Department of Transportation and California Partners for Advanced Transportation Technology (PATH) launched a pilot program to demonstrate the VAA system on transit buses. The system used magnets embedded in the roadway to guide vehicles. Deployed applications of VAA included lane keeping and precision docking at bus rapid transit (BRT) stops. The system was deployed in Eugene, Oregon, on a Lane Transit District 60-foot articulated bus. The on-board equipment included two magnetometer sensor bars (one in front and one under the middle door), a steering actuator, a computer controller, and a human-machine interface (HMI) display. Magnets were installed along 3 miles of a 23-mile BRT line.

Driver Assist System (DAS) Pilot in Minnesota

The Minnesota Valley Transit Authority (MVTA) received $4.2 million from FTA to develop a DAS, a lane guidance system for bus-on-shoulder operations along Cedar Avenue (Trunk Highway 77). The DAS system uses a differential global positioning system (DGPS) and lidar to enable a bus to travel on typically unused shoulder right-of-way, bypassing congestion during peak rush hours.[6] When highway speeds on general-purpose lanes drop below 35 mph, MVTA buses are authorized to use the shoulder along a 22-mile stretch between Apple Valley and Minneapolis. The DGPS aids with triangulation and positioning, while the lidar system scans the environment for objects to avoid collisions. If an object is detected, the system warns the driver through visual (head-up display) and haptic (seat vibration and steering wheel resistance) feedback. MVTA hopes to enhance driver confidence in operating buses on shoulders, particularly during bad weather. Secondary goals include reduced travel times, increased reliability, safety, and customer satisfaction.[7] In 2015, FTA awarded MVTA $1.79 million to upgrade the system, which is being demonstrated in revenue service. An evaluation of the system will be completed in summer 2018.

Active Safety-Collision Warning Pilot in Washington

In 2016, eight transit agencies across the state of Washington participated in a pilot project to test and analyze the Mobileye Shield+ collision avoidance system on buses. Participating transit agencies included Metro Transit, Community Transit, Pierce Transit, Intercity Transit, C-Tran, Kitsap, Ben Franklin, and Spokane Transit. The Mobileye Shield+ system uses bus-mounted cameras to identify and alert bus drivers when other road users, including pedestrians, cyclists, and other vehicles, are dangerously close to the bus. The system was installed on 38 buses statewide. Funding for the project was provided by the

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[6] For more information, see http://www.its.umn.edu/Publications/Sensor/2011/01/buses.html and https://www.mts.com/en/about/news/MTS_2014140.

[7] For more information, see https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_Report_No._0010.pdf.

Washington State Transit Insurance Pool, Alliant Insurance Services, Government Entities Mutual, Pacific Northwest Transportation Consortium, and Munich Re America. The pilot program evaluation was funded by the Transportation Research Board (TRB) with an Innovation Deserving Exploratory Analysis (IDEA) grant.

In January 2017, FTA awarded Pierce Transit a $1.66 million Safety Research and Demonstration (SRD) grant to fund a $2.9 million project to implement and research collision warning and automated braking technology in buses.[8] The Mobileye Shield+ warning system will be installed on 176 buses, and an AEB system will be installed on up to 30 buses. The Virginia Tech Transportation Institute is assisting with the evaluation of impacts on the AEB system on passengers.

Mercedes-Benz Future Bus with CityPilot Demonstration in the Netherlands

In July 2016, the Mercedes-Benz Future Bus with CityPilot was demonstrated in the Netherlands, running along the 12-mile BRT route between Schiphol airport and the town of Haarlem.[9] The bus uses a Level 2 system (operator in the driver seat and ready to reassume control) with automated lane-keeping, acceleration, and braking. The bus also reacts to traffic lights, uses precision docking at stops, and automatically opens the doors for boarding and alighting passengers.

Yutong Bus Project Demonstration in China

In September 2015, Chinese bus manufacturer Yutong conducted a demonstration of its automation system on a 20-mile stretch of public roads through an urban environment from Zhengzhou to Kaifeng.[10] The trip involved automated lane changes, overtaking other vehicles, and responding traffic lights (26 in total) without human intervention. The bus was equipped with a lidar unit and cameras on each side.

[8] For more information, see https://www.transit.dot.gov/research-innovation/fiscal-year-2016-srd-program-grant-selections.

[9] For more information, see https://www.daimler.com/innovation/autonomous-driving/future-bus.html and http://media.daimler.com/marsMediaSite/en/instance/ko/Mercedes-Benz-Future-Bus-safe-ecological-comfortable---semi-automated-driving-with-the-CityPilot.xhtml?oid=12776483.

[10] For more information, see http://en.yutong.com/pressmedia/yutongnews/2015/2015IBKCFbteUf.html.

Automated Bus Testing in Singapore

Singapore's Land Transport Authority (LTA) and Nanyang Technological University (NTU) signed an agreement in October 2016 to equip two hybrid electric buses with sensors and other capabilities to enable automated driving.[11] The roads between NTU and CleanTech Park (located in the Jurong Innovation District) were identified as potential test routes for the trial. In January 2018, Volvo announced that it had signed an agreement with NTU to provide automated electric buses to begin testing in Singapore starting in early 2019.[12]

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[11] For more information, see https://www.lta.gov.sg/apps/news/page.aspx?c=2&id=2bc42aac-6b74-4e58-bca3-e2e819c66d20.

[12] For more information, see http://www.volvobuses.com/en-en/news/2018/jan/volvo-ntu-to-trial-autonomous-electric-buses-in-singapore.html.

SECTION 3

Foundational Vehicle Actuation Systems

This section describes the foundational actuation systems for vehicles, including braking, steering, and powertrain systems. Within each system type, various alternatives are described, along with discussion on what types of vehicles use the system and the degree to which electronic controllers are used for the system.

Brake Systems

The function of a vehicle brake system is to reduce vehicle speed, stop the vehicle, or hold the vehicle stationary if already stopped.[13] Drivers apply traditional brake systems with a foot pedal, and power brake systems supplement driver input forces to slow or stop the vehicle. Additionally, drivers may apply a parking brake with hand or foot control. There are two common engineering architectures of power brake systems for large vehicles – hydraulic brakes and pneumatic (air) brakes. These systems generate supplemental braking forces mechanically. Although not common today, vehicles can also potentially use electric brakes.

Hydraulic Brake Systems

Hydraulic brakes are often used on medium/light-duty vehicles and light-duty vehicles. Hydraulic brakes use brake fluid to transfer pressure from the controlling mechanism to the braking mechanism. This pressure is generally built up from both the driver's manual power and an assisted power source (commonly derived from vacuum pressures in the intake manifold of the internal combustion engine or from a vacuum pump). In a hydraulic brake system, a hydraulic pump builds up sufficient pre-pressure. Solenoid valves receive commands from the electronic control unit (ECU), which regulates the hydraulic pressure in the braking circuits.

A common arrangement of hydraulic brake systems includes the following components:

- Brake pedal
- Pushrod (actuating rod)
- Master cylinder assembly

[13] Heißing, B., and Ersoy, M., 2010, *Chassis Handbook: Fundamentals, Driving Dynamics, Components, Mechatronics, Perspectives*, Springer Science & Business Media.

- Hydraulic lines (brake lines)
- Brake caliper assemblies (pistons, brake pads, brake discs, and brake drums)

Because the system is filled with brake fluid, which is an incompressible liquid, pressure exerted on one end of the system is transferred to the other end of the system. For example, depressing the brake pedal engages the pushrod, which pushes on the piston in the master cylinder, resulting in fluid from the brake fluid reservoir in the master cylinder being pushed through the system to the brake caliper assemblies. The fluid then exerts pressure on the brake pads, causing friction between the pads and the rotor, resulting in braking torque and slowing the vehicle. Drum brakes function similarly – fluid pushes brake shoes against the inner surface of a rotating cylinder, causing friction, resulting in braking torque and slowing the vehicle. Releasing the brake pedal creates suction that removes the pressure on the brake caliper assemblies, allowing the brake pads/shoes to return to their initial positions and removing brake torque.

Traditionally, vehicles used two disk brakes on the front two wheels and a drum brake in the rear, although disc brakes on all four wheels has become an increasingly popular configuration for light-duty vehicles. Hydraulic brake systems are considered closed systems, as the fluid is not lost or consumed in operation, with the exception of a fluid leak, which necessitates repairs.

Electro-hydraulic brake systems use electronic controllers to send signals to an actuator such as an electric motor, which can act on the master cylinder without physical force on the brake pedal as an input. The addition of such a system allows electronic control of hydraulic brake systems. Although not common in vehicles currently, suppliers are working to provide this electro-hydraulic brake systems technology to automakers for heavier light-duty trucks and to heavy-duty truck manufacturers for Class 8 commercial trucks.[14] Current vehicles often include conventional vacuum boosters, which work on the master cylinder plunger to add force when a driver presses the brake pedal using a vacuum provided by the engine or by a vacuum pump.

Pneumatic Brake Systems

Pneumatic brake systems, also known as air brakes or compressed air brake systems, use compressed air pressing on a piston to apply pressure to the brake pad, as requested by the driver. A common arrangement of pneumatic brakes includes the following components:

- Control pedal (foot valve)
- Compressor

[14] For more information, see http://autoweek.com/article/technology/electric-brakes-are-coming-to-your-car.

- Air storage tanks
- Pneumatic lines
- Release valves
- Service brakes
- Parking brakes

The vehicle's air compressor draws in filtered air from outside the vehicle and pumps it into high-pressure reservoirs (storage tanks). The pressure from this air is used to apply and release the vehicles brakes.

Parking brakes are designed to be applied by spring pressure and released with the application of pneumatic pressure. As a result, if there is a leak and the vehicle loses pneumatic pressure, the parking brake will be applied. Drivers use service brakes to slow or stop the vehicle when it is in operation. For the service brakes to be applied, the driver pushes the brake pedal, which routes pressurized air to the brake chamber, engaging the brake, which may be a drum brake or a disc brake.

Air brakes are the most common choice for a heavy-duty combination vehicle (i.e., a semi-truck) and are also the most common choice for transit buses and motor coaches. Reasons for their popularity include the limitless supply of operating fluid (air), easy connection between tractor and trailer, and insensitivity to altitude.[15] In addition, because the parking brake will be applied if air pressure drops too low, air brakes have the built-in safety feature of applying the parking brake and stopping the vehicle in the event of a leak or other system failure resulting in loss of air pressure.

Contemporary commercial vehicle air brake systems are electrified—the pumps are electric, but there is no electronic control mechanism controlling brake pressure in the chamber. An air compressor is the source of energy for the air brake system. Actuators convert the air pressure being applied into a mechanical push-rod force acting on the foundation brakes, wheel speed sensors gather wheel speed information, and an ECU coordinates all the components to generate the desired braking torque.

Steering Systems

The steering mechanism converts the driver's rotational input at the steering wheel into a change in the steering angle of the vehicle's wheels. Modern vehicles are typically equipped with power-assisted steering systems, in which steering force is produced by both the driver and an energy source. In some power steering systems, the system is capable of steering wheels with an electronic

[15] Duffy, O. C., and Wright, G., 2016, *Fundamentals of Medium/Heavy Duty Commercial Vehicle Systems*, Jones & Bartlett Learning.

signal input and a power source, but in many, the steering system still requires physical input from the driver. Most steering systems use electric power steering (EPS) or hydraulic power steering (HPS). To provide some of the characteristics of EPS on HPS systems, some companies have developed electro-hydraulic power steering systems.

Electric Power Steering Systems

Most light-duty vehicles use an EPS system, which employs an electric motor to provide steering assistance. The motor connects to either the steering gear or the steering column and provides varying amounts of assistance in turning the wheel. Sensors are used to detect the position of the steering wheel and torque being applied. An electronic controller module uses that information to calculate the assistive torque need and controls the motor to provide that assistance. EPS differs from "steer-by-wire" systems in that the steering system retains a mechanical linkage between the steering wheel and the steering gear. Currently, EPS is used to make steering easier; if the system fails, the driver would need to exert greater effort to steer the vehicle. EPS may be useful for automation systems, as the electronic controller and motor can be used to apply torque to the steering wheel to electronically control steering.

Hydraulic Power Steering Systems

Before the advent of EPS, light-duty vehicles used HPS systems, although currently, these systems are still used in medium- and heavy-duty vehicles such as semi-trucks and transit buses, because these heavier vehicles would require a much larger motor to enable an EPS system, and cost constraints or other design limitations preclude the possibility of using EPS systems in those vehicles. HPS systems work using hydraulic pressure to augment the force applied to the steering wheel and apply that force to turning the vehicle's front wheels. This is achieved by connecting the steering wheel to a valve that allows hydraulic fluid to move from one side of a hydraulic piston to the other. Pressure from removing liquid on one side and adding it to the other side causes the piston to be pushed to one side, moving the tie rod along with it. The hydraulic fluid is stored in a reservoir and is pressurized using a belt-driven pump. Although turning the steering wheel provides some of the torque needed to steer, the fluid pressure does the majority of the work, significantly reducing the effort needed to steer. Because HPS systems do not use electronic controllers, they cannot be automated as easily as EPS systems.

Electro-Hydraulic Power Steering Systems

As noted, heavy-duty vehicles generally cannot use EPS systems because the motors and gears required would be large and expensive, but hydraulic steering systems can be automated by adding additional equipment that can be electronically-controlled. Solutions have been proposed by companies such as

Bosch, Nexteer, Tedrive, Volvo, and ZF TRW. These electro-hydraulic power steering systems range from adding a torque overlay on the steering column or on the large hydraulic gear to electronically manipulating the rotary valve with a motor or electro-magnetic actuator. In the event of a hydraulic fluid leak, steering wheel-based systems and systems that act on the rotary valve will no longer function, but a system attached to the large hydraulic steering gear will still provide some assistance to the driver. Because these systems allow HPS systems to be controlled electronically, they enable similar functionality as EPS systems for automation. However, electro-hydraulic power steering systems will not provide the same fuel economy benefits as EPS, as the system is still dependent on a belt-driven pump for the hydraulic fluid.

Powertrain Systems

The powertrain system contains all the components that propel the vehicle, including the engine, transmission, drive shafts, differentials, and drive wheels. In traditional vehicle configurations, a driver demands torque from the engine by pressing an accelerator pedal. In older systems, the accelerator pedal is physically connected to a throttle body. On new vehicles, powertrain systems often use electronic signals generated from the accelerator position as an input to powertrain control.

Diesel Systems

For buses and commercial trucks, diesel engines are the primary choice due to low maintenance costs, high torque output, and high reliability. Due to the digital electronic control system of modern diesel engines, computer inputs for automated driving systems may be used to control the powertrain. Specifically, the engine control module (ECM) receives the torque/speed request from a controller and achieves the desired state with the help of actuators and sensors. The control of a modern diesel engine is dependent on three parts—air control, fuel control, and exhaust gas recirculation. Air and fuel controls provide the correct quantity of air and fuel for efficient combustion to the proper cylinder. Control of the diesel engine is achieved by coordination between sensors (e.g., engine position and temperature), the ECM, and actuators (e.g., fuel injector, compressor, and throttle). Given the torque/speed requirement, the ECM gathers the information from several sensors and determines the optimal variables, such as air-fuel ratio, then passes them to the actuators. The feedback control loop formed by the actuators and their sensors ensure the actuators behave as the ECM requested.

Hybrid-Electric Systems

The architecture of a hybrid electric vehicle (HEV) provides inherent automation capability because it is already quasi-automated for efficient powertrain management. Both the engine and the electric motor provide power to the vehicle under the management of an ECM. The transmission is usually an automated mechanical transmission or an electronically-controlled transmission, which couples the torque from the two sources (engine and electric motor) and supplies it to the driveline. Due to several features of the electric motor, advanced automated technologies such as regenerative braking, electric motor drive/assist, and engine start/stop can be enabled.[16] Hybrid diesel buses have electric powertrain components and may have electronically-actuated systems, but they are a more mature technology than are battery electric buses. The share of the transit bus fleet that is composed of hybrid diesel buses is approximately 10% and growing, with more than half of current hybrid diesel models in service being produced since 2010.[17] Although market share varies by year, in 2015, three manufacturers provided more than 70% of all new buses in the United States—Gillig Corporation (44%), New Flyer (24%),[18] and ElDorado National (5%).[19] All three companies produce hybrid diesel buses.

Electric Systems

As with hybrid electric bus architectures, the architecture of electric buses is conducive to automation given the existing sensors, controllers, and actuators needed to support an electric bus. For instance, electric buses use electronically-actuated regenerative braking in addition to other brake systems. It may be easier to enable some automated braking in electric buses than in diesel buses due to the existence of electronically-actuated functions and the communications architecture that supports them.

In the past few years, battery electric buses have become more available, although they represent less than 0.25% of the current bus fleet.[20] Gillig and New Flyer have battery electric bus models. New entrants, such as BYD, Ebus, and Proterra, specifically focus on producing electric buses and have taken the lead in providing them to transit agencies. Smaller low-speed automated shuttles, such as those being produced by EasyMile, Navya, and Local Motors, are also typically electric vehicles.

[16] For more information, see Appendix F: Technology Literature Review and Analysis, Strategic Transit Automation Research Plan document.

[17] *Ibid*. Note that the values used in this analysis reflect buses still in operation as reported by public transit agencies for the 2016 NTD collection.

[18] Including vehicles produced by New Flyer of America, Flyer Industries Ltd., and North American Bus Industries Inc., which was acquired by New Flyer in 2013.

[19] *Ibid*. Note that this market share analysis reflects buses produced in 2015 as reported in the 2016 Annual Database Revenue Vehicle Inventory in NTD.

[20] *Ibid*. Note that the values used in this analysis reflect buses still in operation as reported by public transit agencies for the 2016 NTD collection.

SECTION

4

Comparison of Automation Systems for Light-Duty Vehicles, Commercial Trucks, and Transit Buses

This section describes the general use cases of transit bus automation demonstrations and compares various strategies used by transit bus demonstrations to those used by light-duty vehicles and commercial trucks.[21] These strategies are classified into sensor strategies, algorithm strategies, system control strategies, and safety strategies.

Use Cases

Automated transit bus demonstrations have used predefined routes and lanes with known geometries and limited exposure to other vehicles. These environments include bus-only road shoulders, dedicated bus lanes, high-occupancy vehicle (HOV) lanes, and transit stations with boarding platforms. Recent demonstration efforts may be more capable and use technologies that will be necessary to operate on general routes on which the bus will be operating in mixed traffic. These technologies include better detection of pedestrians, bicyclists, vehicles, and other obstacles, as well as the ability to navigate a wider range of slowly-changing road surface conditions (e.g., crowns, potholes, speed bumps) and road articles (e.g., signs and trees). Light-duty vehicle and commercial truck applications target non-defined routes in general, although specific applications may use specific route types (e.g., limited access highways).

Sensor Strategies

Bus demonstrations have relied on systems with predefined fixed points, either physically embedded in the infrastructure (e.g., magnets or radio-frequency identification [RFID] tags) or marked digitally with global positioning systems (GPS)[22] and geospatial maps. These buses have used sensors such as lidar, radar,

[21] This section considers commercially-available systems for light-duty vehicles and commercial trucks and compares their strategies with those of the prototype bus applications discussed in Section 3, including transit buses and larger bus rapid transit (BRT) vehicles. The literature review did not identify Level 0–2 Automation examples for smaller cutaway vehicles/paratransit buses, so they were not included in this discussion.

[22] These systems may rely on expensive DGPS units, which are enhanced versions of GPS that provide improved locational accuracy via fixed ground-based stations. The additional stations augment signals from satellites to provide locations within several centimeters of accuracy, compared to standard GPS, which is only accurate within several meters.

or camera units for object detection. Light-duty vehicle and commercial truck applications rely primarily on radar or camera systems for both object detection and mapping and localization, although lidar is popular in prototype vehicles and may be found in some commercially-available systems. As with buses, these systems may also use GPS, although, typically, GPS is not required. Ultrasonic sensors are often used for object detection at low speeds (e.g., parking).

Algorithm Strategies

In the bus demonstration systems reviewed, algorithms have been built around the pre-determined mapping of routes, and sensors have been used to establish the location of a bus on a route. In these systems, the position of the bus is used for steering assistance, and object detection is used to enable automated braking. In more recent demonstration efforts, sensors have been used to detect lane markings, pedestrians, and vehicles, and fusion algorithms have been used to control steering, powertrain, and braking as well as to enable object detection.

Steering limitations for some of these demonstration efforts include that the algorithm strategies are limited to the pre-defined routes, technologies that are susceptible to large positioning errors (due to physical inaccuracies of road sensors), lack of robustness of road sensors against the environmental elements and route changes (e.g., due to maintenance) have a large effect on the system. Collision avoidance assistance largely has been limited to warning without automatic mitigation, although some bus automation efforts are deploying automatic emergency brake systems. Some of the most recent bus demonstration efforts are similar in performance potential to light-duty vehicle applications.

In light-duty vehicle and commercial truck applications, sensors are used to establish the instantaneous position of the vehicle in the lane based on lane markings or, in some cases, other landmarks in the absence of lane markings for short durations. GPS and maps may be used as redundant inputs, but they are not necessary. Object detection and classification are used for braking applications. Many steering assistance features are limited in that the algorithm strategies require the presence of lane markings.

System Control Strategies

In the bus demonstration systems reviewed, system control strategies focused on the use of retrofit equipment. For instance, automated steering has been achieved using an actuator (e.g., electric motor) added on the steering column or on the hydraulic steering system under the hood as a torque overlay. The steering assist torque is governed by the bus location data. Collision avoidance is accomplished by warnings sent to the driver. Some projects seek to test automatic emergency braking in buses, but this has yet to be demonstrated. The most recent bus demonstration efforts are not clear on the control strategies used, but manufacturer publications imply that a control strategy similar to those used in light-duty vehicle application may be used.

Bus demonstration systems are limited, in that there is no feedback control of the torque overlay from the lane markings, and inaccuracies in location data will result in inaccuracies in the steering torque overlay. Road construction can easily render the system non-usable if it affects embedded magnets or RFID tags, and systems that rely on GPS may need to be remapped if construction changes the location of a lane.

In light-duty vehicle and commercial truck applications, a torque overlay request from the lane assist control module is sent to the steering system controller, and feedback control from the constant monitoring of lane markings is used to adjust the torque overlay. Collision avoidance is accomplished by providing steering, powertrain, and/or braking requests to the vehicle systems. No limitations have been identified for the system control strategies used in automation systems for light-duty vehicle and commercial truck applications.

Safety Strategies

Bus demonstration systems rely on redundancy techniques. One example is using DGPS as an independent source of measurement and location referencing and having two controller computers, each with its own power supply, perform sensor fusion, lateral control, fault detection, and management. Full information on safety strategies is not available for many of the more recent bus demonstration efforts. Light-duty vehicle and commercial truck applications rely on a system safety approach guided by state-of-the-art standards such as ISO 26262. These vehicles use many safety techniques such as redundancy. Often, several levels of redundancy are used, with the level of complexity depending on the severity or criticality of the potential failure mode.

SECTION 5

Automation System Evaluation Approach

The objective of this report is to assess the transferability of automation systems from light-duty vehicles and heavy truck applications to transit bus applications. The approach to address this objective was to investigate current SAE Level 2 and lower automation systems as well as literature on transit bus automation pilots and demonstrations. The strategy consisted of three primary elements:

- Catalog the most relevant automation systems in light-duty vehicles and heavy truck applications.
- Select potential automation systems for transit bus applications based on bus use cases and the potential benefits of the system to bus operators.
- Identify the technological challenges to the transferability of the selected automation systems to transit bus applications.

Challenges considered include cost, lessons learned from national and international bus automation projects, safety implications of the systems as they would likely be implemented on transit buses, and the technical feasibility of the transfer based on an understanding of the state-of-the-art of foundational systems (e.g., steering, braking, and powertrain). The analysis of feasibility considered the technology modifications that might be required to support the automation systems, particularly any sensor limitations that may be problematic in a transit bus implementation.

Particular attention was paid to any cascading impacts on interfacing systems (e.g., communication system, park brake system, wheel speed measurement sub-system). For example, the steering system of a transit bus is typically hydraulic, with little or no electronic control. If the system were changed to electro-hydraulic, sensors for the steering torque and steering wheel angle would be added. The new sensors would dictate changes to the wiring system and the mechanical (packing) configuration. The communication system would have to accommodate signals from the sensors to the motor controller and the steering system controller. A specialized system for hardwired signals could be inefficient and expensive. Thus, when an automation system is transferred to a transit bus, the safety design of the communication system of the bus will need to be considered. In particular, signals quality could directly affect vehicle safety. Therefore, protocols would be needed to check for correct signal transmission and reception of the signals as well as signal plausibility and rationality.

Each application includes an overall summary assessment (grade) that considers both the feasibility and the safety of transferring the automation system to bus applications.

Automation Systems

The research into Automation Level 1 and 2 systems identified light-duty vehicle and heavy truck automation systems that are either currently in production or expected to be in production soon. Table 5-1 lists these systems and indicates whether or not they are presently in large-scale production.

Potential Automation Systems for Bus Applications

Automation systems are typically tailored to support important use cases of the vehicle in question. The use cases consider environmental, infrastructure, and operational elements. Table 5-2 lists use cases that were used to identify automation systems included in this study. Each use case was assessed for relevance to the operation of the specific vehicles.

Based on the evaluation of these use cases, transit buses would benefit from automation systems that improve safety, improve the operation of the bus during passenger pick-up and drop-off, or facilitate the handling of the bus in the bus yard/barn and maintenance facility.

Transit bus safety can be improved by providing assistance to the driver in maintaining the bus in the intended lane and avoiding collision with other vehicles and (more importantly) pedestrians. Automation systems that provide steering and braking assist under most operating conditions should improve bus safety.

Automation systems that improve the entry and exit of the passengers into the bus include those that provide assistance to the driver for improved docking at bus stops regardless of the complexity of the road geometry. These systems can help optimize the distance between the bus entrance and the passenger pick-up spot.

Park assist automation systems might provide assistance in parking the bus in different orientations (e.g., perpendicular or parallel) and getting the bus out of the parking spot. Some automation systems can provide assistance in maneuvering the bus safely through pre-determined paths to a parking location.

Based on the above strategy, a subset of available automation systems was selected for detailed analysis of transferability.

Table 5-1 *Level 1 and Level 2 Automation Systems*

System	Category	Description	Application	In Production?	Comment
Automatic Emergency Braking (AEB)	Braking	Provides automatic braking in case of imminent collision	Light-duty vehicles, commercial trucks	Yes	Most system configurations include warning
Lane Keeping/ Lane Centering (LK/LC)	Steering	Provides assist to prevent unintended lane departure or to keep vehicle in center of lane	Light-duty vehicles, commercial trucks	Yes	Heavy truck manufacturers working toward adopting this system
Steering Assist	Steering	Steers system within lane with driver hands off steering wheel	Light-duty vehicles	Yes	Not under consideration for heavy trucks at time of this report
Reverse Brake Assist	Braking	Detects objects or pedestrians and brakes automatically during backing maneuvers	Light-duty vehicles	Yes	Not under consideration for heavy trucks at time of this report
Docking	Steering	Steers vehicle into stop position (e.g., at a curb)	None	No	Similar to parking assist feature in light-duty vehicles
Park Assist	Steering	Steers vehicle into parking slot selected by driver	Light-duty vehicles	Yes	Not under consideration for heavy trucks at time of this report
Park Out	Steering	Steers vehicle out of parking slot	Light-duty vehicles	Yes	Not under consideration for heavy trucks at time of this report
Full Park Assist	Steering, Braking, and Powertrain	Parks vehicle in slot selected by driver	Light-duty vehicles	Yes	Not under consideration for heavy trucks at time of this report
Valet Parking (Bus Yard)	Steering, Braking, and Powertrain	Parks vehicle in confined slot with driver outside of vehicle	Light-duty vehicles	Yes	Not under consideration for heavy trucks at time of this report
Yard Park	Steering	Maneuvers vehicles to pre-determined location in specified area	Light-duty vehicles	No	Under development for light-duty vehicles
Adaptive Cruise Control (ACC) with/without Stop- and-Go	Braking and Powertrain	Controls vehicle distance to other vehicles and controls speed down to 0 km/h	Light-duty vehicles, commercial trucks	Yes	May be considered combination of two automation systems, Adaptive Cruise Control and Stop-and-Go
Traffic Jam Assist (TJA) with Lane Keeping/Lane Centering (LK/LC)	Steering, Braking, and Powertrain	Controls vehicle distance to other vehicles in stop-and-go traffic with steering assist	Light-duty vehicles	Yes	May be considered combination of two automation systems, Traffic Jam Assist with Stop-and-Go and LK/LC
Object Detection and Collision Avoidance (ODCA)	HMI (in standalone warning system, driver actuates steering, braking, and powertrain)	Provides assistance to driver (via HMI) or higher level automation system to detect objects and avoid collisions	Light-duty vehicles, commercial trucks	Yes	May provide input to other systems; several transit agencies piloting this system in transit buses

Table 5-2 *Relevance of Use Cases to Vehicles under Consideration*

Use Case	Light-duty Vehicle	Heavy Truck	Transit Bus
Driving in heavy rain/snow/fog/dust	High	High	High
Driving into a flooded road/shallow water	High	High	High
Driving in sun-glare effect conditions	High	High	High
Exiting a tunnel into a high ambient light condition (glare or >100,000 Lux) (Not a common use case)	Medium	Medium	Medium
Entering a tunnel from a high ambient light condition (>100,000 Lux) (Not a common use case)	Medium	Medium	Medium
Driving in a long tunnel *(Not a common use case)*	Medium	Medium	Medium
Driving on roads with surface discontinuities (potholes and bumps)	High	High	High
Driving on roads with faded lane markers or tar strips	High	High	High
Driving on roads with old lane markers and new lane markers painted offset	Medium	Medium	Medium
Driving on roads with lanes separated by Botts' Dots*	High	High	High
Driving on roads with lanes partially covered (debris, leaves, and snow)	High	High	High
Driving on roads with small lanes for bicyclists	High	High	High
Driving into a construction zone with barrels and cones redirecting traffic	High	Medium	High
Driving on roads with flares used by police and emergency crews to temporarily close lanes	Low	Low	Low
Driving on roads with large debris/objects moving (objects) on road (e.g., people and animals)	High	Low	High
Driving on roads with flying debris (e.g., items falling off of truck with different sizes)	Low	Low	Low
Driving on road with stalled vehicle partially in lane ahead of it	Low	Low	Low
Another vehicle partially invades vehicle's lane while driving	Medium	Medium	Medium
Another vehicle traveling at high speed passes while vehicle trying to change lanes	Medium	Medium	Medium
Driving with vehicles (motorcycles, bicycles) doing lane-splitting	Low	Low	Low
Driving behind traffic on curvy roads	High	High	High
Different objects around and ahead of vehicle	High	High	High
Object(s) <1m from vehicle	High	Medium	High
Object(s) >3m from vehicle	High	High	High
Driving on lane that splits into two lanes	Low	Low	Low
Diverging off ramp from lane	High	High	Low
Driving through toll booth with drive-through	Medium	Medium	Low
Driving behind chrome trailer that reflects traffic images	Low	Low	Low
Vehicle with trailer crossing road horizontally in front of vehicle	Medium	Medium	Medium
Docking into curved stop location	Low	Low	High
Driving toward stop with heavy pedestrian presence – pedestrians: small, big, slow, fast, on bicycle, with shopping cart, with stroller, with grocery bags-different weather conditions/day/night	Low	Low	High
Pulling out of parking space moving in reverse through barn	Low	Low	High
Pulling out of parking space moving forward through barn	Low	Low	High
Pulling out of parking space moving in reverse in lot	High	High	High
Pulling out of parking space moving forward in lot	High	High	High
Pulling into parking space moving in reverse in barn	Low	Low	High
Pulling into parking space moving forward in barn	Low	Low	High
Pulling into parking space moving in reverse in lot	High	High	High

Use Case	Light-duty Vehicle	Heavy Truck	Transit Bus
Pulling into parking space moving in reverse in lot with link fence behind or to side	Low	Medium	High
Pulling into parking space moving forward in lot	High	High	High
Pulling into parking space moving forward in a lot with link fence behind or to side	Low	Medium	High
Navigating through yard to exit	Low	Medium	High
Navigating through barn to exit	Low	Low	High
Stopping for passenger – curb-cut	Low	N/A	High
Stopping for passenger – dedicated curbside	Low	N/A	High
Stopping for passenger– roadside with parking	Low	N/A	High
Stopping for passenger – roadside without parking	Low	N/A	High
Stopping for passenger – loading passengers with mobility devices (ramp-equipped)	N/A	N/A	High
Stopping for passenger – loading passengers with mobility devices (cassette lift-equipped)	N/A	N/A	High
Stopping for passenger – loading passengers with mobility devices (step lift-equipped)	N/A	N/A	High
Stopping for passenger– loading passengers with mobility devices (under-vehicle lift-equipped)	N/A	N/A	High
Stopping for passenger – securing passengers with mobility devices	Low	N/A	High
Stopping for passenger – flagged service	Low	N/A	High
Driving in stop and go heavy traffic - different weather conditions/day/night	High	High	High

* Botts' dots, or "raised pavement markers," are small bumps lining the centerline or edgeline of a roadway, often used on curves where vehicles have a tendency to deviate outside of the proper lane, risking collision. Raised reflectors improve the nighttime visibility of the roadway edges.

Identification of the Technological Barriers to Transferability

In order to understand the technological gaps that might limit the transferability of the automation systems from light-duty vehicles and heavy trucks to buses, the following technical issues were assessed:

- *Light-duty vehicle foundational systems architectures and controls* – This includes steering system, brake system, and powertrain. System architectural elements were researched to understand the interfaces between the foundational systems and the automation system that are required for the safe and robust operation of the automation system.
- *Heavy truck foundational systems architecture and controls* – Heavy truck applications are closer to buses than light-duty vehicles, and the foundational systems technological gaps maybe smaller than those between light-duty vehicles and buses. The automation system transferability strategy between light-duty vehicles and buses may benefit from the driver assistance technologies used in heavy trucks.
- *Transit bus foundational systems architectures and controls* – The technological differences between these systems and those of light-duty vehicles and heavy trucks were identified. The assessment also concentrated on determining the minimum changes necessary to the components of the transit bus systems

or sub-systems to implement the automation system. This approach was driven by the fact that present bus system architectures have been optimized for safety and life cycle operational cost over many years. Thus, drastic design changes may lead to prohibitive development cost for manufacturers or implementation and maintenance cost for operators. When feasible, incremental system changes would more likely hasten transferability of the automation systems.

- *Automation systems impact on other light-duty vehicle systems* – The systems to be evaluated include the HMI, communication system, parking brake system, and speed monitoring system, among others.
- *Sensors required to support the automation systems and their limitations* – This assessment determines if changes to the automation system control and sensor fusion algorithms would be required in use cases unique to transit buses. For example, light-duty vehicles usually avoid regions with heavy pedestrian presence, whereas transit buses intentionally move toward pedestrian-heavy areas. Therefore, transferring an existing automation control system from a light-duty vehicle to a transit bus may require a modified sensor suite and modified control algorithms. The additional requirements on sensors for transit bus use cases and the possibility that limitations in legacy sensor technology will not meet those requirements could complicate direct transference of these automation systems. The sensor technology gaps may drive specific changes in the automation system control or sensor fusion algorithms.
- *Functional safety relevance of automation systems* – The safety of light-duty vehicle systems has been the focus of the industry in light of the expanded use of electrical and electronic controls. Most, if not all, systems safety design is based on the state-of-the-art standard for functional safety (ISO 26262) published in 2011 that provides a process for classifying the vehicle systems safety levels. The Automotive Safety Integrity Levels (ASIL) range from A (least critical) to D (most critical). The degree of system or component design and validation rigor increases with ASIL rating. Although the standard's current scope is limited to light-duty vehicles, a revision currently in process will apply to heavy trucks and buses as well. The new version is expected to be published in 2018.

The functional safety assessment component of this transferability study sought to identify additional important technological gaps that might be introduced by the transfer. System functional safety encompasses the system's hardware, software, design, testing, and production. The approach extends to the interfaces of the system to other systems. For example, for a steering-based automation system, a functional safety assessment should consider the automation system, the steering system, and all interfacing systems that support the automation system. Those systems may include the communications system and the HMI.

A preliminary functional safety assessment of each automation systems safety level (ASIL) was carried out that took into account the bus application's use cases and other relevant factors, such as the expertise of the driver. The impact of the safety level on the bus foundational and interfacing systems was assessed and the technology gaps were identified.

- *Cost of bridging technological gaps to enable automation systems transfer* – A high-level qualitative assessment of the cost for bridging the technology gaps was carried out that considered:
  - impact on the bus foundational systems and interfacing systems in light of the technology that is currently most predominant in industry
  - state of the technology of these systems in heavy truck applications and the possibility of transferring this technology to bus applications
  - impact of functional safety (i.e., if a bus use case results in a higher ASIL, there may be additional design and production costs)
- *Lessons learned from bus automation demonstration projects* – Bus automation projects conducted nationally and internationally were reviewed. The strategies considered and the results reported are important data for assessing the technological steps necessary to successfully transfer the automation systems to transit buses.

Safety Classification

An output of the functional safety assessment is the safety classification, which applies to each of the 13 automation systems considered herein. In this context, the safety classification indicates the level of risk associated with a system failure in terms of exposure, controllability, and severity. Exposure is the likelihood of a system failure occurring, controllability is the ability of the driver to manage the situation in the event of a system failure, and severity considers the degree of potential consequences (i.e., injuries and fatalities). These three factors interact with each other to create lower (or less risky) safety classifications (e.g., low exposure, high controllability, low severity) and higher (or more risky) safety classifications (high exposure, low controllability, high severity). Higher safety classification implies a greater level of risk associated with the system. Therefore, the higher the safety classification, the more is required to be implemented in terms of safety design.

Grade

The overall summary assessment uses a color coding of green, yellow, or red to indicate the level of the complexity associated with the transferability of the automation system to bus application, as follows:

- **Green** – Minor modifications to foundational bus systems may be required. Upgrades to the system(s) are easily transferable from heavy-duty truck or light-duty vehicle applications. The overall classification for safety issues or concerns is low. The required modifications are simple in terms of design, manufacturing, and cost.
- **Yellow** – Major modifications to one or more foundational bus systems may be required. Upgrades are transferable from heavy truck or light-duty vehicles but with major changes to support the bus applications (e.g., use of electro-hydraulic steering system). The overall classification for safety issues or concerns is low to moderate.
- **Red** – Significantly new technology may be required for one or more foundational bus systems. The impact of the automation system cannot be effected without major updates to the current design technology. The overall classification for safety issues or concerns is moderately high.

SECTION 6 Transferability of Automation Systems

The analysis in this section seeks to evaluate the transferability of each system considered in this report. It provides a functional description (how it currently operates in existing applications), a list of foundational vehicle systems affected, anticipated use cases in transit bus applications, and required sensor technology. It then assesses the technical feasibility of transferring the technology to transit buses, specifically considering sensor limitations and use-case limitations. Use-case limitations can be determined by conditions that result in deterioration in system performance and not necessarily complete absence of system function. The use-case limitations of an automation system can be driven by limitations of either the system's sensor technology or its control algorithm. For example, most automation systems rely on object detection algorithms that have false positive and false negative limitations because no sensor is 100% accurate under all operating conditions. False positive is when the system acts (e.g., brakes) when it should not; false negative is when the system does not act (e.g., does not brake) when it should. The technical transferability analysis discusses the current algorithms and how the system effects vehicle control.

Functional safety implications are considered for the system as it would be implemented in transit buses. Automation system safety design in light-duty vehicles is driven by ISO 26262, which requires that all associated hardware and software components adhere to the standard, including all vehicle interfacing systems. This includes the automation system, the communication channels between the automation system, and the foundational systems (braking, steering, powertrain), and their relevant components.

Finally, a transferability grade is assigned as an overall summary assessment. The grade uses a color coding of Green, Yellow, or Red to indicate the level of the complexity associated with the transferability of the automation system to bus application.

Automatic Emergency Braking (AEB) System

System Description

Functional Description

The AEB system monitors vehicles, pedestrians, and objects in the path of the bus based on distance, speed, and time. When the potential for a collision is detected, a warning is sent to the driver. If the driver does not react and a distance or time-to-collision threshold is crossed, the brake system pressurizes the brake lines to reduce the time it takes to apply brake torque if necessary. When the next distance or time threshold is crossed, the system applies a brake jerk. If the driver still does not apply the brakes, the system commands zero propulsion torque and a brake torque sufficient in time and magnitude to avoid the collision. If the driver does not apply sufficient brake force to avoid the collision, the system commands additional brake torque to avoid the collision. Most systems in the market operate above a minimum speed threshold (e.g., 5 kph or 3.1 mph).

Vehicle Systems Affected

The primary vehicle systems affected are braking, power train, communications, and HMI.

Bus Application Use Cases

Given that a transit bus typically has a different operational domain than an automobile, the AEB system may be turned on during all road conditions and most operating locations, including roads, expressways, highways, intersections, tunnels, bridges, underpasses, construction zones, fully- or partially-covered surface roads, split mu,[23] parking or maintenance yards, and passenger pick-up stations. It may also be operated during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow. AEB operates where other vehicles are present, stopped, or moving in any direction (e.g., same, opposite, perpendicular) relative to the bus. It also may operate in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees and signs).

Sensors Required

Most AEB systems operate using only a front camera, although systems with both a camera and radar have been emerging into the market. The use of radar improves the robustness of the operation of the system. Both camera and radar were considered in this analysis.

[23] Split mu, or split friction, is a condition when the friction between the wheels and the road significantly differs between the left and right sides of the vehicle. For example, this condition can be caused by road spot repair that results in heterogeneous road surfaces or by sand collecting on part of the road (e.g., near the road gutter, leading to less friction on the sand-covered surface). If the left side of the lane were repaired more recently than the right side, it may be darker in color, resulting in different rates of ice melting or rain drying on the road, in which case the right side may be more slippery than the left, causing a friction differential between the right and left wheels.

Feasibility of Transferability

Sensor Limitations

The front camera works well for object classification, 3D reconstruction, detection of dynamic and stationary objects, and yaw rate[24] detection. The camera works to a good degree in use cases in which rain or dust are present and when trying to detect the relative distance to another object. The camera does not work well in cases of fog or snow and should not be relied on to detect the differential velocity between the bus and another vehicle. Long-range radar operates very well in detecting objects at a long range (e.g., more than 30m) and detecting dynamic and stationary objects. It operates to a good degree in snow, rain, and fog conditions. The radar does not work well for object classification, 3D reconstruction, or yaw rate detection. Short-range radar has the same operational limitations as long-range radar, except that it works very well at short distances (e.g., less than 30m). It does not work well below very short distances (e.g., less than 1m). The frequency of the radar signal is modified based on the application, so radar systems are designed to detect objects within a short or long range, depending on the needs of the application.

Use Case Limitations

The implementation of an AEB automation system in a transit bus may experience deteriorated performance in the following cases:

- Driving in heavy rain/snow/fog/dust
- Driving in sun-glare effect conditions
- Exiting a tunnel into a high ambient light condition (glare or more than 100,000 Lux)
- Entering a tunnel from a high ambient light condition (more than 100,000 Lux)
- Driving in a long tunnel (excessive multiple path reflections)
- Driving on roads with flares used by police and emergency crews to temporarily close lanes
- Driving behind traffic on curvy roads
- Driving behind a chrome trailer that reflects traffic images
- Vehicle with trailer crossing road horizontally in front of bus
- Driving on roads with large debris/objects moving (objects) on road (e.g., people and animals)
- Driving on roads with flying debris (e.g., different-sized items falling off of truck)

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[24] Yaw rate is the angular velocity of a vehicle as it is turning (e.g., all else equal, a vehicle making a tight turn would have a higher yaw rate than a vehicle making a wider turn).

- Driving on road with stalled vehicle partially in lane ahead of it
- Another vehicle partially invades vehicle's lane while driving
- Another vehicle traveling at high speed passes while vehicle trying to change lanes
- Driving with vehicles (motorcycles, bicycles) doing lane-splitting

System Control Algorithm

In a system equipped with a front camera, AEB operates based on input from the one sensor. In the presence of radar, the AEB control algorithm fuses camera data and radar data. For example, the camera can detect objects and classify them, and the radar detects relative speed and location of the other vehicles or objects. Radar can bridge the range limitations of the camera. The addition of the radar data provides confirmation of object location and differential speed.

System Actuator Control

The AEB control in light-duty vehicle applications can be described on a high level as follows: an AEB ECU sends requests to the powertrain control module and/or brake system control module via the CAN[25] bus. The powertrain and/or brake system control modules arbitrate between requests from the automation system controller and other vehicle systems. Communications to the driver of the status of AEB operations are sent via CAN from the AEB ECU or other vehicle controllers to the HMI display. Activation and deactivation of AEB are controlled by the driver via the HMI system.

Transferability to Bus Applications

The brake systems used on buses are typically pneumatic, with little electronic control. AEB will not likely be transferable to bus applications without modification of the brake system technology. Although it is possible to modify some pneumatic system components to support AEB, the modifications necessary would likely be extensive and are unproven in terms of the effect on the overall brake system performance.

Heavy trucks use hydraulic brake systems with Electronic Stability Control, which lends itself to supporting AEB. Similar system technology may be transferable to buses with AEB. The transferability from heavy trucks to buses will likely require design changes to the system. This is driven by differences in weight, packaging, and use cases between buses and heavy trucks.

[25] CAN is a vehicle bus standard that allows controllers and devices to communicate with each other. Vehicles have many ECUs to manage a variety of systems, such as the engine, transmission, airbags, antilock braking, cruise control, EPS, audio systems, and power windows. A CAN bus is used to enable messages between these systems, enabling a wide range of applications.

The bus powertrain system can support AEB without major technology modifications because the system includes an electronic controller and control software for basic operations. Input from the automation system may be handled in a manner similar to the input from the accelerator pedal.

The impact of AEB is not limited to the bus braking and powertrain systems. As the communication system on bus applications is usually hardwired, the electronic control required by AEB will likely require upgrades to the communication system. Most light-duty vehicles use CAN systems, so the bus electrical and communication systems will be affected to a large degree.

Light-duty vehicle AEB applications limitations include the ability to classify pedestrians, small-size pedestrians, and pedestrians with other objects (e.g., shopping carts, bicycles, strollers, walkers). These limitations are more important for bus applications given that the bus tends to move toward pedestrians during segments of their standard use cases, whereas light-duty vehicles tend to universally avoid them. Reasonable changes to the AEB control algorithms used in light-duty vehicles will, therefore, be required when they are transferred to bus applications.

Advancements in radar technology for better detection of pedestrians are under development; major enhancements are expected in the next five years.

In summary, AEB requires a major change to the bus brake system technology to be transferred from light-duty vehicles or heavy trucks.

Safety of Transferability

The safety classification level of this system is moderately high for light-duty vehicles and will be the same for bus applications, especially since buses operate in pedestrian-heavy environments. The inclusion of the foundational brake system in AEB application results in stringent safety design, development, and manufacturing requirements. The AEB system safety effect on the bus applications will be challenging because the change in technology will affect not only the braking and powertrain systems but other bus systems as well (e.g., communication channels and HMI). Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability,[26]

[26] Proven-in-use arguments apply to developed products that have a proven history of use in service without incident, but are being applied in a new environment. For example, many systems in light-duty vehicles were designed and manufactured to a high level of safety before ISO 26262 was created, and, given that these components have been proven to have highly reliable and safe behavior, it may not make sense to recertify all of those systems to comply with ISO 26262. This concept can apply in the case of transferring automation systems from other vehicles to buses; some components developed for light-duty vehicles or commercial trucks may be able to be used in an automation system for a transit bus without all the rigorous analysis, design, and testing that would be needed for an entirely new system or component.

which is akin to the ISO 26262 proven-in-use concept for certifying functional safety of electrical and electronic systems in light-duty vehicles.

Grade

Based on the above analysis, the transferability of the AEB system to transit bus applications is rated Red. The changes required to the bus braking and communication systems to support the functionality and safety of AEB imply significant technological changes. The brake system technology needs to be changed to allow for electronic control. The communication system needs to be changed to support fast, reliable, and safe signals between the automation system and the brake and powertrain systems, requiring a change to the equivalent of the light-duty vehicle CAN system. Although the technologies for the required brake and communication systems exist in the automobiles and heavy trucks, transit buses would require changes in system suppliers, system design and validation, manufacturing and assembly operations, and service and maintenance operations. The time required for these changes could be several years and could incur significant cost.

Lane Keeping/Lane Centering (LK/LC)

System Description

Functional Description

The LK/LC system identifies lane boundaries by either directly detecting lane markings or interpolating lane boundaries based on landmarks or by monitoring the position of the traffic directly ahead. If the bus starts to move too close to the edge of the lane (LK) or simply away from the center (LC), the system commands a torque overlay from the steering system that returns the bus toward the center of the lane. The main difference between the two approaches is whether or not small adjustments are made if the vehicle is only slightly away from the center of the lane. In either case, the driver is required to remain engaged at all times. Driver engagement is typically monitored via a sensor in the steering wheel. If driver engagement is not detected, the system will use a multi-level warning system to prompt the driver to resume control. If the driver does not exhibit sufficient engagement within a specified time, the system is disengaged. Similarly, if the system cannot determine the location of the lane boundaries or there is a system fault, a similar warning strategy is employed and the system is turned off after a period of time.

Vehicle Systems Affected

The primary vehicle systems affected are steering, communications, and the HMI.

Bus Application Use Cases

The main condition for the proper operation of the LK/LC system is the identification of road lane boundaries. Given that a transit bus typically has a different operational domain than an automobile, the system may be turned on during all road conditions and most operating locations, including roads, expressways, highways, intersections, tunnels, bridges, underpasses, construction zones, fully- or partially-covered surface roads, split mu, parking or maintenance yards, and passenger pick-up stations. It may also be operated during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow. LK/LC systems operate where other vehicles are present, stopped, or moving in any direction (e.g., same, opposite, perpendicular) relative to the bus and in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees and signs). This system is not intended for use in bus yards or maintenance facilities.

Sensors Required

Most LK/LC systems operate with a front camera only. This sensor has proven sufficient to support this system.

Feasibility of Transferability

Sensor Limitations

The front camera works well for detecting lane markings and stationary and moving objects as well as classifying objects and estimating yaw rate detection. These capabilities all support the identification of lane boundaries. The camera has some utility even when rain or dust are present and some ability to estimate distance to an object. The camera does not work well on partially- or fully-covered roads or in fog or snow.

Use Case Limitations

The implementation of an LK/LC automation system in a transit bus may experience deteriorated performance in the following cases:

- Driving in heavy rain/snow/fog/dust
- Driving into a flooded road/shallow water
- Driving in sun-glare effect conditions
- Exiting a tunnel into a high ambient light condition (glare or more than 100,000 Lux)
- Entering a tunnel from a high ambient light condition (more than 100,000 Lux)
- Driving on roads with surface discontinuities (potholes and bumps)
- Driving on roads that have faded lane markers or tar strips

- Driving on roads that have old lane markers with new lane markers painted offset
- Driving on roads with lanes separated by Botts' Dots (raised pavement markers)
- Driving on roads with lanes partially covered (debris, leaves, snow)
- Driving into a construction zone
- Driving on roads with flares used by police and emergency crews to temporarily close lanes
- Driving on lane that splits into two lanes

System Control Algorithm

The front camera detects the lane boundary, and the system locates the bus within the lane (LK) or at the center of the lane (LC). If the camera is unable to detect the lane markings, the system relies on landmarks or traffic ahead of the bus to interpolate the lane boundaries.

System Actuator Control

LK/LC control in light-duty vehicle applications can be described on a high level as follows: a LK/LC ECU sends torque overlay (to be added or subtracted from the torque requested by the driver) requests to the steering system control module via CAN. The steering system control module arbitrates between the requests from the automation system controller and other vehicle systems. Communications to the driver of the status of LK/LC operations are sent via CAN from the automation system ECU or other vehicle controllers to the HMI display. Activation/deactivation of the automation is controlled by the driver via the HMI system.

Transferability to Bus Applications

The majority of bus steering systems are hydraulic, with little or no electronic control. The absence of electronic control complicates the transferability of LK/LC automation systems to bus applications.

Heavy trucks use "variable effort" systems for driver assistance. These systems introduce a torque overlay to the steering torque requested by the driver. The torque overlay is speed-dependent and is applied via an actuator (motor) at either at the steering wheel column or the steering gear. The concept of variable effort can be expanded to support automation systems such as lane keeping or lane centering. A similar approach was used on bus demonstration projects in the US and abroad. However, vehicle dynamics will need to be better understood for bus applications if the variable effort concept is to be expanded as described above. A key question regards system response time at high speeds.

Moving the bus steering system technology to electro-hydraulic technology will facilitate the implementation of LK/LC systems. This move is considered not very challenging from the technology point of view, given that it is already widely used in heavy truck applications.

The impact of LK/LC is not limited to bus steering systems. As the communication system on bus applications is mostly hardwired, the electronic control required by LK/LC will likely require upgrades to the communications system. Most light-duty vehicles use CAN systems. Bus electrical and communications systems will be affected to a large degree.

In summary, LK/LC requires changes to the bus steering system to be transferred from light-duty vehicles or heavy trucks. The changes are complex, but they are less complicated than the changes required for the bus brake system to support AEB, for example.

Safety of Transferability

The safety classification level of this system is moderate for light-duty vehicles and is expected to be the same or slightly lower for bus applications because they require expert drivers.

The safety of variable effort systems will need to be demonstrated. In heavy truck applications, the variable effort system is used to reduce the physical effort required by the driver, so these systems are not classified as safety-relevant in that application. Therefore, they are not required to comply with ISO 26262 in trucks. If such systems were to be used to support LK/LC in buses, then the classification of these systems changes to safety-relevant, which would lead to more stringent design, development, and manufacturing requirements than currently required.

The safety of the bus communications channels between the automation system and the steering system and for the bus HMI system also need to be demonstrated. Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

A transition to an electro-hydraulic steering system will benefit from the safety designs that currently are successfully applied in light-duty vehicle steering systems. The elements of the safety design have also been adopted by many heavy truck electro-hydraulic steering systems.

Grade

Based on the above analysis, the transferability of the LK/LC system to bus applications is rated Yellow, as the changes required to the bus steering and communication systems to support the functionality and safety of this automation system imply major technological changes. The steering system needs to be changed to allow for electronic control. The communication system needs to be changed to support the transfer of many signals quickly, reliably, and safely between the automation system and the steering system, requiring a change into something similar to the light-duty vehicle CAN system. Although the technologies for the required steering and communication systems exist in the automotive industry and in heavy trucks, the adaptation to bus applications will require changes by system suppliers and bus manufacturers, including changes to the design and validation of the systems, manufacturing and assembly operations, and service and maintenance operations. The safety classification will also introduce another level of complexity across the steering and communication systems and all bus interfacing systems. The safety impact will cascade into manufacturing, maintenance, and service operations changes. The time required for these changes may be a few years, and the cost will be high.

Steering Assist

System Description

Functional Description

A Steering Assist system operates in a limited access zone such as a highway or pre-defined route. The system identifies lane boundaries by detecting lane markings or interpolating lane boundaries based on landmarks or the traffic ahead of the bus, locating the bus within the lane. The system steers the bus within the lane independent of the driver for a maximum specified time duration (e.g., 5 minutes), and the driver is required to be engaged during this time duration at all times; driver engagement is sensed via a sensor in the steering wheel. If the system is unable to detect lane markings or lane boundaries or if there is a system fault, the system prompts the driver to take control using a multi-level warning strategy. If the driver does not take control within a specified time duration, the system turns off. If driver engagement is not detected, a similar warning strategy is employed, and the system turns off after a period of time.

Vehicle Systems Affected

The primary vehicle systems affected are steering, communications, and the HMI.

Bus Application Use Cases

The main conditions for the proper operation of a Steering Assist system are identification of road lane boundaries and a limited access zone. Given that a transit bus typically has a different operational domain than an automobile, the system may be turned on during all road conditions and most operating locations, including roads, expressways, highways, intersections, tunnels, bridges, underpasses, construction zones, fully- or partially-covered surface roads, split mu, parking or maintenance yards, and passenger pick-up stations. It may also be operated during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow. Steering Assist operates where other vehicles are present, stopped, or moving in any direction (e.g., same, opposite, perpendicular) relative to the bus. It also may operate in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees and signs). This system is not used in bus yards or maintenance facilities.

Sensors Required

Many Steering Assist systems operate with a front camera only. However, to improve system availability, front short- and long-range radar is used, which is very valuable in lead car-following when lane markings are not sufficient for proper system operation. Lower-grade systems opt for using only a front camera. In this analysis, radar was considered. The use of the radar does not change the assessment of transferability analysis to bus applications.

Feasibility of Transferability

Sensors Limitations

A front camera works well for detecting lane markings, object classification, 3D reconstruction, and detection of dynamic objects, detection of stationary objects, and yaw rate detection. This supports the identification of the lane boundaries. The camera works to a good degree in use cases where rain or dust are present and when trying to detect distance to another object. The camera does not work well in cases of partially- or fully-covered roads, fog, or snow.

Long-range radar operates very well in detecting objects at a long range (e.g., more than 30m), detecting dynamic and stationary objects, and operating in fog conditions. It operates to a good degree in snow and rain conditions. Radar works well in detecting the lead-in vehicle and its location; it does not work well for object classification, 3D reconstruction, or yaw rate detection.

Short-range radar has the same operational limitations as long-range radar, except it works very well at short distances (e.g., less than 30m); it does not work well below very short distances (e.g., less than 1m).

Use Case Limitations

The implementation of a Steering Assist automation system in a transit bus may experience deteriorated performance in the following cases:

- Driving in heavy rain/snow/fog/dust
- Driving into a flooded road/shallow water
- Driving in sun-glare effect conditions

- Exiting a tunnel into a high ambient light condition (glare or more than 100,000 Lux)
- Entering a tunnel from a high ambient light condition (more than 100,000 Lux)
- Driving on roads with surface discontinuities (potholes and bumps)
- Driving on roads that have faded lane markers or tar strips
- Driving on roads that have old lane markers with new lane markers painted offset
- Driving on roads with lanes separated by Botts' Dots
- Driving on roads with lanes partially covered (debris, leaves, snow)
- Driving into a construction zone
- Driving on roads with flares used by police and emergency crews to temporarily close lanes
- Driving on lane that splits into two lanes
- Diverging off ramp from lane
- Driving behind a chrome trailer that reflects traffic images
- Vehicle with trailer crossing the road horizontally in front of the vehicle

System Control Algorithm

In a front-camera-only system, Steering Assist operates based on input from one sensor. In the presence of radar, the system's control algorithm fuses camera data and radar data. For example, when the camera can no longer establish lane boundaries, both the camera and radar data are used to establish the location and direction of the lead vehicle and to improve the availability of the system.

System Actuator Control

Steering Assist control in light-duty vehicle applications can be described on a high level as follows: a Steering Assist ECU sends torque overlay (to be added or subtracted from the torque requested by the driver) requests to the steering system control module via CAN. The steering system control module arbitrates between the requests from the automation system controller and other vehicle systems. Communications to the driver on the status of Steering Assist operations are sent via CAN from the automation system ECU or other vehicle controllers to the HMI display. Activation/deactivation of the automation is controlled by the driver via the HMI system.

Transferability to Bus Applications

The majority of bus steering systems are hydraulic, with little or no electronic control. The absence of electronic control complicates the transferability of Steering Assist automation systems to bus applications.

Heavy trucks use variable effort systems for driver assistance. The concept of the variable effort can be expanded to support Steering Assist. A similar approach was used on bus demonstration projects in the US and abroad. However, vehicle dynamics will need to be better understood for bus applications if the variable effort concept is to be expanded as described above. A key question is system response time at high speeds, which is much more important for Steering Assist than it is for LK/LC because Steering Assist steers the vehicle on its own, whereas LK/LC provides only an overlay to the steering torque requested by the driver.

Moving the bus steering system technology to electro-hydraulic technology will facilitate the implementation of Steering Assist systems and is considered not very challenging from the technology point of view, given that it is already widely used in heavy truck applications.

The impact of Steering Assist is not limited to bus steering systems. As the communication system on bus applications is mostly hardwired, the electronic control required by Steering Assist will likely require upgrades to the communications system. Most light-duty vehicles use CAN systems. Bus electrical and communication systems will be affected to a large degree.

In summary, Steering Assist requires changes to the bus steering system to be transferred from light-duty vehicles or heavy trucks. The changes are complex, but they are less complicated than the changes required for the bus brake system to support automation systems affecting the bus brake system.

Safety of Transferability

The safety classification level of this system is high for light-duty vehicles and is expected to be the same or slightly lower for bus applications because bus applications require expert drivers. The high safety classification coupled with the inclusion of the steering system results in very stringent safety design, development, and manufacturing requirements.

The safety of the variable effort systems will need to be demonstrated. In heavy truck applications, the variable effort system is used to reduce the physical effort required by the driver, so these systems are not classified as safety-relevant and are not required to comply with ISO 26262 in trucks. If such systems were to be used to support Steering Assist, then the classification of these systems would change to safety-relevant, which leads to more stringent design, development, and manufacturing requirements than what is currently required. This will also be more stringent than in the case of the LK/LC automation system.

The safety of the bus communications channels between the automation system, steering system, and bus HMI system also will need to be demonstrated.

Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

A transition to an electro-hydraulic steering system will benefit from the safety designs that are currently successfully applied in light-duty vehicle steering systems. The elements of the safety design have also been adopted by many heavy truck electro-hydraulic steering systems.

Grade

Based on the above analysis, the transferability of the Steering Assist system to bus applications is rated Yellow, as the changes required to the bus steering and communication systems to support the functionality and safety of this automation system imply major technological changes. The steering system needs to be changed to allow for electronic control. The communication system has to be changed to support the transfer of many signals quickly, reliably, and safely between the automation system and the steering system, which requires a change into something similar to the light-duty vehicle CAN system. Also, the HMI system required to ensure that the driver is engaged adds a significant challenge; driver monitoring systems are advanced systems even by light-duty vehicle industry standards.

Although the technologies for the required steering, HMI, and communication systems exist in the automotive industry and heavy trucks, the adaptation to bus applications will require changes by system suppliers and bus manufacturers. These changes include the design and validation of the systems, changes to the manufacturing and assembly operations, and changes to the service and maintenance operations. The high safety classification will also introduce another level of complexity across the steering, communication, and HMI systems as well as all bus interfacing systems. The safety impact will also cascade into manufacturing, maintenance, and service operations changes. The time required for these changes may be a few years, and the cost will be high.

Reverse Brake Assist

System Description

System Function

A Reverse Brake Assist system provides driver assist when driving in reverse. It detects objects in the path of the bus, and in case of the presence of an object, the system provides multi-level warnings to the driver. In case of a high probability of collision, the system commands a braking torque to prevent collision. The system also detects vehicles coming into the bus path from cross traffic. Most Reverse Brake Assist systems operate at low speeds (e.g., up to 10–15 kph or 6.2–9.3 mph).

Vehicle Systems Affected

The primary vehicle systems affected are braking, communications, and the HMI.

Bus Application Use Cases

The primary use case of the Reverse Brake Assist system is the backing maneuver. This includes traveling in reverse, parking, or park out. For bus application, the use case will be limited to a bus yard or maintenance facility. Therefore, the system will operate on paved or unpaved surfaces, fully- or partially-covered surfaces, inside a structure (barn) or outside, split mu, and, to a lesser degree, on regular roads. Reverse Brake Assist may be turned on where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus. It may also operate in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs, posts fences, chains, debris). It may also be operated during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow.

Sensors Required

Reverse Brake Assist systems may be offered with one or more sensors, depending on the system capability provided. For example, an ultrasonic sensor-only based system works well for detecting vehicles and some objects during parking; an ultrasonic plus camera-based system provides expanded capabilities to detect pedestrians. An ultrasonic camera and radar-based system provides the additional capabilities of detecting cross traffic. In this analysis, a system that includes ultrasonic sensors, a rear-view camera, and rear short-range radar were considered.

Feasibility of Transferability

Sensors Limitations

An ultrasonic sensor works very well in almost all weather and other environmental conditions; changes in temperature are addressed in the calibration of the sensor parameters internally. It also works very well for detecting peripheral objects, both moving and stationary, within short distances. An ultrasonic sensor works to a good degree in detecting the relative velocity and acceleration of other objects. This sensor technology does not work well in the presence of other ultrasonic sensors (cross talk with other ultrasonic sensors), which may lead to false detection. It also does not work well in detecting road curvature, lane width, ground scene complexity, object classification, motion detection, or at long distances (e.g., more than 6m).

A rear-view camera works well for object classification, 3D reconstruction, and detection of dynamic objects, detection of stationary objects, and yaw rate detection. The camera works to a good degree in uses cases in which rain or dust are present and when attempting to detect distance to another object. The camera does not work well in cases of fog or snow. It should not be relied on to detect the differential velocity between the bus and another vehicle.

Short-range radar operates very well in detecting objects at a short range (e.g., less than 30m) and the detection of dynamic and stationary objects, as well as operating in fog conditions. It operates to a good degree in snow and rain conditions. It does not work well for object classification, 3D reconstruction, yaw rate detection, or below very short distances (e.g., less than 1m).

Use Case Limitations

The implementation of a Reverse Brake Assist automation system in a transit bus may experience deteriorated performance in the following cases:

- Operating near other vehicles with ultrasonic sensors
- Operating in areas with high sound pressure (e.g., construction area with jack hammers in use)
- Operating in a construction zone with barrels and cones
- Operating in flooded areas/shallow water
- Operating in areas with moving pedestrians or animals
- Moving into a parking space in a lot with a chain link fence behind or to the side
- Operating in areas with semi-stationary objects (e.g., trees, signs, posts, and chains)

System Control Algorithm

The Reverse Brake Assist algorithm works through the fusion of camera, radar, and ultrasonic sensor data for detecting free space and maneuvering around close-proximity objects. Ultrasonic sensors are capable of operating very accurately from almost 0 to 4m distance in most cases. The camera helps to classify objects and reduce false positive detections. The radar supports detecting cross vehicle traffic as well as chain link fences, chains, and posts.

System Actuator Control

Reverse Brake Assist control in light-duty vehicle applications can be described on a high level as follows: an ECU processes the sensor data, fuses it, and sends requests to the brake system control module via CAN; this electronic unit can be a dedicated unit or a unit that serves other functions. The brake system control modules arbitrate between the requests from the automation system and other vehicle systems. Communications to the driver of the status of the Reverse Brake Assist operations are sent via CAN from the ECU or other vehicle controllers to the HMI display. Activation/deactivation of automation system is controlled by the driver via the HMI system.

Transferability to Bus Applications

Most brake systems on buses are pneumatic, with little electronic control. Reverse Brake Assist will likely not be transferable to bus applications without a change to the brake system technology. Although it is possible to modify some pneumatic system components to support this automation system, the modifications necessary would likely be very extensive and are unproven.

Heavy trucks use hydraulic brake systems with Electronic Stability Control; the system lends itself to supporting Level 2 automation. Similar system technology may be transferable to bus application that supports Reverse Brake Assist. The transferability from heavy trucks to bus application will likely also require design changes to the system because of differences in weight, packaging, and use cases between buses and heavy trucks.

The impact of Reverse Brake Assist is not limited to the bus brake system. As the communications system on bus applications is mostly hardwired, the electronic control required by the automation system will likely require upgrades to the communication system. Most light-duty vehicles use CAN systems. The bus electrical and communication systems will be affected to a large degree.

Light-duty vehicle Reverse Brake Assist applications limitations include the ability to classify pedestrians, small-size pedestrians, and pedestrians with other objects (shopping carts, bicycles, strollers, walkers). These limitations are more important for bus applications, given that Reverse Brake Assist will likely be used mostly in a bus yards and maintenance facilities with heavy pedestrian presence. Changes to the Reverse Brake Assist control algorithms used in light-duty vehicles will be required when transferred to bus applications, but these changes are not complex.

Advancements in radar technology for better detection of pedestrians are under development, and major enhancements are expected in the next five years.

In summary, Reverse Brake Assist requires a major change to the bus brake system technology to be transferred from light-duty vehicles.

Safety of Transferability

The safety classification level of this system is high for light-duty vehicles and is expected to be the same for bus applications. This is due to the failure mode that is independent of the system's intended use cases (namely, unintended braking that could occur while the bus is driving on the road) and the size and weight of the bus. The high safety classification coupled with the inclusion of the brake system will result in very stringent safety design, development, and manufacturing requirements.

The safety of the bus communication channels between the automation system, the HMI, and the brake sytstem will also likely need to be demonstrated. Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

Grade

Based on the above analysis, the transferability of the Reverse Brake Assist system to bus applications is rated Red due to the significant technological changes required to the bus braking and communication systems to support the functionality and safety of this automation system. The brake system technology has to be changed to allow for electronic control. The communication system has to be changed to support the transfer of many signals quickly, reliably, and safely between the automation system and the brake system. This requires a change into something similar to the light-duty vehicle CAN system. Although the technologies for the required brake and communication systems exist in the automotive industry and heavy trucks, the adaptation to bus applications will require changes by system suppliers and bus manufacturers. These changes include changes to the design and validation of the systems, manufacturing and assembly operations, and service and maintenance operations. The high safety classification also will introduce another level of complexity across the brake and communication systems and all bus interfacing systems; the safety impact will also cascade into the manufacturing, maintenance, and service operations changes. The time required for these changes may be several years, and the cost will be significant.

Docking

System Description

System Function

A Docking system detects the curb at the bus stop/station and maneuvers the bus to stop at a pre-determined distance from the curb. The distance is set by the driver, and the driver controls the powertrain and braking.

Vehicle Systems Affected

The primary vehicle systems affected are steering, communications, and the HMI.

Bus Application Use cases

The main condition for the proper operation of a Docking system is identification of bus stop curb and lane boundaries. The system will be turned on primarily near bus stops and passenger pick-up stations, which may include all road conditions, including construction zones, fully- or partially-covered surface roads (possible limited system operation), split mu, and passenger pick-up stations. It may also be operated during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow. Docking operates where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus and in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs). This system may also be used in bus yards or maintenance facilities.

Sensors Required

Docking can operate effectively by using ultrasonic sensors and cameras. Given that this system is new and implemented in light-duty vehicle applications, its actual implementation and testing in bus applications may reveal the need for front short-range radar. In this analysis, a system that includes ultrasonic sensors and front and side cameras was considered. This decision did not have a noticeable effect on the analysis for transferability.

Feasibility for Transferability

Sensors Limitations

An ultrasonic sensor works very well in almost all weather and other environmental conditions; changes in temperature are addressed in the calibration of the sensor parameters internally. It also works very well for detecting peripheral objects both moving and stationary within short distances. Ultrasonic sensors work to a good degree in detecting curbs, but careful design and calibration are required to optimize the sensor performance for a Docking automation system's need of robustly detecting the curb. This may also require careful consideration of the packaging of the sensors on the bus. Ultrasonic sensor technology does not work well in the presence of other ultrasonic sensors (cross talk with other ultrasonic sensors), which may lead to false detection; it also does not work well in detecting road curvature, lane width, ground scene complexity, object classification, motion detection, or at long distances (e.g., more than 6m).

The camera works well for detecting lane markings, object classification, 3D reconstruction, and detection of dynamic objects, detection of stationary objects, and yaw rate. The camera works to a good degree in identifying a curb and when trying to detect distance to another object and in uses cases where rain or dust are present. The camera does not work well in cases of partially- or fully-covered roads, fog, or snow.

Use Case Limitations

The implementation of a docking automation system in a transit bus may experience deteriorated performance in the following cases:

- Operating near other vehicles with ultrasonic sensors
- Operating in areas with high sound pressure (e.g., construction area with jack hammers in use)
- Operating in a construction zone with barrels and cones
- Driving in heavy rain/snow/fog/dust
- Driving into a flooded road/shallow water
- Driving in sun-glare effect conditions
- Exiting a tunnel into a high ambient light condition (glare or more than 100,000 Lux)
- Entering a tunnel from a high ambient light condition (more than 100,000 Lux)
- Driving on roads with surface discontinuities (potholes and bumps)
- Driving on roads that have faded lane markers or tar strips
- Driving on roads that have old lane markers with new lane markers painted offset
- Driving on roads with lanes separated by Botts' Dots
- Driving on roads with lanes partially covered (debris, leaves, snow)
- Driving on roads with flares used by police and emergency crews to temporarily close lanes
- Driving on lane that splits into two lanes
- Driving on roads with large debris/objects moving (objects) on the road (e.g., people and animals)
- Operating in areas with semi-stationary objects (e.g., trees, signs, posts, and chains)

System Control Algorithm

Although this system is not used in light-duty vehicle applications, similar systems in existence give a very good idea of what the control algorithm would entail. The Docking system algorithm would work by fusion of the camera and ultrasonic sensor data for detecting curb and free space and maneuvering around close-proximity objects at a distance set by the driver. Ultrasonic sensors are capable of very accurately detecting a curb from close to 0 to 4m of distance in most cases. The cameras detect lane boundaries and help with classifying a curb and other objects and reducing false positive detections.

System Actuator Control

Docking control can be described on a high level as follows: the automation system ECU sends torque overlay (to be added or subtracted from the torque requested by the driver) requests to the steering system control module via CAN. The steering system control module arbitrates between the requests from the automation system controller and other vehicle systems. Communications to the driver of the status of the Docking operations, including the distance to the curb, are sent via CAN from the automation system ECU or other vehicle controllers to the HMI display. Activation/deactivation and distance to the curb setting is controlled by the driver via the HMI system.

Transferability to Bus Applications

The majority of the bus steering systems are hydraulic, with little or no electronic control. The absence of electronic control complicates the implementation of the Docking automation systems in bus applications.

Heavy trucks use variable effort systems for driver assistance. The concept of variable effort can be expanded to support automation systems such as Docking. A similar approach was used on bus demonstration projects in the US and abroad. However, vehicle dynamics will need to be better understood for bus applications if the variable effort concept is to be expanded as described above. A key question regards system response time at high speeds. System response is not as crucial in Docking as it is for LK/LC, because the Docking system will likely be activated at lower bus speed than LK/LC.

Moving bus steering system technology to electro-hydraulic technology will facilitate the implementation of Docking and is considered not very challenging from the technology point of view, given that it is already widely used in heavy truck applications.

The impact of Docking is not limited to bus steering systems. As the communications system on bus applications is mostly hardwired, the electronic control required by Docking will likely require upgrades to the communication system. Most light-duty vehicles use CAN systems. Bus electrical and communication systems will be affected to a large degree.

In summary, Docking requires changes to the bus steering system that are complex, but they are less complicated than the changes required for the bus brake system to support automation systems affecting the bus brake system.

Safety of Transferability

The safety classification level of this system would likely be moderate for light-duty vehicles and is expected to be the same or slightly lower for bus applications because bus applications require expert drivers.

The safety of the variable effort systems will need to be demonstrated. In heavy truck applications, the variable effort system is used to reduce the physical effort required by the driver, so these systems are not classified as safety-relevant in that application. Therefore, they are not required to comply with ISO 26262 in trucks. If such systems are to be used to support Docking, then the classification of these systems changes to safety-relevant, which leads to more stringent design, development, and manufacturing requirements than what is currently required.

The safety of the bus communications channels between the automation system, the HMI, and the steering system will also need to be demonstrated. Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

A transition to an electro-hydraulic steering system will benefit from the safety designs that currently are successfully applied in light-duty vehicle steering systems. The elements of the safety design also have been adopted by many heavy truck electro-hydraulic steering systems.

Grade

Based on the above analysis, the implementation of a Docking system in bus applications is rated Yellow, as the changes required to the bus steering and communication systems to support the functionality and safety of this automation system imply major technological changes. The steering system has to be changed to allow for electronic control. The communication system has to be changed to support the transfer of many signals quickly, reliably, and safely between the automation system and the steering system. This requires a change into something similar to the light-duty vehicle CAN system. Although the technologies for the required steering and communication systems exist in the automotive industry and heavy trucks, the adaptation to bus applications will require changes by system suppliers and bus manufacturers. These include changes to the design and validation of the systems, manufacturing and assembly operations, and service and maintenance operations. The safety classification, although moderate, will introduce a level of complexity across the steering and communication systems and all bus interfacing systems; the safety impact will also cascade into manufacturing, maintenance, and service operations changes. The time required for these changes may be a few years, and the cost will be high.

Park Assist

System Description

Functional Description

A Park Assist system identifies an available parking spot and offers it to the driver; the driver selects the spot, and the system steers the bus into the spot. The driver controls gear shifting, powertrain, and braking. Perpendicular, angular, parallel, and back-up parking assist are provided.

Vehicle Systems Affected

The primary vehicle systems affected are steering, communications, and the HMI.

Bus Application Use Cases

The primary use case of a Park Assist system is parking maneuvers, including moving forward and in reverse to complete the parking maneuver. For the bus application, the use case will likely be limited most of the time to a bus yard or maintenance facility. Therefore, the system will likely operate on paved or unpaved surfaces, fully- or partially-covered surfaces, inside a structure (barn) or outside, split mu, and, to a lesser degree, on regular roads. Park Assist may be operational where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus. It also may operate in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs, posts fences, chains, and debris) and during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow.

Sensors Required

Most Park Assist systems on the market operate with ultrasonic sensors placed only in the front, side, and rear of the vehicle. Some systems are offered with short-range radar to improve the robustness of the system. In this analysis, a system that includes radar was assumed. The use of the radar does not change the assessment of transferability analysis to bus applications

Feasibility of Transferability

Sensors Limitations

Ultrasonic sensors are relied on primarily to detect a free parking spot; the primary function is detecting free space between parked vehicles. It works very well in almost all weather and other environmental conditions; changes in temperature are addressed in the calibration of the sensor parameters internally. It also works very well for detecting peripheral objects, both moving and stationary, within short distances. Ultrasonic sensors work to a good degree in detecting relative velocity and acceleration of other objects. This sensor technology does not work well in the presence of other ultrasonic sensors (cross talk with other ultrasonic sensors), which may lead to false detection. It also does not work well in detecting road curvature, lane width, ground scene complexity, object classification, motion detection, or at long distances (e.g., more than 6m).

The short-range radar operates very well in detecting objects at a short range (e.g., less than 30m), and the detection of dynamic and stationary objects, as well as operating in fog conditions. It works very well in detecting posts, chain link fences, and chains and operates to a good degree in snow and rain conditions.

The radar does not work well for object classification, 3D reconstruction, yaw rate detection, or below very short distances (e.g., less than 1m).

Use Case Limitations

The implementation of a Park Assist automation system in a transit bus may experience deteriorated performance in the following use cases:

- Operating near other vehicles with ultrasonic sensors
- Operating in areas with high sound pressure (e.g., construction area with jack hammers in use)
- Operating in a construction zone with barrels and cones
- Operating in flooded areas/shallow water
- Operating in areas with moving pedestrians or animals
- Pulling into a parking space moving forward in a lot with chain link fence in front or to the side
- Operating in areas with semi-stationary objects (e.g., trees, signs, posts, chains)
- Pulling into a parking space moving in reverse in a lot with a chain link fence behind or to the side

System Control Algorithm

A Park Assist algorithm works by fusion of the ultrasonic sensor and radar data for detecting the free space and maneuvering around close-proximity objects into the parking spot. Ultrasonic sensors are capable of operating from close to 0 to 4m of distance, very accurately in most cases; they are the primary sensors that are used to detect the available parking spot. The radar improves the robustness of detecting the available parking spot through the detection of objects such as posts, cones, chain link fences, and chains.

System Actuator Control

Park Assist control in light-duty vehicle applications can be described on a high level as follows: an ECU processes the sensor data, fuses it, and sends requests to the steering system control module via CAN. The steering system control module arbitrates between the requests from the automation system and other vehicle systems. Communications to the driver during the operation of the system to shift, propel, and brake are sent via CAN from the ECU or other vehicle controllers to the HMI display. Activation/deactivation of Park Assist is controlled by the driver via the HMI system.

Transferability to Bus Applications

The majority of the bus steering systems are hydraulic, with little or no electronic control. The absence of electronic control complicates the transferability of Park Assist automation systems to bus applications.

Heavy trucks use variable effort systems for driver assistance. The concept of variable effort can be expanded to support automation systems such as Park Assist. A similar approach was used on bus demonstration projects both in the US and abroad. However, the vehicle dynamics will need to be better understood for the bus applications if the variable effort concept is to be expanded as described above. Key questions are with regard to system response time and accuracy. The accuracy of the system response is crucial in Park Assist given the close proximity of the bus to other vehicles during the parking maneuver.

Moving the bus steering system technology to electro-hydraulic technology will facilitate the implementation of Park Assist. This move is viewed as not very challenging from the technology point of view, given that it is already widely used in heavy truck applications.

The effect of Park Assist is not limited to bus steering systems. The communication system on bus applications is mostly hardwired. The electronic control required by Park Assist will likely require upgrades to the communication system. Most light-duty vehicles use CAN systems. The bus electrical and communications systems will be affected to a large degree.

In summary, Park Assist requires changes to the bus steering system to be transferred from light-duty vehicles or heavy trucks. The changes are complex, but they are easier, to a large degree, than the changes required for the bus brake system to support automation systems affecting the bus brake system.

Safety of Transferability

The safety classification level of this system is very low for light-duty vehicles and is expected to be the same or slightly lower for bus applications due to the fact that bus applications require expert drivers. In case of the use of the variable effort concept used in heavy trucks, the safety of the variable effort systems will need to be demonstrated.

The safety of bus communications channels between the automation system, the HMI, and the steering system will also need to be demonstrated. Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

A transition to an electro-hydraulic steering system will benefit from the safety designs that are presently successfully applied in light-duty vehicle steering systems. The elements of the safety design also have been adopted by many heavy truck electro-hydraulic steering systems.

Grade

Based on the above analysis, the transferability of the Park Assist system to bus applications is rated Yellow because the changes required to the bus steering and communication systems to support the functionality and safety of this automation system imply major technological changes. The steering system has to be changed to allow for electronic control, and the communication system has to be changed to support the transfer of many signals quickly, reliably, and somewhat safely between the automation system and the steering system; this requires a change into something similar to the light-duty vehicle CAN system. Although the technologies for the required steering and communication systems exist in the automotive industry and heavy trucks, the adaptation to bus applications will require changes by system suppliers and bus manufacturers; these changes include the design and validation of the systems, changes to manufacturing and assembly operations, and changes to service and maintenance operations. The safety classification, while low, will also introduce some complexity across the steering and communication systems and all bus interfacing systems; the safety impact will also cascade into the manufacturing, maintenance, and service operations changes. The time required for these changes may be a few years, and the cost will be high.

Park Out

System Description

System Function

A Park Out system maps out a path for a vehicle to exit from a parking spot; the system steers the vehicle. The driver controls gear shifting, powertrain, and braking; when the system charts a path to safely get the vehicle out of a parking spot, it stops the steering wheel at the specified steering angle and informs the driver to take control. The driver takes control and drives the vehicle out of the parking spot at the system specified steering angle.

Vehicle Systems Affected

The primary vehicle systems affected are steering, communications, and the HMI.

Bus Application Use Cases

The primary use case of a Park Out system is the getting the bus out of a parking spot, including moving forward and in reverse to complete the Park Out maneuver. For bus application, the use case will likely be limited most of the time to a bus yard or maintenance facility. Therefore, the system will likely operate on paved or unpaved surfaces, fully- or partially- covered surfaces, inside a structure (barn) or outside, split mu, and, to a lesser degree, on regular roads. Park Out may be operational where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus. It may also operate in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs, posts fences, chains, and debris) and during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow.

Sensors Required

Most Park Out systems on the market operate with ultrasonic sensors placed only in the front, side, and rear of the vehicle. Some systems are offered with short-range radar to improve the robustness of the system, especially since the system goes hand-in-hand with a Park Assist system. In this analysis, a system that includes radar was assumed. The use of the radar does not change the assessment of transferability analysis to bus applications.

Feasibility of Transferability

Sensors Limitations

An ultrasonic sensor is relied on primarily to detect objects/vehicles around the bus. It works very well in almost all weather and other environmental conditions; changes in temperature are addressed in the calibration of the sensor parameters internally. It also works very well for detecting peripheral objects, both moving and stationary, within short distances. Ultrasonic sensors work to a good degree in detecting relative velocity and acceleration of other objects. This sensor technology does not work well in the presence of other ultrasonic sensors (cross talk with other ultrasonic sensors), which may lead to false detection. It also does not work well in detecting road curvature, lane width, ground scene complexity, object classification, motion detection, or at long distances (e.g., more than 6m).

The short-range radar operates very well in detecting objects at a short range (e.g., less than 30m) and the detection of dynamic and stationary objects, as well as operating in fog conditions. It works very well in detecting posts, chain link fences, and chains and operates to a good degree in snow and rain conditions. The radar does not work well for object classification, 3D reconstruction, yaw rate detection, or below very short distances (e.g., less than 1m).

Use Case Limitations

The implementation of a Park Out automation system in a transit bus may experience deteriorated performance in the following cases:

- Operating near other vehicles with ultrasonic sensors
- Operating in areas with high sound pressure (e.g., construction area with jack hammers in use)

- Operating in a construction zone with barrels and cones
- Operating in flooded areas/shallow water
- Operating in areas with moving pedestrians or animals
- Pulling out of a parking space moving forward in a lot with a chain link fence in front or to the side
- Operating in areas with semi-stationary objects (e.g., trees, signs, posts, and chains)
- Pulling out of a parking space moving in reverse in a lot with a chain link fence behind or to the side

System Control Algorithm

The Park Out algorithm works by fusion of the ultrasonic sensor and radar data for charting the free path and maneuvering around close-proximity objects out of the parking spot. Ultrasonic sensors are capable of operating from close to 0 to 4m of distance very accurately in most cases; they are the primary sensors that are used to detect a free path. The radar improves the robustness of the detection through the detection of objects such as posts, cones, chain link fences, and chains.

System Actuator Control

Park Out control in light-duty vehicle applications can be described on a high level as follows: an ECU processes the sensor data, fuses it, and sends requests to the steering system control module via CAN. The steering system control module arbitrates between the requests from the automation system and other vehicle systems. Communications to the driver during the operation of the system to shift, propel, brake, and take control are sent via CAN from the ECU or other vehicle controllers to the HMI display. Activation/deactivation of Park Out is controlled by the driver via the HMI system.

Transferability to Bus Applications

The majority of the bus steering systems are hydraulic, with little or no electronic control. The absence of electronic control complicates the transferability of Park Out automation systems to bus applications.

Heavy trucks use variable effort systems for driver assistance. The concept of variable effort can be expanded to support automation systems such as Park Out. A similar approach was used on bus demonstration projects in the US and abroad. However, vehicle dynamics will need to be better understood for bus applications if the variable effort concept is to be expanded as described above. Key questions to be answered are with regard to system response time and accuracy. The accuracy of the system response is crucial in Park Out given the close proximity of the bus to other vehicles during the Park Out maneuver.

Moving the bus steering system technology to electro-hydraulic technology will facilitate the implementation of Park Out. This move is viewed as not very challenging from the technology point of view, given that it is already widely used in heavy truck applications.

The effect of Park Out is not limited to bus steering systems. The communications system on bus applications is mostly hardwired. The electronic control required by Park Out will likely require upgrades to the communications system. Most light-duty vehicles use CAN systems. The bus electrical and communications systems will be affected to a large degree.

In summary, Park Out requires changes to the bus steering system to be transferred from light-duty vehicles or heavy trucks. The changes are complex, but they are easier, to a large degree, than the changes required for the bus brake system to support automation systems affecting the bus brake system.

Safety of Transferability

The safety classification level of the Park Out system is very low for light-duty vehicles and is expected to be the same or slightly lower for bus applications; this is due to the fact that bus applications require expert drivers.

In case of the use of the variable effort concept used in heavy trucks, the safety of the variable effort systems will need to be demonstrated.

The safety of bus communications channels between the automation system, the HMI, and the steering system will also need to be demonstrated. Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

A transition to an electro-hydraulic steering system will benefit from safety designs that are presently successfully applied in light-duty vehicle steering systems. The elements of the safety design also have been adopted by many heavy truck electro-hydraulic steering systems.

Grade

Based on the above analysis, the transferability of the Park Out system to bus applications is rated Yellow because changes required to the bus steering and communication systems to support the functionality of this automation system imply major technological changes. The steering system has to be changed to allow for electronic control. The communication system has to be changed to support the transfer of many signals quickly, reliably, and somewhat safely between the automation system and the steering system; this requires a change into something similar to the light-duty vehicle CAN system. Although the technologies for the required steering and communication systems exist in the automotive industry and heavy trucks, the adaptation to bus applications will require changes by system suppliers and bus manufacturers, including the design and validation of the systems, changes to manufacturing and assembly operations, and changes to service and maintenance operations. The time required for these changes may be a few years, and the cost will be high.

Full Park Assist

System Description

System Function

A Full Park Assist system identifies an available parking spot and offers it to the driver; the driver selects the parking spot. The system controls powertrain, steering, braking, and shifting to park the bus into a spot; the driver waits for the notification from the system that the parking maneuver is complete to take over. Perpendicular, angular, parallel, and back-up parking assist are provided.

Vehicle Systems Affected

The primary vehicle systems affected are steering, powertrain, transmission, braking, parking brake, wheel speed information, communications, and the HMI.

Bus Application Use Cases

The primary use cases of the Full Park Assist system are parking maneuvers. This includes moving forward and in reverse to complete a parking maneuver. For bus application, the use case will likely be limited most of the time to a bus yard or maintenance facility. Therefore, the system will likely operate on paved or unpaved surfaces, fully- or partially-covered surfaces, inside a structure (barn) or outside, split mu, and, to a lesser degree, on regular roads. Full Park Assist may be operational where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus. It also may operate in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs, posts fences, chains, and debris) and during all weather conditions, including low visibility, dust, smoke, fog, rain or snow.

Sensors Required

Many Full Park Assist systems on the market operate with ultrasonic sensors placed only in the front, side, and rear of the vehicle. Other systems are offered with front and rear short-range radar to improve the robustness of the system. In this analysis, a system that includes radar was assumed. The use of the radar does not change the assessment of transferability analysis to bus applications.

Feasibility of Transferability

Sensors Limitations

Ultrasonic sensors are relied on primarily to detect a free parking spot and vehicles/objects around the spot. It works very well in almost all weather and other environmental conditions; changes in temperature are addressed in the calibration of the sensor parameters internally. It also works very well for detecting peripheral objects both moving and stationary within short distances. Ultrasonic sensors work to a good degree in detecting the relative velocity and acceleration of other objects. This sensor technology does not work well in the presence of other ultrasonic sensors (cross talk with other ultrasonic sensors), which may lead to false detection. It also does not work well in detecting road curvature, lane width, ground scene complexity, object classification, motion detection, or at long distances (e.g., more than 6m).

The short-range radar operates very well in detecting objects at a short range (e.g., less than 30m) and the detection of dynamic and stationary objects, as well as operating in fog conditions. It works very well in detecting posts, chain link fences, and chains and operates to a good degree in snow and rain conditions. The radar does not work well for object classification, 3D reconstruction, yaw rate detection, or below very short distances (e.g., less than 1m).

Use Case Limitations

The implementation of a Full Park Assist automation system in a transit bus may experience deteriorated performance in the following use cases:

- Operating near other vehicles with ultrasonic sensors
- Operating in areas with high sound pressure (e.g., construction area with jack hammers in use)
- Operating in a construction zone with barrels and cones
- Operating in flooded areas/shallow water
- Operating in areas with moving pedestrians or animals
- Pulling into a parking space moving forward in a lot with a chain link fence in front or to the side
- Operating in areas with semi-stationary objects (e.g., trees, signs, posts, and chains)
- Pulling into a parking space moving in reverse in a lot with a chain link fence behind or to the side

System Control Algorithm

The Full Park Assist algorithm works by fusion of the ultrasonic sensor and radar data for detecting the free space and maneuvering around close-proximity objects into the parking spot.

Path planning for this automation system requires input from the wheel speed information system of the vehicle. Ultrasonic sensors are capable of operating from close to 0 to 4m of distance very accurately in most cases; they are the primary sensors used to detect the available parking spot and the appropriate size of the spot. The radar improves the robustness of detecting the available parking spot through the detection of objects such as posts, cones, chain link fences, and chains.

System Actuator Control

The Full Park Assist control in light-duty vehicle applications can be described on a high level as follows: an ECU processes the sensor data, fuses it, plots a vehicle movement path, incorporates the wheel speed information system, and sends requests to the steering, braking, and powertrain systems control modules via CAN. A primary controller (powertrain control module or another vehicle module like the body control module) arbitrates between the requests from the automation system and other vehicle systems. Upgrade to the vehicle brake system to incorporate electric brake boost is required. Communications to the driver during the operation of the system to take control are sent via CAN from the ECU or other vehicle controllers to the HMI display. Activation/deactivation of Full Park Assist is controlled by the driver via the HMI system.

Transferability to Bus Applications

Full Park Assist affects the steering, braking, and powertrain systems in addition to other vehicle systems. An assessment of this impact is as follows:

- *Braking*: The brake systems used on buses are mostly pneumatic, with little electronic control. Full Park Assist will require a change to the brake system technology. Modifications to some of the pneumatic system components to support this automation system will not be sufficient. Common light-duty vehicle brake systems also require an upgrade to support Full Park Assist to mitigate the system issues that arise when the system is in operation and the driver applies the brake then releases them. In this situation, a conventional light-duty vehicle brake system may not be able to compensate in time for proper operation. To support Full Park Assist, light-duty vehicles require an advanced technology (vacuum-less or electric brake boost) brake system, which further complicates the transferability of this automation system to bus applications.

- *Transmission/Park Brake*: If the vehicle is not equipped with a Park by Wire transmission system, then an Electric Park Brake system is required to address issues that arise if the driver leaves the vehicle without moving the transmission into Park.
- *Steering*: The majority of bus steering systems are hydraulic, with little or no electronic control. The absence of electronic control complicates the transferability of Full Park Assist automation systems to bus applications.

  Heavy trucks use variable effort systems for driver assistance. The concept of variable effort can be expanded to support automation systems such as Full Park Assist. A similar approach was used on bus demonstration projects in the US and abroad. However, the vehicle dynamics will need to be better understood for bus applications if the variable effort concept is to be expanded as described above. Key questions to be answered are with regard to system response time and accuracy. The accuracy of the system response is crucial in Full Park Assist given the close proximity of the bus to other vehicles during the parking maneuver.

  Moving the bus steering system technology to electro-hydraulic technology will facilitate the implementation of Full Park Assist. This move is viewed as not very challenging from the technology point of view, given that it is already widely used in heavy truck applications.

  The bus powertrain system will be able to support Full Park Assist without major technology modifications because the system includes an electronic controller and control software for basic operations. Input from the automation system may be handled in a similar manner as input from the accelerator pedal.

- *Wheel Speed Information* – Full Park Assist will also require a sophisticated wheel speed information system capable of providing count information in both forward and reverse direction.
- *Communications* – The communications system on bus applications is mostly hardwired. The electronic control required by Full Park Assist will probably require upgrade to a CAN system.

In summary, Full Park Assist requires major changes to the bus systems; some of these changes are considered advanced technology even for high end light-duty vehicles.

Safety of Transferability

The safety classification of Full Park Assist in light-duty vehicles is high and is expected to be the same for bus application.

The impact of this automation system on several foundational bus systems will lead to stringent requirements for design and manufacturing for many systems and components; this adds a high level of complexity to the transferability of these automation systems to bus applications. An assessment is as follows:

- *Brakes* – As stated above, a sophisticated brake system similar to what is used in light-duty vehicle is required to support this automation system; the safety design would already be incorporated into the system.
- *Transmission/Electric Park Brake* – If a Park by Wire transmission system is adopted, then the safety aspects will need to be incorporated into the system. If an Electric Park Brake is used, then the safety aspects will need to be incorporated into the system.
- *Steering* – In case of the use of variable effort concept used in heavy trucks to support the steering portion of this system, the safety of the variable effort systems will need to be demonstrated.
- *Powertrain* – The bus powertrain system will need to be updated to incorporate the required safety aspects.
- *Safety* – The safety of the bus communications channels between the automation system, the HMI, and the rest of the vehicle systems also have to be demonstrated.

Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

In summary, the safety impact of Full Park Assist on bus applications is a major challenge for transferability.

Grade

Based on the above analysis, the transferability of a Full Park Assist system to bus applications is rated Red. The reason for this rating is that the changes required for several bus systems to support the functionality and safety of Full Park Assist imply significant technological challenges. The brake system technology needs to be changed to allow for electronic control. The required transmission or park brake systems changes are significant. The steering system changes to allow for electronic control are major. The communication system has to be changed to support the transfer of many signals quickly, reliably, and safely between the automation system and the rest of the affected vehicle systems; this requires a change into something similar to the light-duty vehicle CAN system. Although the technologies required for steering, braking, transmission, park brake, and communication systems exist in the automotive industry and heavy trucks, some of these technologies, as stated previously, are considered advanced technology even for the light-duty vehicle industry. Adaptation to bus applications will require significant changes by system suppliers and bus manufacturers, including the design and validation of the systems, changes to manufacturing and assembly operations, and changes to service and maintenance operations; these changes will likely dictate significant changes to the bus systems packaging and layout. The high safety classification will also introduce another level of complexity across the affected systems and all bus interfacing systems and will cascade into manufacturing, maintenance, and service operations changes. The time required for these changes may be close to a decade, and the cost will be extremely high.

Valet Parking (Bus Yard)

System Description

System Function

A Valet Parking (Bus Yard) system allows the driver to exit the bus in the bus yard and use a remote control instrument (e.g., cell phone or tablet) to activate the system while he/she is outside of the bus. The system drives the bus, identifies an available parking spot, and offers it to the driver. The driver accepts the parking spot, and the system parks the bus. The system controls powertrain, steering, and braking systems to park the bus in the spot. The driver waits for the notification from the system that the parking maneuver is complete. Perpendicular, angular, parallel, and back-up parking are provided. Park Out is also supported.

Vehicle Systems Affected

The primary vehicle systems affected are steering, powertrain, transmission, braking, parking brake, wheel speed information, external communication network (e.g., Dedicated Short Range Communication [DSRC]), communications, and the HMI.

Bus Applications Use Cases

The primary use cases of a Valet Parking (Bus Yard) system are parking maneuvers. This includes moving forward and in reverse to complete the parking maneuver. For bus application, the use case will be limited to a bus yard or maintenance facility. Therefore, the system will likely operate on paved or unpaved surfaces, fully- or partially-covered surfaces, inside a structure (barn) or outside, split mu, and, to a lesser degree, on regular roads. Valet Parking (Bus Yard) may be operational where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus. It also may operate in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs, posts fences, chains, and debris) and during all weather conditions, including low visibility, dust, smoke, fog, rain or snow.

Sensors Required

Valet Parking (Bus Yard) systems are not common on the market at this time. The system requires ultrasonic sensors placed in the front, side, and rear of the vehicle; it also requires front and rear short-range radar.

Feasibility of Transferability

Sensors Limitations

The ultrasonic sensor in combination with radar detects the free parking spot and the vehicles around the spot. It works very well in almost all weather and other environmental conditions; changes in temperature are addressed in the calibration of the sensor parameters internally. It also works very well for detecting peripheral objects both moving and stationary within short distances. Ultrasonic sensors work to a good degree in detecting relative velocity and acceleration of other objects. This sensor technology does not work well in the presence of other ultrasonic sensors (cross talk with other ultrasonic sensors), which may lead to false detection. It also does not work well in detecting road curvature, lane width, ground scene complexity, object classification, motion detection, or at long distances (e.g., more than 6m).

The short-range radar operates very well in detecting objects at a short range (e.g., less than 30m) and the detection of dynamic and stationary objects, as well as operating in fog conditions. It works very well in detecting posts, chain link fences, and chains and to a good degree in snow and rain conditions. The radar does not work well for object classification, 3D reconstruction, yaw rate detection, or below very short distances (e.g., less than 1m).

Use Case Limitations

The implementation of a Valet Parking (Bus Yard) automation system in a transit bus may experience deteriorated performance in the following use cases. For bus applications, the use case limitations include:

- Operating near other vehicles with ultrasonic sensors
- Operating in areas with high sound pressure (e.g., construction area with jack hammers in use)
- Operating in a construction zone with barrels and cones
- Operating in flooded areas/shallow water
- Operating in areas with moving pedestrians or animals
- Pulling into a parking space moving forward in a lot with a chain link fence in front or to the side
- Operating in areas with semi-stationary objects (e.g., trees, signs, posts, chains)

- Pulling into a parking space moving in reverse in a lot with a chain link fence behind or to the side
- Operating in areas with high EMC/EMI interference that interferes with the wireless communications system

System Control Algorithm

The Valet Parking (Bus Yard) algorithm works by fusion of the ultrasonic sensor and radar data for detecting a free space and maneuvering around close proximity objects into the parking spot.

Path planning for this automation system requires input from the wheel speed information system of the vehicle. Ultrasonic sensors are capable of operating from close to 0 to 4m of distance very accurately in most cases. Both the ultrasonic sensor and radar data are used to detect the available parking spot and the appropriate size of the spot. The radar improves the robustness of detecting the available parking spot through the detection of objects such as posts, cones, chain link fences, and chains.

System Actuator Control

Valet Parking (Bus Yard) control in light-duty vehicle applications can be described on a high level as follows: A wireless controller is used to communicate with the automation system ECU; this ECU processes the sensor data, fuses it, plots a vehicle movement path, incorporates the wheel speed information system, and sends requests to the steering, braking, and powertrain systems control modules via CAN. A primary controller (powertrain control module or another vehicle module like the body control module) arbitrates between the requests from the automation system and other vehicle systems. Communications to the driver during the operation of the system are sent via the wireless communication system to the remote control unit. The remote controller is used to activate/deactivate the system and to ensure that the driver is constantly monitoring the vehicle operation from the start to the end of the parking maneuver.

Transferability to Bus Applications

Valet Parking (Bus Yard) affects the steering, braking, and powertrain systems, in addition to other vehicle systems. An assessment of this impact is as follows:

- *Braking* – The brake systems used on buses are mostly pneumatic with little electronic control. Valet Parking (Bus Yard) will require a change to the brake system technology. Although it is possible to modify some of the pneumatic system components to support this automation system, the modifications necessary would likely be very extensive and are unproven.

- *Transmission* – A Shift by Wire transmission system is required to support this automation system
- *Steering* – The majority of bus steering systems are hydraulic, with little or no electronic control. The absence of electronic control complicates the transferability of Park Assist automation systems to bus applications.

  Heavy trucks use variable effort systems for driver assistance. The concept of the variable effort can be expanded to support automation systems such as Valet Parking (Bus Yard). A similar approach was used on bus demonstration projects in the US and abroad. However, the vehicle dynamics will need to be better understood for the bus applications if the variable effort concept is to be expanded as described above. Key questions to be answered are with regard to system response time and accuracy. The accuracy of the system response is crucial in Valet Parking (Bus Yard) given the close proximity of the bus to other vehicles during the parking maneuver.

  Moving the bus steering system technology to electro-hydraulic technology will facilitate the implementation of Valet Parking (Bus Yard). This move is viewed as not very challenging from the technology point of view, given that it is already widely used in heavy truck applications.

  The bus powertrain system will be able to support Valet Parking (Bus Yard) without major technology modifications, because the system includes an electronic controller and control software for basic operations. Input from the automation system may be handled in a similar manner as the input from the accelerator pedal.

- *Wheel Speed Information* – Valet Parking (Bus Yard) will require a sophisticated wheel speed information system capable of providing count information in both forward and reverse direction.
- *Dedicated Short Range Communication* – A wireless communication system is required to be added to the bus to support Valet parking (Bus Yard).
- *Communications* – The communications system on bus applications is mostly hardwired. The electronic control required by Valet Parking (Bus Yard) will likely require upgrade to a CAN system.

In summary, Valet Parking (Bus Yard) requires major changes to bus systems; some of these changes are considered advanced technology for high-end light-duty vehicles such as the DSRC system.

Safety of Transferability

The safety classification of Valet Parking (Bus Yard) in light-duty vehicles is high and is expected to be the same for bus application.

The impact of this automation system on several foundational bus systems will lead to stringent requirements for design and manufacturing of many systems and components; this adds a high level of complexity to the transferability of these automation systems to bus applications. An assessment is as follows:

- *Brakes* – The high safety classification coupled with the inclusion of the brake system results in very stringent safety design, development, and manufacturing requirements.
- *Transmission* –Shift by Wire transmission system safety aspects will need to be incorporated into the system.
- *Steering* – In case of the use of the variable effort concept used in heavy trucks to support the steering portion of this system, the safety of the variable effort systems will need to be demonstrated.
- *Powertrain* – The bus powertrain system will need to be updated to incorporate the required safety aspects.
- *Dedicated Short Range Communications* – The safety of the DSRC system will need to be incorporated into the system.

The safety of bus communications channels between the automation system, the HMI, and the rest of the vehicle systems also need to be demonstrated.

Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

In summary, the safety impact of the Valet Parking (Bus Yard) on bus applications is a major challenge for transferability.

Grade

Based on the above analysis, the transferability of the Valet Parking (Bus Yard) system to bus applications is rated Red. The reason for this rating is that the changes required for several bus systems to support the functionality and safety of this automation system imply significant technological challenges. The brake system technology needs to be changed to allow for electronic control. The required transmission system changes are significant. The steering system changes to allow for electronic control are major. The addition of the DSRC system is a significant change. The communication system needs to be changed to support the transfer of many signals (both wire-based and wireless) quickly, reliably, and safely between the automation system and the rest of the affected vehicle systems. Although the technologies required for steering, braking, transmission, and communication systems exist in the automotive industry and in heavy trucks, some of these technologies, as noted previously, are considered advanced technology for the light-duty vehicle industry, and they still require development work to address robustness of the function. The adaptation to bus applications will require significant changes by system suppliers and bus manufacturers. These changes include the design and validation of the systems, changes to manufacturing and assembly operations, and changes to service and maintenance operations, which will likely dictate significant changes to bus systems packaging and layout. The high safety classification will also introduce another level of complexity across the affected systems and all bus interfacing systems; the safety impact will also cascade into manufacturing, maintenance, and service operations changes. The time required for these changes may be close to a decade, and the cost will be extremely high.

Yard Park

System Description

System Function

A Yard Park system steers a bus into the same "home" location when the system is activated; the driver activates the system when it enters the bus yard or maintenance facility. The system learns the specified environment and path, including objects classification and location, and maneuvers through the environment to a pre-specified "home" location. The system controls steering only.

Vehicle Systems Affected

The primary vehicle systems affected are steering, communications, and the HMI.

Bus Applications Use Cases

The primary use case of a Yard Park system is the homing maneuver. This includes moving forward to complete the homing maneuver. For bus application, the use case will be limited to a bus yard or maintenance facility. Therefore, the system will likely operate on paved or unpaved surfaces, fully-or partially-covered surfaces, inside a structure (barn) or outside, split mu, and, to a lesser degree, on regular roads. Yard Park may be turned on where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus. It also may operate in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs, posts fences, chains, and debris) and during all weather conditions, including low visibility, dust, smoke, fog, rain or snow.

Sensors Required

A Yard Park system requires ultrasonic sensors placed in the front, side, and rear of the vehicle; it also requires front and side cameras.

Feasibility of Transferability

Sensors Limitations

The ultrasonic sensor in combination with cameras chart and learn the homing path and end location. The ultrasonic sensor works very well in almost all weather and other environmental conditions; changes in temperature are addressed in the calibration of the sensor parameters internally. It also works very well for detecting peripheral objects both moving and stationary within short distances. Ultrasonic sensors work to a good degree in detecting relative velocity and acceleration of other objects. This sensor technology does not work well in the presence of other ultrasonic sensors (cross talk with other ultrasonic sensors), which may lead to false detection. It also does not work well in detecting road curvature, lane width, ground scene complexity, object classification, motion detection, or at long distances (e.g., more than 6m).

The cameras work well for detecting path boundaries, object classification, 3D reconstruction, detection of dynamic objects, detection of stationary objects, and yaw rate detection. This supports the identification of the path based on previously-existing objects as well as updating the path with newly-introduced objects. The cameras work to a good degree in identifying the curb and when trying to detect distance to another object and work to a good degree in uses cases where rain or dust are present. The cameras do not work well in cases of partially- or fully-covered roads, fog, or snow.

Use Case Limitations

The implementation of a Yard Park automation system in a transit bus may experience deteriorated performance in the following use cases:

- Operating near other vehicles with ultrasonic sensors
- Operating in areas with high sound pressure (e.g., construction area with jack hammers in use)
- Operating in a construction zone with barrels and cones
- Operating in flooded areas/shallow water
- Operating in areas with moving pedestrians or animals
- Pulling into a space moving forward in a lot with a chain link fence in front or to the side
- Operating in areas with semi-stationary objects (e.g., trees, signs, posts, and chains)

- Pulling into a space moving in reverse in a lot with a chain link fence behind or to the side
- Operating with different but similar objects around and ahead of the vehicle

System Control Algorithm

The Yard Park algorithm works by fusion of the ultrasonic sensor and camera data to first learn the path and the home location. The data are used for detecting free space, occupied space, object location, and classification and for maneuvering around close-proximity objects into the home spot. The algorithm continues to learn and update the path and its surroundings every time the system is activated. The ultrasonic sensor plays a major role in detecting the free and occupied space, and the cameras play a major role in object detection and classification.

System Actuator Control

The Yard Park control in light-duty vehicle applications can be described on a high level as follows: an ECU processes the sensor data, fuses it, compares the object location classifications to a previously-stored set, and sends requests to the steering system control module via CAN. The steering system control module arbitrates between the requests from the automation system and other vehicle systems. Communications to the driver during the operation of the system to shift, propel, and brake are sent via CAN from the ECU or other vehicle controllers to the HMI display. Activation/deactivation of the Yard Park is controlled by the driver via the HMI system; if the system is activated outside the area of "homing" operation, the system will not function.

Transferability to Bus Applications

The majority of the bus steering systems are hydraulic, with little or no electronic control. The absence of electronic control complicates the transferability of Yard Park automation systems to bus applications.

Heavy trucks use variable effort systems for driver assistance, and the concept of the variable effort can be expanded to support automation systems such as Yard Park. A similar approach was used on bus demonstration projects in the US and abroad. However, the vehicle dynamics will need to be better understood for bus applications if the variable effort concept is to be expanded as described above. Key questions that need to be answered are with regard to the system response time and accuracy. The accuracy of the system response is crucial in Yard Park given the close proximity of the bus to other vehicles during the homing maneuver.

Moving the bus steering system technology to electro-hydraulic technology will facilitate the implementation of Yard Park. This move is viewed as not very challenging from the technology point of view, given that it is already widely used in heavy truck applications.

The impact of Yard Park is not limited to bus steering systems. The communications system on bus applications is mostly hardwired. The electronic control required by Yard Park will likely require upgrades to the communication system. Most light-duty vehicles use CAN systems. The bus electrical and communications systems will be affected to a large degree.

In summary, Yard Park requires changes to the bus steering system to be transferred from light-duty vehicles or heavy trucks.

Safety of Transferability

The safety classification level of this system is low for light-duty vehicles and is expected to be the same or slightly lower for bus applications; this is due to the fact that bus applications require expert drivers.

In case of the use of the variable effort concept used in heavy trucks, the safety of the variable effort systems will need to be demonstrated. In heavy truck applications, the variable effort system is used to reduce the physical effort required by the driver, so these systems are not classified as safety relevant in that application. Therefore, they are not required to comply with ISO 26262 in trucks. If such systems are to be used to support Yard Park, then the classification of these systems changes to safety-relevant; this leads to more stringent design, development, and manufacturing requirements than what is currently required.

The safety of the bus communication channels between the automation system, the HMI, and the steering system will also need to be demonstrated. Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

A transition to an electro-hydraulic steering system will benefit from the safety designs that are presently successfully applied in light-duty vehicle steering systems. The elements of the safety design have also been adopted by many heavy truck electro-hydraulic steering systems.

Grade

Based on the above analysis, the transferability of the Yard Park system to bus applications is rated Yellow. The reason for this rating is that the changes required to the bus steering and communication systems to support the functionality and safety of this automation system imply major technological changes. The steering system needs to be changed to allow for electronic control. The communication system needs to be changed to support the transfer of many signals quickly, reliably, and safely between the automation system and the steering system; this requires a change into something similar to the light-duty vehicle CAN system. Although the technologies for the required steering and communication systems exist in the automotive industry and in heavy trucks, the adaptation to bus applications will require changes by system suppliers and bus manufacturers; these changes include the design and validation of the systems, changes to manufacturing and assembly operations, and changes to service and maintenance operations. The time required for these changes may be a few years, and the cost will be high.

Adaptive Cruise Control (ACC) with/without Stop-and-Go

System Description

System Function

An Adaptive Cruise Control (ACC) with/without Stop-and-Go system maintains a time gap between the bus and the vehicle in front of it without exceeding a set speed. The system may also control speed based on information from speed limit signs or geocoded speed limit data. The system controls powertrain and braking. Without Stop-and-Go, the system operates above a set speed threshold (e.g., 10 kph or 6.2 mph); with Stop-and-Go, the system operates down to zero speed, shuts off the engine, and restarts when the conditions for the bus movement are met (e.g., vehicle ahead moves and reaches a certain distance).

Vehicle Systems Affected

The primary vehicle systems affected are starting, powertrain, transmission, braking, parking brake, communications, and the HMI.

Bus Application Use Cases

The system may be turned on during all road conditions and most operating locations, including all roads, expressways, highways, intersections, tunnels, bridges, under-bridges, construction zones, fully- or partially-covered surfaces roads, and split mu. The system is not intended to operate in a bus yard or maintenance facility or at passenger pick-up stations. It may be operated during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow. This system operates where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus and in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs).

Sensors Required

ACC with/without Stop-and-Go requires a front camera and front short- and long-range radars.

Feasibility of Transferability

Sensors Limitations

The front camera works well for object classification, 3D reconstruction, detection of dynamic objects, detection of stationary objects, and yaw rate detection. The camera works to a good degree in uses cases where rain or dust are present and when trying to detect distance to another object. The camera does not work well in cases of fog or snow, and it should not be relied on to detect the differential velocity between the bus and another vehicle.

Long-range radar operates very well in detecting objects at a long range (e.g., more than 30m) and the detection of dynamic and stationary objects. It operates very well in foggy conditions and to a good degree in snowy and rainy conditions. The radar does not work well for object classification, 3D reconstruction, or yaw rate detection.

Short-range radar has the same operational limitations as long-range radar except it works very well for short distances (e.g., less than 30m); it does not work well below very short distances (e.g., less than 1m).

Use Case Limitations

The implementation of an ACC with/without Stop-and-Go automation system in a transit bus may experience deteriorated performance in the following use cases:

- Driving in heavy rain/snow/fog/dust
- Driving in sun-glare effect conditions
- Exiting a tunnel into a high ambient light condition (glare or more than 100,000 Lux)
- Entering a tunnel from a high ambient light condition (more than 100,000 Lux)
- Driving in a long tunnel (excessive multiple path reflections)
- Driving behind traffic on curvy roads
- Driving behind a chrome trailer that reflects traffic images
- Vehicle with trailer crossing the road horizontally in front of the bus
- Driving on roads with large debris/objects moving (objects) on the road (e.g., people and animals)
- Driving on roads with flying debris (e.g., items falling off of a truck with different sizes)
- Driving on a road with a stalled vehicle partially in the lane ahead of it
- Another vehicle partially invades vehicle's lane while driving

- Another vehicle traveling at high speed passes while vehicle trying to change lanes
- Driving with vehicles (motorcycles, bicycles) doing lane-splitting

System Control Algorithm

ACC with/without Stop-and-Go operates based on the fusion of camera and radar data. The cameras can detect objects and classify them, and the radar detects relative speed and location of the other vehicles or objects. The radar can bridge the range limitations of the cameras. The addition of radar data provides confirmation of object location and differential speed, so the algorithm detects the location, direction, and relative speed of other vehicles and objects and controls the distance between the bus and the vehicle in front at a set speed. A Stop-and-Go system detects the zero speed of the vehicle in front, stops the bus, and shuts down the engine. It then restarts it when the conditions for vehicle movement are met.

System Actuator Control

The ACC with/without Stop-and-Go control in light-duty vehicle applications can be described on a high level as follows: an ECU sends requests to the powertrain control module and/or brake system control module via CAN. The powertrain and/or brake system control modules arbitrate between the requests from the automation system controller and other vehicle systems. Communications to the driver on the status of automation system operations are sent via CAN from the system's ECU or other vehicle controllers to the HMI display.

Activation/deactivation of the system is controlled by the driver via the HMI system. With the Stop-and-Go feature, the automation system control unit sends a request to the power train control module to shut off the engine when the traffic is stopped ahead of the vehicle; the control unit sends a request to the powertrain control module or another vehicle controller (e.g., body control module) to restart the engine when conditions for vehicle movement are met.

Transferability to Bus Applications

ACC with/without Stop-and-Go affects the braking and powertrain systems in addition to other vehicle systems. An assessment of this effect is as follows:

- *Braking* – The brake systems used on buses are mostly pneumatic, with little or no electronic control. ACC with/without Stop-and-Go will require a change to the brake system technology. Modifications to some pneumatic system components to support this automation system will not be sufficient. The modifications necessary would likely be very extensive and are unproven in terms of the effect on the overall brake system performance.

- *Park Brake* – An Electric Park Brake system is required to support this automation system if Stop-and-Go is included to address if the vehicle is stopped for an extended period.
- *Powertrain* – The bus powertrain system can support ACC with/without Stop-and-Go without major technology modifications, as the system includes an electronic controller and control software for basic operations. Input from the automation system may be handled in a similar manner as input from the accelerator pedal.
- *Communications* – The communications system on bus applications is mostly hardwired. The electronic control required by ACC with/without Stop-and-Go will likely require upgrade to a CAN system.

Safety of Transferability

The safety classification of this automation system in light-duty vehicles is moderately high and is expected to be the same for bus application.

The impact of this automation system on several foundational bus systems will lead to stringent requirements for design and manufacturing for many systems and components; this adds a high level of complexity to the transferability of these automation systems to bus applications. An assessment is as follows:

- *Brakes* – The inclusion of the brake system coupled with the high safety classification leads to very stringent design and manufacturing requirements.
- *Electric Park Brake* – Safety aspects will need to be incorporated into the system.
- *Powertrain* – The bus powertrain system will need to be updated to incorporate the required safety aspects.
- *Communications* – The safety of the bus communications channels between the automation system, the HMI, and the rest of the vehicle systems will also need to be demonstrated.
- *Mechanical* – Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

In summary, the safety impact of ACC with/Without Stop-and-Go on bus applications is a major challenge for transferability.

Grade

Based on the above analysis, the transferability of the ACC with/Without Stop-and-Go system to bus applications is rated Red. The reason for this rating is that the changes required for several bus systems to support the functionality and safety of ACC with/Without Stop-and-Go imply significant technological challenges. The brake system technology needs to be changed to allow for electronic control. The park brake system changes are significant. The communication system needs to be changed to support the transfer of many signals quickly, reliably, and safely between the automation system and the rest of the affected vehicle systems; this requires a change into something similar to the light-duty vehicle CAN system. Although the technologies required for brake, powertrain, starting, park brake, and communication systems exist in the automotive industry and in heavy trucks, adaptation to bus applications will require significant changes by system suppliers and bus manufacturers. These changes include the design and validation of the systems, changes to manufacturing and assembly operations, and changes to service and maintenance operations. The high safety classification will also introduce another level of complexity across the affected systems and all bus interfacing systems; the safety impact will also cascade into manufacturing, maintenance, and service operations changes. The time required for these changes may be several years, and the cost will be significant.

Traffic Jam Assist (TJA) with Lane Keeping/Lane Centering (LK/LC)

System Description

System Function

A Traffic Jam Assist (TJA) with Lane Keeping/Lane Centering (LK/LC) system provides a combination of Stop-and-Go, ACC, and LK/LC to the bus driver in heavy traffic. The system maintains a set distance between the bus and the vehicle in front and controls the speed down to zero, shuts off the engine, restarts the engine, and moves the vehicle forward when conditions are met. The system also maintains the vehicle within lane boundaries or at the center of the lane.

Vehicle Systems Affected

The primary vehicle systems affected are starting, steering, powertrain, transmission, braking, parking brake, communications, and the HMI.

Bus Application Use Cases

The system may be turned on during all road conditions and most operating locations, including all roads, expressways, highways, intersections, tunnels, bridges, under-bridges, construction zones, fully- or partially-covered surfaces roads, and split mu. The system is not intended to operate in a bus yard or maintenance facility or at light-duty pick up stations. It may be operated during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow. This automation system operates where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus and in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs).

Sensors Required

The TJA with LK/LC system requires a front camera and front short- and long-range radars.

Feasibility of Transferability

Sensors Limitations

The front camera works well for object classification, 3D reconstruction, detection of dynamic objects, detection of stationary objects, and yaw rate detection. It works to a good degree in uses cases where rain or dust are present and when trying to detect distance to another object. The camera does not work well in cases of fog or snow and should not be relied on to detect the differential velocity between the bus and another vehicle.

Long-range radar operates very well in detecting objects at a long range (e.g., more than 30m) and the detection of dynamic and stationary objects. It operates very well in foggy conditions and to a good degree in snowy and rainy conditions. The radar does not work well for object classification, 3D reconstruction, or yaw rate detection.

Short-range radar has the same operational limitations as a long-range radar, except it works very well for short distances (e.g., less than 30m); it does not work well below very short distances (e.g., less than 1m).

Use Case Limitations

The implementation of a TJA with LK/LC automation system in a transit bus may experience deteriorated performance in the following use cases:

- Driving in heavy rain/snow/fog/dust
- Driving into a flooded road/shallow water
- Driving in sun-glare effect conditions
- Exiting a tunnel into a high ambient light condition (glare or more than 100,000 Lux)
- Entering a tunnel from a high ambient light condition (more than 100,000 Lux)
- Driving on roads with surface discontinuities (potholes and bumps)
- Driving on roads that have faded lane markers or tar strips
- Driving on roads that have old lane markers with new lane markers painted offset
- Driving on roads with lanes separated by Botts' Dots

- Driving on roads with lanes partially covered (debris, leaves, snow)
- Driving into a construction zone
- Driving on roads with flares used by police and emergency crews to temporarily close lanes
- Driving on a lane that splits into two lanes
- Driving in a long tunnel (excessive multiple path reflections)
- Driving behind traffic on curvy roads
- Driving behind a chrome trailer that reflects traffic images
- Vehicle with trailer crossing the road horizontally in front of the bus
- Driving on roads with large debris/objects moving (objects) on the road (e.g., people and animals)
- Driving on roads with flying debris (e.g., items falling off a truck with different sizes)
- Driving on road with a stalled vehicle partially in the lane ahead of it
- Another vehicle partially invades vehicle's lane while driving
- Driving with vehicles (motorcycles, bicycles) doing lane-splitting
- Driving with different objects around and ahead of the vehicle

System Control Algorithm

For the powertrain portion of the TJA with LC/LK, the system operates based on the fusion of camera and radar data. The cameras can detect objects and classify them, and the radar detects relative speed and location of the other vehicles or objects. The addition of radar data provides confirmation of object location and differential speed, so the algorithm detects the location, direction, and relative speed of other vehicles and objects and controls the distance between the bus and the vehicle in front at a set speed.

For the LK/LC portion, the front camera detects the lane boundary, and the system locates the bus within the lane (LK) or at the center of the lane (LC). If the camera is unable to detect the lane markings, the radar is relied on to detect the traffic ahead and keep the bus within the lane boundaries; also, the system relies on landmarks to interpolate lane boundaries if necessary.

System Actuator Control

The TJA with LK/LC control in light-duty vehicle applications can be described on a high level as follows: an ECU sends requests to the powertrain control module and/or brake system control module and/or steering system control module via CAN. These foundational systems controllers arbitrate between the requests from the automation system controller and other vehicle systems. Communications to the driver on the status of the automation system operations are sent via CAN from the system's ECU or other vehicle controllers to the HMI display. Activation/deactivation of the automation is controlled by the driver via the HMI system.

Transferability to Bus Applications

TJA with LK/LC affects the braking, steering, and powertrain systems in addition to other vehicle systems. An assessment of this impact is as follows:

- *Braking* – The brake systems used on buses are mostly pneumatic, with little electronic control. TJA with LK/LC will require a change to the brake system technology. Modifications to some pneumatic system components to support this automation system will not be sufficient.
- *Park Brake* – An Electric Park Brake system is required to support this automation system; this is to address if the vehicle is stopped for an extended period.
- *Powertrain* – The bus powertrain system can support TJA with LK/LC without major technology modifications because the system includes an electronic controller and control software for basic operations. Input from the automation system may be handled in a manner similar to input from the accelerator pedal.
- *Steering* – Most bus steering systems are hydraulic, with little electronic control. This complicates the transferability of this automation system to bus. In case of the use of the variable effort concept used in heavy trucks to support the steering portion of this system, vehicle dynamics will need to be better understood for bus applications. Key questions to be answered are with regard to system response time. Moving the bus steering system technology to electro-hydraulic technology will facilitate the implementation of TJA with LK/LC. This move is viewed as not very challenging from the technology point of view, given that it is already widely used in heavy truck applications.
- *Communications* – The communications system on bus applications is mostly hardwired. The electronic control required by TJA with LK/LC likely will require upgrading to a CAN system.

Safety of Transferability

The safety classification of this automation system in light-duty vehicles is moderate and is expected to be the same for bus applications.

The impact of this automation system on several foundational bus systems will lead to stringent requirements for design and manufacturing for many systems and components; this adds a high level of complexity to the transferability of this system to bus applications. An assessment is as follows:

- *Brakes* – Although the safety level of this automation system is expected to be moderate, the impact on the design and manufacturing of the brake system will be significant.
- *Park Brake* –Safety aspects will need to be incorporated into the system via an Electric Park Brake system.
- *Steering* – Steering system safety design and manufacturing aspects will need to be demonstrated. In case of the use of the variable effort concept used in heavy trucks to support the steering portion of this system, the safety of the variable effort systems will need to be demonstrated.
- *Powertrain* – The bus powertrain system will need to be updated to incorporate the required safety aspects.
- *Communications* – The safety of the bus communications channels between the automation system, the HMI, and the rest of the vehicle systems also must be demonstrated.
- *Mechanical* – Mechanical components of the affected bus systems may benefit from the proven-in-use argument for safety and reliability.

Grade

Based on the above analysis, the transferability of the TJA with LK/LC system to bus applications is rated Red. The reason for this rating is that the changes required for several bus systems to support the functionality and safety of TJA with LK/LC imply significant technological challenges. The brake system technology needs to be changed to allow for electronic control. The steering system changes to allow for electronic control are major. Park Brake systems changes are significant. The communication system needs to be changed to support the transfer of many signals quickly, reliably, and safely between the automation system and the rest of the affected vehicle systems; this requires a change into something similar to the light-duty vehicle CAN system. Although the technologies required for brake, steering, powertrain, starting, park brake, and communication systems exist in the automotive industry and in heavy trucks, the adaptation to bus applications will require significant changes by system suppliers and bus manufacturers. These changes include the design and validation of the systems, changes to manufacturing and assembly operations, and changes to service and maintenance operations. The safety classification will also introduce another level of complexity across the affected systems and all bus interfacing systems; the safety impact will also cascade into manufacturing, maintenance, and service operations changes. The time required for these changes may be several years, and the cost will be significant.

Object Detection and Collision Avoidance (ODCA)

System Description

System Function

An Object Detection and Collision Avoidance (ODCA) system may be considered one of the fundamental building blocks for many automation systems, including the 12 other systems considered herein. The system identifies stationary and moving objects around the bus and provides input to human vision systems (image displays) or automation systems. In case of potential collision, the system provides a multi-level warning to the driver; in case of a high probability of collision, the system is the basis for commanding braking or steering torque depending on the system it is supporting. The system may make steering or brake systems more sensitive to help the drivers avoid collisions.

Vehicle Systems Affected

Depending on the automation system supported by ODCA, the primary vehicle systems that may be affected are steering, powertrain, transmission, braking, communications, and the HMI.

Bus Applications Use Cases

Given that ODCA may be used in support of many automation systems, this function may be active during all road conditions and most operating locations, including all roads, expressways, highways, intersections, tunnels, bridges, under-bridges, construction zones, fully- or partially-covered surfaces roads, and split mu. The system may be operate in a bus yard or maintenance facility or at passenger pick-up stations. It may be operated during all weather conditions, including low visibility, dust, smoke, fog, rain, or snow. This automation system operates where vehicles are present, stopped, or moving in all directions (same, opposite, across) relative to the bus and in the presence of pedestrians, animals, debris, or semi-stationary objects (e.g., trees, signs, etc.).

Sensors Required

ODCA, depending on the automation system it supports, may require one or all of the three base sensor technologies—ultrasonic sensors, cameras, and radar.

Feasibility of Transferability

Sensors Limitations

For automation systems that involve detection of pedestrians, ultrasonic sensors and radar are deficient in detecting and classifying humans, so the effect of their limitation is mitigated to a good degree by the use of cameras.

For automation systems that require the detection of moving objects and differential speeds at long and short distances, cameras and ultrasonic sensor are deficient; radar addresses these deficiencies.

In automation systems that require detection of objects at very close distances, as well as operations in bad weather conditions, the camera and radar deficiencies are mitigated, to a large degree, by ultrasonic sensors.

Use Case Limitations

Depending on the automation system supported by ODCA, the use case limitation includes those in which the detection of objects, vehicles, or pedestrians is impaired by the sensor or algorithm limitations. If the ODCA system is supporting an automation system, there may be additional use case limitations. These limitations are discussed in the other 12 systems included herein.

System Control Algorithm

Object detection and free space determination are the basis for most automation algorithms. Occupancy maps, object tracks, and free paths are determined based on input from one or more sensors. In general, sensor data are fused, but input from sensors may be used independently. Automation system needs are established based on maps, tracks, and paths and are provided to the automation system controller. For example, in the case of AEB, camera and radar data are used to establish the object track (location, direction, differential speed), and track information is delivered to the controller to determine system actions.

System Actuator Control

The automation system may have a dedicated electronic controller, or it may share a controller with other functions. A trend in the industry is to consolidate all automation systems controls into one electronic controller to save cost and space. The automation system controller sends requests to the associated foundational vehicle system controller (brakes, powertrain, or steering) based on the output of the control algorithm. Most of the time, the vehicle system controller arbitrates between the request from the automation system and other vehicle inputs; for example, in the case of Full Park Assist, the brake system controller may receive requests for braking torque from the driver and the automation system at the same time. The foundational system controller takes action considering the arbitration strategy.

Most, if not all, automation systems have a default setting and are controlled by the driver via the vehicle's HMI system. Communications between all vehicle systems involved is via the vehicle's communications systems (mostly CAN based).

Transferability to Bus Applications

Although the addition of the required sensors and automation system controller to bus application is not a major challenge, the extent of the changes to the associated bus foundational systems to support the automation system range from minor (powertrain-related) to extremely difficult (brake system-related). If the ODCA system is supporting an automation system, there may be additional transferability considerations. These considerations are discussed in the other 12 systems included herein.

Safety of Transferability

In light-duty vehicle applications, ODCA safety is developed per the recommendations of ISO 26262, which provides recommendations that cover all aspects from design to hardware and software components. Therefore, the automation system sensors, their output, and the control algorithm itself (including occupancy maps, object tracks, and free paths) adhere to the requirements of ISO 26262. These are established approaches in the light-duty vehicle industry and can be carried over to bus applications.

Most automation systems that can operate during high-speed scenarios and involve collision avoidance have a high safety classification. The associated bus foundational systems will need to demonstrate compliance with the high safety requirements of the system. If the ODCA system is supporting an automation system, there may be additional safety considerations. These considerations are discussed in the other 12 systems included herein.

Grade

ODCA functions are rated Green given that the system involves the transfer of sensors and an electronic controller from light-duty vehicles to bus applications; the algorithms are well-known and have been in use for several years. Packaging into the bus is relatively easy, especially because styling and space are less constrained for bus applications than for light-duty vehicles. Some work may need to be done to determine the type, number, and positioning of various sensors due to their larger footprint and the different shape of buses compared to light-duty vehicles and commercial trucks.

The actual rating in terms of Green, Yellow, or Red will follow the automation system that ODCA supports. Every system discussed in this section uses a form of ODCA; objects detected range from vehicles moving to high-speed, to semi-stationary objects found in a parking lot or a maintenance facility, to people. Collision avoidance involves vehicles, objects, and people.

System Transferability Summary

This section describes 13 systems and assesses their transferability in terms of feasibility and safety. Based on these assessments, each system is assigned a grade of Green, Yellow, or Red. A grade of Green suggests that that minor modifications to foundational bus systems may be required but the technologies are easily transferable from light-duty vehicle or commercial truck applications. A grade of Green also indicates that safety issues or concerns are few and of low severity. A grade of Yellow suggests that major modifications to one or more foundational bus systems may be required to transfer applications from other vehicle type and that safety issues or concerns are considered low to moderate. A grade of Red suggests that significantly new technology may be required for one or more foundational bus systems and that safety issues may be moderately high.

The following summarizes the grading of the 13 systems considered:

- Green
  - Object Detection and Collision Avoidance (ODCA)
- Yellow
  - Lane Keeping/Lane Centering (LK/LC)
  - Steering Assist
  - Docking
  - Park Assist
  - Park Out
  - Yard Park
- Red
  - Automatic Emergency Braking (AEB)
  - Reverse Brake Assist
  - Full Park Assist
  - Valet Parking (Bus Yard)
  - Adaptive Cruise Control (ACC) with/without Stop-and-Go
  - Traffic Jam Assist (TJA) with Lane Keeping/Lane Centering (LK/LC)

Object detection systems are the most ready for transfer and were graded as Green, although it should be noted sensors for those systems can include component inputs and automation systems that are graded Yellow or Red. Applications using only automated steering were graded as Yellow due to the modifications required. Automation of current transit bus brake systems, particularly electronic actuation of braking, is more challenging, so applications using automated braking or a combination of automated braking and automated steering were graded as Red.

SECTION

7

Concluding Remarks

This technical review of SAE Level 2 and lower automation systems analyzes the technical feasibility and safety implications of their transferability to transit buses from other motor vehicle applications, such as light-duty vehicles and commercial trucks. The analysis has implications for both FTA and industry. Identified herein are core elements of foundational systems that will need to be addressed to enable automation in transit buses. These findings are directly relevant for FTA's strategic decisions regarding research programming. Similarly, the findings have strategic implications for industry's research and development. Key findings from the report include the following:

- Transferring existing automation systems from other vehicle formats is not straightforward. Beyond the minor adjustments needed to install an automation system on a new vehicle model (e.g., modifying the number and placement of sensors to accommodate a new vehicle footprint), transferring these systems to buses requires modification, replacement, or redesign of components and systems on the bus.
- To enable automation systems, the transit bus industry will need to implement foundational and interfacing systems that can support electronic actuation.
- Modifications to powertrain systems in support of automation should be made more easily than modifications to other foundational systems (i.e., steering and braking).
- Bus steering systems may require more modification, but heavy-duty vehicle steering solutions exist to enable automation and may not require extensive changes.
- With respect to technologies currently found in light-duty vehicles and commercial trucks, automated steering applications may be easier to transfer to transit buses than automated braking applications.
- Implementation of electronic control of a transit bus brake system appears to be a major challenge, as pneumatic brakes found in buses are less conducive to automation and more extensive design changes may be needed.
- Automated applications, especially those requiring a braking component, may require a new communication system architecture with bandwidth to carry numerous complex signals reliably.
- Buses will require new human-machine interfaces to control automation systems, although these should be relatively easy to design and implement.

- Sensors are relatively mature and should be able to be adapted to buses without modification.

Implications for FTA

This report assesses the transferability of automation technologies to inform FTA on the state of the industry generally and to inform future research priorities. Grades (Red/Yellow/Green)[27] were given to various applications as indications of the ease of transferability as compared to the need for additional development. Object detection systems are the most ready for transfer and were generally graded as Green. Technologies for the actuation of automated collision avoidance strategies are less conducive to direct transfer and were typically graded as Yellow or Red. Applications using only automated steering (e.g., LK/LC, Steering Assist, Docking, and Park Assist) were graded as Yellow due to the modifications required to enable automated steering. Automation of current transit bus brake systems, particularly electronic actuation of braking, is more challenging. Consequently, applications using automated braking or a combination of automated braking paired with automated steering (e.g., AEB, ACC, and TJA) were typically graded as Red.

A significant part of FTA's research mission is to fund demonstration of transit technologies, with the goal of improving system performance throughout the industry. When considering research and demonstration priorities, FTA might consider not only the relative transferability of an application, but also the objectives that federal research and demonstration can serve. For example, if proof-of-concept demonstrations are anticipated to stimulate the transfer of automation technologies to transit buses, it may make sense to prioritize the most easily-transferable technologies (graded as Green or Yellow). If facilitating the transition to more versatile foundational systems is a goal, it may make more sense to prioritize less easily-transferable technologies (graded as Yellow or Red). The strategic decision to incentivize either or both should be carefully considered given the analytical results presented in Section 6.

Other factors to consider beyond the ease and safety of transferring a technology. Transit agencies have particular issues that are conducive to automation solutions (e.g., eliminating gaps at boarding platforms or keeping buses centered in narrow lanes or road shoulders). FTA should consider the importance and value of the problem to be addressed when prioritizing research and demonstration projects. Similarly, some technologies may help

[27] Section 5 contains an in-depth explanation of the grades used in this report. Applications graded as Green are technically simple to implement and have a low safety classification, meaning that they pose little safety risk associated with failure of the automated system, whereas those graded as Red may require significantly new technology and have a high safety classification, meaning that they pose substantial safety risk associated with failure of the automated system. Applications graded as Yellow are in-between and may require major modifications to one or more foundational systems and have a low to moderate safety classification.

reduce operational or other costs (e.g., maintenance and repair or insurance liability) more than others and, hence, be more valuable to transit agencies than applications that may be more readily transferable.

Implications for Industry

Automation systems work by assessing the current status of a vehicle and commanding appropriate action by one or more vehicle foundational systems (e.g., braking, steering, and powertrain). The commands are communicated to controllers that drive actuators, such as motors, valves, and switches. For an automation system to perform its function in a vehicle, the foundational system must be able to accept and understand electronic signals and control the actuators accordingly. The foundational system must also be able to communicate with the automation system and other vehicle interfacing systems.

In the case of electronic control systems that directly affect vehicle and occupant safety, functional safety concepts require that they be able to ensure the integrity of the received and transmitted communications and verify the actions taken by its components. The foundational system must be able to implement commands in a timely manner.

System Requirements

To leverage existing automation systems, the transit bus industry will need to implement foundational (e.g., steering and powertrain) and interfacing systems (e.g., communication and HMIs) that can support the electronic actuation requirements of automation systems. Transit bus designs have evolved, with braking, steering, and powertrain systems that are effective in terms of function and efficient in terms of cost. To support automation, however, transit buses will need foundational systems that can also be electronically-controlled. In addition to light vehicles, commercial trucks are also a good source of technologies that might be transferred to buses given similarities in terms of vehicle size and weight. Additional findings are discussed for powertrain systems, communications systems, steering systems, and brake systems in the subsections below.

Powertrain System

The bus powertrain system may be the most straightforward to modify for automation applications due to its current use of electronic sensors and controls. Since the late 1980s, engine controls for heavy-duty diesel engines have used ECUs to manage fuel injection. Modern electronic controls manage inputs from a numerous sensors (e.g., to monitor position, speed, pressure, temperature, and status of various components) and actuators (e.g., to control injectors, compressors, heaters, fans, and valves). Hybrid and electric powertrains are electronically-controlled to an even greater extent. Many of the same engine sensors and actuators in current systems can be used and controlled by automation systems.

Communications System

Upgrading existing transit bus communication systems (i.e., CAN) to support automation will be a greater challenge. A new communication system architecture that can support future enhancements to the brake system and other vehicle systems will be necessary. Communication systems will be required to have the bandwidth to carry numerous complex signals reliably.

Steering System

Although most current transit bus steering systems are partially or completely mechanical in nature, electronically-controllable options are being deployed for heavy vehicles. Electro-hydraulic steering systems for heavy vehicles are, in fact, currently available from multiple suppliers. Presumably, therefore, transit bus steering systems that are capable of electronic actuation might be available within a few years. The bus industry may also benefit from research to understand the barriers for adopting transmission by wire.

Electronically-actuated steering systems such as electro-hydraulic steering are required for compatibility with the implementation of automated steering systems. These automated steering systems include revenue service automation systems (such as LK/LC, Docking, and Steering Assist) and yard operations service automation systems (such as Park Assist and Park Out). Steering-based automation systems that require continuous driver engagement (LK/LC) have a moderate or low safety classification,[28] and automation systems that require only periodic driver engagement (such as Steering Assist as defined in this report) have a high safety classification. Overall, the implementation of electronically-controllable steering represents a good opportunity to enable important automation systems.

Brake System

Implementation of electronic control of a transit bus brake system appears to be a major challenge. Most transit buses employ pneumatic brake systems, which are challenging to control electronically. Some heavy truck applications use a hydraulic brake system with electronic stability control, which may represent a viable starting point for the transit bus industry. However, such a transition

[28] Safety classification in this context is the result of the safety assessment, which determines the level of risk associated with a system failure in terms of exposure, controllability, and severity. Higher safety classification implies a greater level of risk associated with the system; therefore, the higher the safety classification, the more is required to be implemented in terms of safety design.

would essentially be a paradigm shift in the design and development of the brake system that could fundamentally affect manufacturing, maintenance, and service.

An electronically-controlled brake system will allow for the implementation of safety automation systems such as AEB, ACC, and Reverse Brake Assist. Brake systems are a critical foundational system for vehicle safety. Therefore, automation systems that rely on the brake system will require careful safety analysis. The implementation of functional safety principles will need to be considered early in the process of the technology transition. Early implementation also will help limit the cost and time required for transition, as the new bus architecture will lend itself to automation rather than needing major changes after the fact.

The bus industry may also need to invest in research to understand the barriers for adopting advanced automotive technology, such as vacuum-less brakes and electric parking brakes. Advanced braking technology research will support possible long-term implementation of advanced automation systems such as Full Park Assist and Valet Park (Bus Yard).

APPENDIX

A

SAE Automated Driving Taxonomy

This report refers to automation with respect to the SAE taxonomy (SAE J2016). [29] In general, SAE levels and definitions include the following:

- **Level 0 – No Automation**: Full-time performance by a human driver of all aspects of a dynamic driving task, even when enhanced by warning or intervention systems
- **Level 1 – Driver Assistance**: Driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task
- **Level 2 – Partial Automation**: Driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task
- **Level 3 – Conditional Automation**: Driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene
- **Level 4 – High Automation**: Driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene
- **Level 5 – Full Automation**: Full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.

Table A-1 provides further description of the SAE levels of automation.

[29] For more information, see: https://www.sae.org/standards/content/j3016_201609/.

Table A-1 *Levels of Automation*

Level	Name	Narrative definition	DDT		DDT fallback	ODD
			Sustained lateral and longitudinal vehicle motion control	OEDR		
Driver* performs part or all of the *DDT						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
***ADS* ("*System*") performs the entire *DDT* (while engaged)**						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

APPENDIX B

ACC	Adaptive Cruise Control
AEB	Automatic Emergency Braking
ASIL	Automotive Safety Integrity Levels (ISO 26262)
BRT	Bus Rapid Transit
CAN	Controller Area Network bus
DAS	Driver Assist System
DGPS	Differential Global Positioning System
ECM	Engine Control Module
ECU	Electronic Control Unit
EPS	Electric Power Steering
FTA	Federal Transit Administration
GPS	Global Positioning System
HEV	Hybrid Electric Vehicle
HMI	Human-Machine Interface
HPS	Hydraulic Power Steering
IDEA	Innovation Deserving Exploratory Analysis grant
ISO	International Organization for Standardization
LK/LC	Lane Keeping/Lane Centering
LTA	Land Transport Authority [Singapore]
MVTA	Minnesota Valley Transit Authority
NTU	Nanyang Technological University [Singapore]
ODCA	Object Detection and Collision Avoidance
PATH	California Partners for Advanced Transportation Technology
SAE	Society of Automotive Engineers
SRD	Safety Research and Demonstration grant
TJA	Traffic Jam Assist
VAA	Vehicle Assist and Automation

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