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Technical Report

***Review of Cooperative Truck Platooning
Systems***

Prepared for:
ecoTECHNOLOGY for Vehicles
Stewardship and Sustainable Transportation Programs
Transport Canada

Prepared by:
Bruce Gaudet, P. Eng.

Project A1-002600

ST-GV-TR-0011

September 3, 2014

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UNCLASSIFIED

Canada

REVIEW OF COOPERATIVE TRUCK PLATOONING SYSTEMS



(image from <http://www.sae.org/mags/sve/sfty/11937>)

Prepared for:
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National Research Council – Surface Transportation
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Technical Report

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ABSTRACT

The National Research Council Canada – Automotive and Surface Transportation portfolio conducted a literature review of cooperative truck platooning systems (CTPS), exploring potential benefits, enabling technologies, tests and demonstrations, factors affecting safety and fuel consumption, and other considerations. The literature review will provide Transport Canada with background information, and gather the intelligence required to define a workplan for a possible CTPS test and evaluation campaign, quantifying energy savings and emissions reduction, and exploring safety issues and feasibility. Important knowledge gaps, particularly with regard to conditions and constraints unique to Canada (e.g. geography, climate, infrastructure, social-political issues, etc.), were identified.

EXECUTIVE SUMMARY

The purpose of this literature review was to provide Transport Canada with background information on cooperative truck platooning systems (CTPS), summarizing the potential benefits, enabling technologies, significant tests and demonstrations, factors affecting safety and fuel consumption, and other considerations. Pertinent information was extracted from technical papers, reports, presentations, conference proceedings, and public websites. Important knowledge gaps, particularly with regard to conditions and constraints unique to Canada (e.g. geography, climate, infrastructure, social-political issues, etc.), were identified.

CTPS employs wireless communication and automation to create a convoy or “platoon” of two or more trucks which follow closely behind one another. Each following truck uses information from its own in-vehicle sensors, plus data received via wireless link from the lead truck, to “cooperatively” measure and adjust its position, based on the speed, direction and acceleration of the preceding truck. The platoon is typically led by a skilled professional driver, with drivers in the following trucks actively involved in the driving task; however, higher levels of automation are possible. The study focuses on heavy truck platoons operating around mixed traffic in non-dedicated lanes of divided highways, with limited consideration given to mixed platoons of cars and trucks, or fully automated truck platoons.

Potential Benefits of CTPS

CTPS may present an opportunity to significantly reduce fuel consumption and emissions, while potentially improving road safety and efficiency. Reducing the spacing between vehicles reduces the aerodynamic drag experienced by all vehicles in a platoon, and maintaining a consistent speed reduces the frequency of acceleration and deceleration, thereby reducing fuel consumption and CO₂ emissions. Since long-haul trucks accumulate high annual mileage, most of which is at highway speed, the savings could be substantial. The tests and demonstrations reviewed during the study indicated a range of fuel savings between 4.5 and 21 percent.

The literature revealed that through the use of sensors, vehicle-to-vehicle (V2V) communication, and some automated vehicle control, it may be possible to reduce or eliminate chain collisions, which often result from an inability of drivers to react quickly in emergency situations. In a cooperative truck platoon, the requirement for speed changes or manoeuvres is communicated automatically throughout the platoon in real time such that the platoon operates as a synchronized unit, smoothing traffic flow and improving traffic efficiency. Furthermore, as the gap between vehicles is reduced, traffic density is increased such that roadways are used more efficiently.

Enabling Technologies

CTPS is enabled by the emergence of several complementary technologies, including various advanced driver assistance systems (ADAS), V2V communication, and modern vehicle control methods and human-machine interfaces. Adding V2V communication to adaptive cruise control (ACC), known as cooperative adaptive cruise control, is ultimately what makes CTPS possible.

Technologies used to monitor the field surrounding a vehicle include long-range and short-range Radar, LiDAR, cameras and ultrasonic sensors. Sensors are often combined and integrated to exploit the features of the different technologies, using “sensor fusion” to gain a more accurate

picture of the surrounding environment, and to reduce integration complexity. Electronic vehicle control and actuation systems, permitting remote throttle control, steering and braking, are also important technologies for the automation required for CTPS. Modern instrument clusters and dash displays are intuitive and interactive, and may be configured to provide additional information required for platooning.

Various media (frequency bands) have been used for V2V communication in platooning trials, such as ultra-high frequency (UHF), microwave, millimetre wave and infrared. While each of these media and frequency bands has its own advantages and limitations, 5.9 GHz dedicated short range communication (DSRC) has evolved as the “standard” V2V (and vehicle-to-infrastructure) medium.

Studies, Tests and Demonstrations

Major projects have been undertaken in the U.S., Europe and Asia to evaluate the benefits and feasibility of CTPS. The PATH program has been operating in California since 1986, and has conducted several platooning trials including two- and three-truck platoons. The European PROMOTE-CHAUFFEUR project was one of the earlier demonstrations of CTPS with two trucks, using an “electronic towbar” system. A second phase demonstrated the feasibility of a three-truck platoon operating in real world environments. The German KONVOI project investigated the benefits and deployment issues associated with CTPS operating in mixed traffic on autobahns. The European SARTRE project demonstrated a mixed platoon of cars and trucks operated in a public, mixed-traffic environment, where the platoon was led by a manually-driven truck followed by automated vehicles. The Japanese Energy ITS project demonstrated a platoon of three identical 25-tonne single unit trucks, all of which (including the lead vehicle) were controlled automatically while in the platoon. Scania was preparing to start platooning trials between the Swedish cities of Södertälje and Helsingborg, coordinating the daily departure of several trucks, such that they would form a platoon as soon as they reached the motorway. Peloton has proposed a CTPS concept for two class 8 trucks based on the installation of commercial-off-the-shelf components. The proposal includes operation of a platoon network operations centre, where Peloton would coordinate linking opportunities and manage platoon activities to enforce safe platooning conditions.

The Connected Vehicle Safety Pilot program includes driver clinics across the U.S., and a large-scale model deployment conducted in Ann Arbor, MI, from August 2012 to December 2013. Over 2800 vehicles, including cars, trucks and buses, have been outfitted with V2V devices using 5.9 GHz DSRC. The model deployment will assess the effectiveness of numerous safety applications, and driver clinics will be used to explore driver reactions to the technology and the safety applications. The results will be used by the National Highway Traffic Safety Administration (NHTSA) to decide whether to advance the technology through regulatory proposals, additional research, or a combination of both.

Factors Affecting Safety

CTPS safety is dependent upon several factors, including equipment reliability; vehicle and platoon spacing; platoon length, speed and composition; platooning manoeuvres; the level of automation; surrounding traffic; weather conditions; data security; and human factors. The system design must incorporate a high level of health monitoring (e.g. diagnostics, built-in test), and employ fail-safe modes to mitigate the danger associated with an equipment failure. The driver (if present) must be able to assume control and override the system at any time.

Communication delays and system response times must be considered in determining minimum safe following distances. The use of dedicated lanes could enhance the safety of CTPS, since the behaviour of other vehicles can be reasonably predicted, and speed is much more consistent. Adverse weather can affect the feasibility, effectiveness and safety of CTPS, and there may be conditions when safe platooning is not possible. Data security issues must also be considered, and suitable countermeasures developed.

Factors Affecting Fuel Consumption

The reduction in fuel consumption and CO₂ emissions that can be achieved by CTPS is affected by several factors, including vehicle size, type and weight; vehicle and platoon spacing; platoon length and speed; lateral alignment of platoon vehicles, and cross winds; and the duration of effective platooning. Platooning at close following distances can significantly reduce the aerodynamic drag, leading to a reduction of fuel consumption and emissions. The potential fuel savings increase as the gap between vehicles is decreased, to a gap of approximately 8 m for heavy trucks. The most significant fuel savings are experienced by those vehicles between the lead and tail vehicles, so the longer the platoon, the greater the net savings. Similarly, the shorter the gap and the longer the platoon, the greater the traffic density and therefore the road capacity. The length of the platoon is bounded by the V2V communication speed and reliability required in order to maintain string stability. The length must also be limited to avoid bottlenecks at highway entrances and exits. The platoon speed should be optimized to achieve the greatest fuel economy for the individual vehicles. While fuel consumption is affected by vehicle weight (due to rolling resistance), the actual reduction in fuel consumption due to CTPS, expressed in L/100 km, is independent of the vehicle weight. The potential fuel savings are sensitive to the lateral alignment of the vehicles, and crosswinds tend to increase the aerodynamic drag experienced by all vehicles in a platoon. The duration of an established platoon determines the fuel savings that can be achieved due to CTPS. In mixed traffic, cut-ins by non-platoon traffic present the biggest obstacle to maintaining platoon integrity. The acceleration required by all following vehicles to close the gap and re-establish the platoon following a cut-in is inefficient. Since aerodynamic drag varies with air density, and the reduction in the drag coefficient due to CTPS should be similar at all ambient temperatures, the reduction in fuel consumption should be greater at colder temperatures.

Other Considerations

In order to conduct CTPS, coordination is required to design and establish the platoon, considering factors such as truck type, weight, performance parameters, installed equipment, current location, destination, etc. Cooperation and financial arrangements between carriers may be required. Provincial regulations will be required to authorize and control platooning, perhaps similar to those developed for long combination vehicles (LCVs). Similarly, equipment specifications, driver training and qualifications, inspecting agency certifications, etc. must also be established. Since data is exchanged between vehicles, privacy issues will need to be addressed. Liability issues must also be addressed since partially-automated systems and a lead driver are assuming some responsibility for the operation of the platoon. Managed lanes or dedicated truck lanes may facilitate the introduction of CTPS with minimal impact to the existing infrastructure. Finally, truck drivers must demonstrate an interest in CTPS for it to become popular. Enhanced driving comfort, safety, and efficiency, as well as reduced fuel consumption, would likely influence driver acceptance.

Comparison with Long Combination Vehicles (LCVs)

LCVs are single vehicles comprised of one tractor and two or three full length trailers, which are well suited for hauling lightweight goods which tend to “cube out”. The fuel consumption and emissions are significantly reduced due to the elimination of one or two tractors, plus the reduction of aerodynamic drag between the trailers due to the close spacing. Restrictions typically include where and when LCVs can operate, as well as the maximum speed and weight. Since an LCV only uses one tractor, it must travel as a complete combination vehicle at all times, usually between terminals designed to accommodate LCVs. Platoons, on the other hand, can be easily formed and dissolved as required. They offer more flexibility because each trailer is physically hitched to a suitably sized tractor, so the tractor-trailer combinations can operate independently. However, there is no reduction of the number of tractors (or drivers), and the minimum gap is greater than that possible with LCVs; therefore, the potential fuel savings are considerably less than that which is possible with LCVs.

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1 INTRODUCTION

1.1 Purpose

Transport Canada (TC) has retained the National Research Council Canada – Automotive and Surface Transportation (NRC-AST) portfolio, to conduct a literature review of cooperative truck platooning systems (CTPS). The literature review will provide TC with background information, and gather the intelligence required to define a workplan for a possible CTPS test and evaluation campaign, quantifying energy savings and emissions reduction, and exploring safety issues and feasibility. Further investigations are also proposed to benchmark the environmental and safety limits and performance requirements, and the costs and benefits of CTPS, with specific emphasis on cold climate and the effects of all-weather and road conditions and the impact of various types of aggregates (e.g. salt, sand, grit) under winter driving conditions.

1.2 Background

TC, through its ecoTECHNOLOGY for Vehicles (eTV) program, promotes and supports the conduct of in-depth safety, environmental and performance testing on a range of new and emerging advanced vehicle technologies for passenger cars and heavy-duty trucks. The results help to inform various stakeholders that are engaged in the development of regulations, codes and standards, to ensure that new technologies can be introduced in Canada in a safe and timely manner.

CTPS employs wireless communication and automation to create a convoy or “platoon” of two or more trucks which follow closely behind one another. Each following truck uses information from its own in-vehicle sensors, plus data received via wireless link from the lead truck, to “cooperatively” measure and adjust its following distance, based on the speed, direction and acceleration of the preceding truck. Different levels of automation may be employed, from a fully automated platoon (with no drivers), to a platoon led by a skilled professional driver (with either no drivers in the following vehicles, or drivers who are completely relieved of the driving task while in platoon formation), to the most basic configuration involving a professional lead driver and fully engaged following drivers, where the longitudinal control of the following vehicles is automated.

1.3 Scope

The literature review addresses the following topics:

- summary of potential benefits of CTPS (rationale for consideration of the concept)
- enabling technologies which make CTPS possible
- summary of significant tests and demonstrations related to CTPS
- factors affecting safety and fuel consumption, and other considerations
- comparison with long combination vehicles (LCVs)
- next steps to provide guidance on developing a workplan for a possible CTPS test and evaluation campaign

1.4 Limitations

This literature review introduces vehicle platooning in general, focusing where possible on cooperative truck platooning. However, recent advancements in autonomous vehicles and intelligent transportation systems (ITS), and in particular vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, have increased the feasibility of CTPS, even though the focus of these activities has been primarily road safety and not platooning. Therefore current “connected vehicle” activities and test results are considered for their applicability to CTPS. Conclusions are drawn from papers, reports and presentations, rather than empirical data. Inevitably the literature review presents a snapshot in time.

Given current Canadian infrastructure constraints, the study focuses on heavy truck platoons operating around mixed traffic in non-dedicated lanes of divided highways. Limited consideration is given to mixed platoons of cars and trucks, or fully automated truck platoons. It is generally assumed that the truck configuration is a typical tractor-trailer combination, involving an aerodynamic sleeper cab and a 53-foot dry van semi-trailer, as depicted in Figure 1.



Figure 1: Assumed Tractor-Trailer Combination¹

¹ http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/21centurytruck/21ct_goals_teams.html

2 THEORY

2.1 Aerodynamic Drag

The longitudinal forces acting on a vehicle in motion are depicted in Figure 2. The vehicle engine and powertrain generate a force to propel the vehicle forward, and that forward motion is resisted by rolling resistance, F_{roll} , and aerodynamic drag, $F_{airdrag}$. If the ground is level, then the grade, α , is zero, and there is no resistance due to gravity. If the grade is positive (i.e. an uphill), the gravitation force, $F_{gravity}$, opposes the forward motion of the vehicle. If the grade is negative (i.e. a downhill), the gravitation force, $F_{gravity}$, complements the powertrain force to propel the vehicle forward.

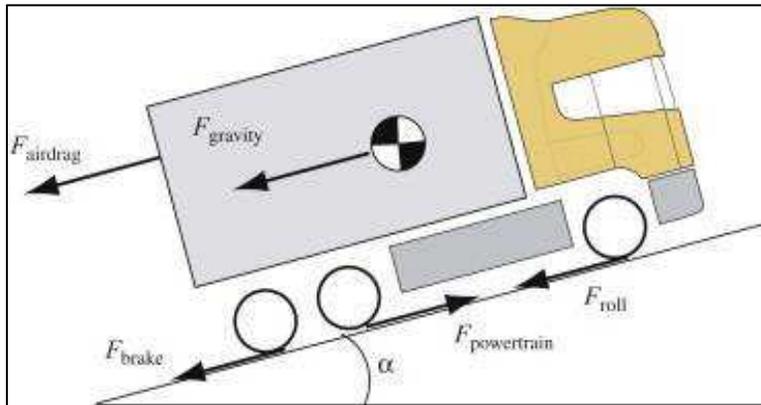


Figure 2: Longitudinal Forces on a Vehicle in Motion [1]

Assuming level ground and constant speed, rolling resistance varies linearly with vehicle speed, while aerodynamic drag varies with the square of vehicle speed. At approximately 53 km/h, the power required to overcome rolling resistance is approximately double that required to overcome aerodynamic drag. At 80 km/h the power requirement is roughly equal, and at higher speeds the aerodynamic losses dominate. [2]

The total aerodynamic drag results from a combination of pressure drag and friction drag. In general, pressure drag is caused by the difference in pressure between the front face (high pressure region) and blunt rear face (low pressure region) of the vehicle, while the friction drag is caused by friction along the vehicle surfaces aligned with the wind. Pressure drag typically accounts for approximately 70-90 percent of the aerodynamic drag of a heavy-duty vehicle.

Pressure drag can be reduced by “streamlining”, achieved by reducing or eliminating gaps where air can be entrained and trapped, and easing the transitions in the airflow over the vehicle. On a tractor-trailer combination, this could include gap reduction devices (between the tractor and the trailer), side skirts, and boat tails. Aerodynamic drag can also be reduced by operating vehicles relatively close together. The low-pressure wake of the leading vehicle will reduce the high-pressure region on the front face of the trailing vehicle. Conversely, the high-pressure region in front of the trailing vehicle will increase the base pressure on the rear face of the leading vehicle. These effects are complementary and lead to a reduction in the pressure drag (difference in pressure from front-to-back) for both vehicles. As detailed in this report, the potential fuel savings and emissions reduction due to platooning result from vehicles following

closely behind one another, thereby reducing the aerodynamic drag experienced by all of the vehicles in the platoon.

Although fuel savings due to the reduction of aerodynamic drag of vehicle platoons have been attributed to close vehicle spacing, such fuel savings will also be sensitive to the size and location of the air-wake in which the following vehicles reside. The following factors can affect the aerodynamic performance of the vehicles, but have generally not been considered when evaluating the potential fuel savings of platoons:

- **Vehicle Configuration:** The potential drag reduction of the following vehicles will depend on the size and strength of the air-wake of the leading vehicle. This air-wake is affected by tractor and trailer configuration. Classic-style tractors with non-streamlined shapes, or even aero tractors without a roof fairing, will generate larger wakes than streamlined vehicles. Add-on trailer technologies such as side-skirts and boat-tails tend to reduce the size of the wake.
- **Vehicle Alignment:** Platoon vehicles may not always be directly in-line with one another. Lateral offset may be present, and this affects the location within the wake that a following vehicle will reside.
- **Crosswinds:** In general, atmospheric winds are present which may be blowing from any direction. Relative to the vehicle direction of motion, any lateral component of the atmospheric wind will induce a crosswind that affects the drag of a heavy-duty vehicle and its air-wake characteristics. The wake will be larger in a crosswind, having a greater potential for reduced drag on a following vehicle; however, it will also be convected in the direction of the crosswind and, depending on the crosswind strength, the following vehicle may not be fully enveloped by the leading vehicle wake and therefore have a reduced potential for fuel savings.

2.2 Fuel Consumption

On a road with a grade, α , assuming a constant relative velocity to the surrounding air, fuel consumption is related to drag force, rolling resistance, and gravitational slope resistance. In a simple theoretical model, fuel consumption is expressed as a function of air density, cross sectional area, drag coefficient, speed, mass, and angle of incline [3] [4].

$$FC = k \left(\frac{1}{2} \rho A C_D(\psi) v^2 + f_{roll} m g \cos(\alpha) + m g \sin(\alpha) \right)$$

where FC = fuel consumption
 k = constant
 ρ = air density
 A = cross sectional area
 $C_D(\psi)$ = drag coefficient (a function of wind yaw angle)
 v = velocity (relative to the surrounding air)
 f_{roll} = rolling coefficient (considered as constant)
 m = mass
 g = gravitational constant
 α = angle of incline

The drag coefficient of a heavy truck is affected by several tractor-trailer features, including tractor design (shape), trailer configuration, gap between tractor and trailer, and appendages (e.g. mirrors). These features do not normally change while a truck is in motion (assuming the

truck is operating in a straight line). However, the drag coefficient is significantly affected by crosswinds, such that it is often expressed as a function of the wind yaw angle.

Although the total fuel consumption is a function of vehicle weight, the fuel savings achieved through a reduction in aerodynamic drag are independent of vehicle weight. Therefore care must be taken when expressing fuel savings as a percentage of fuel consumption. In other words, if platooning under certain conditions results in a reduction in fuel consumption of “x” L/100 km, the percentage fuel savings is reduced as the vehicle weight increases (since rolling resistance and therefore fuel consumption increases). Note that fuel consumption measurements are sensitive to test conditions such as temperature and wind conditions, and care must be exercised to eliminate any effects of grades (e.g. conduct testing in both directions). Comparative tests should be performed back-to-back to minimize changes in environmental conditions.

3 POTENTIAL BENEFITS

CTPS may present an opportunity to significantly reduce fuel consumption and emissions, while potentially improving road safety and efficiency.

3.1 Reduced Fuel Consumption

It is expected that the fuel consumption of heavy trucks could be reduced by cooperative platooning, since reducing the spacing between trucks reduces the aerodynamic drag experienced by all trucks in the platoon. As well, maintaining a consistent speed and anticipating speed changes permits more gentle acceleration and deceleration, thereby maximizing fuel efficiency. Since long-haul trucks accumulate high annual mileage, most of which is at highway speed, the savings could be substantial.

The overall reduction in the aerodynamic drag experienced by a platoon cannot be easily expressed in a theoretical model. It is affected by many factors, including vehicle spacing, geometry, alignment, speed, etc. Results can only be obtained by using simulation techniques, wind tunnel testing, or empirical data.

3.2 Reduced Emissions

There are a variety of pollutants that enter the atmosphere when any fossil fuel powered vehicle is operated, including hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter (PM). With the exception of CO₂, the pollutants are all “regulated tailpipe emissions”. CO₂ is considered a greenhouse gas (GHG), and it is widely considered that CO₂ emissions are the leading contributor to global warming.²

The regulated emissions are difficult to measure, and they are dependent upon numerous engine operating parameters. Reduced fuel consumption may result in reduced regulated emissions. However, CO₂ emissions are directly related to fuel consumption: 2.7 kg of CO₂ is released for every litre of diesel fuel that is burned.³ Therefore reduced fuel consumption will result in a reduction in GHG emissions. Throughout the report, reduced fuel consumption will imply a reduction in GHG emissions, specifically CO₂.

3.3 Improved Road Safety

Although vehicles in a platoon operate at relatively close spacing (which may be as close as 4 m), studies have shown that road safety could be improved by cooperative platooning. The inability of drivers to react quickly enough in emergency situations often results in chain collisions. Drivers are frequently unable to detect emergency situations far ahead due to an inability to see past the vehicle in front of them. In this case, they must rely on the illumination of brake lights on the vehicle immediately ahead to alert them to a developing emergency situation, and then decide on appropriate action to take to avoid a collision. If the vehicles are too close, or the driver of the following vehicle is inattentive, the driver may not be able to respond in time.

² <http://www.epa.gov/climatechange/ghgemissions/gases/co2.html>

³ <http://oee.nrcan.gc.ca/publications/transportation/fuel-guide/2007/calculating-co2.cfm?attr=8>

In a cooperative platoon, emergency messages are broadcast wirelessly to all vehicles in the platoon, and automated systems would respond with appropriate brake application to avoid any collisions (or at least minimize the relative velocity between vehicles to mitigate the severity of any impacts). Assuming negligible communication delay, a suitable braking response could typically be applied automatically within approximately 20 ms. The driver interface for vehicles within the platoon could also include a display with a forward-looking view as seen by the lead vehicle, which could reduce the response time for the driver of a following vehicle in the event of a developing situation where the driver is required to perform emergency manoeuvres.

A cooperative platoon would likely be led by a professional driver, with a proven safe driving record and enhanced training and skills to lead a platoon. The lead vehicle could be equipped with modern advanced driver assistance systems (ADAS) to further enhance the driver's ability to drive safely. Since the following vehicles simply follow the lead vehicle, the likelihood of a collision for any of the vehicles in the platoon may be reduced.

With speed automatically adjusted to maintain desired spacing between vehicles in a platoon, speed oscillations within the platoon may be reduced or eliminated, further decreasing the likelihood of collisions due to sudden braking. Platoons following platoons, each led by a skilled driver, could further reduce the incidence of speed oscillations.

3.4 Improved Efficiency of Existing Roadways

The capacity of a highway lane is expressed in terms of vehicles per hour, and it is a function of vehicle density (spacing) and speed. Cooperative platooning could increase highway capacity by reducing vehicle-following gaps, and enhancing string stability (maintaining more consistent speeds).

The capacity that can be achieved is also sensitive to lane use policy – i.e. which vehicles are permitted to use a particular lane. A strict policy permitting only vehicles with V2V communication capability, and/or vehicles with a specified minimum braking capability, can achieve higher capacity since following distances can be reduced without compromising safety. In this case, all vehicles behave consistently and predictably, avoiding potential hazards created by manual operation of vehicles.

At 100 km/h (27.8 m/s), a two-second headway spacing results in an inter-vehicle gap of 55.6 m. In Ontario, the maximum overall length of a typical tractor-trailer combination⁴ is 23.0 m, so this spacing would accommodate 13 trucks per km. If three trucks were operating in a cooperative platoon, with a constant spacing of 10 m, the platoon would occupy 89 m of highway. With a two-second spacing between platoons, a density of seven platoons (21 vehicles) per km would be achieved. The result is a 62 percent increase in capacity. As shown in Figure 3, extracted from National Automated Highway Systems Consortium (NAHSC) work in 1997 [5], highway capacity essentially doubled for a 3-truck platoon at approximately 65 mph (104 km/h) with 8 m spacing. The capacity is essentially tripled for a 10-truck platoon.

⁴ http://www.e-laws.gov.on.ca/html/regs/english/elaws_regs_050413_e.htm#BK37

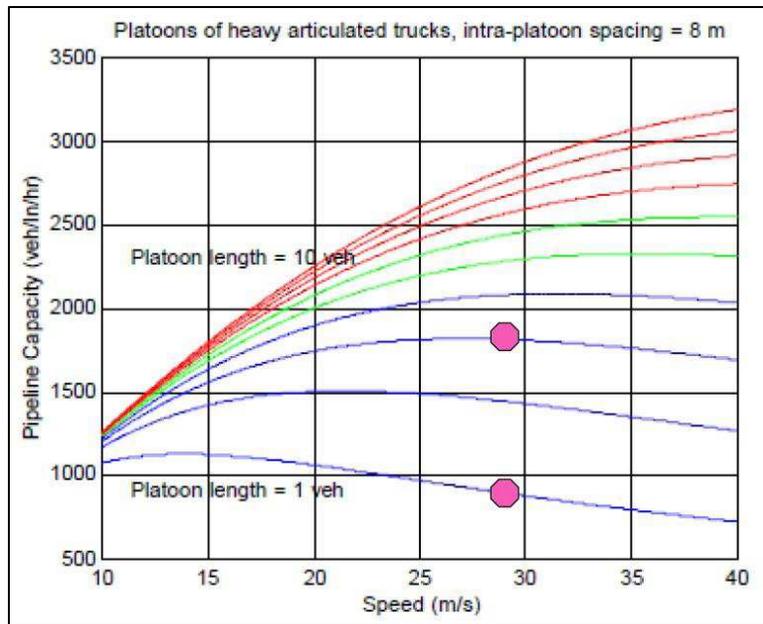


Figure 3: Automated Truck Platoon Capacity [5]

Shippers could experience an increase in the efficiency of movement of goods, as well as reduced costs, if traffic efficiency were improved through reduced congestion. Scheduling and timeliness of shipping would also be improved.

4 ENABLING TECHNOLOGIES

CTPS is enabled by the emergence of several complementary technologies, including ADAS and V2V communication. Modern vehicle control methods and human-machine interfaces, and the integration of these technologies, facilitate equipping trucks to participate in cooperative platooning. The following sections outline these technologies.

4.1 Advanced Driver Assistance Systems

Various comfort and safety systems, generally referred to as ADAS, have been developed and fielded in recent years, using one or a combination of the technologies described in Section 4.2. Some systems provide a warning to the driver, while others provide some level of automatic vehicle control. While manufacturers have developed numerous unique trade names for their systems, a brief description of the most relevant (generic) ADAS which enable CTPS is provided below. [6]

4.1.1 Adaptive Cruise Control

An adaptive cruise control (ACC) system uses a radar or LiDAR sensor to measure the distance to a preceding vehicle, and adjusts the speed to maintain the selected time headway between the vehicles. It actuates engine, transmission and brake controls as required. If there is no preceding vehicle or obstacle, the ACC system functions as a traditional cruise control system, establishing and maintaining the speed set by the driver.

4.1.2 Lane Departure Warning System

A lane departure warning system (LDWS) typically uses a camera system to monitor vehicle lane position, and provides a warning to the driver if the vehicle is leaving the current lane without the use of a turn signal. The warning is either audible, visual and/or haptic (such as vibrating the steering wheel to act as a simulated highway rumble strip). It may also include variable steering effort to gently oppose deviating from the marked lane, or more invasive counter-steering to keep the vehicle within the lane (requiring greater steering effort by the driver to depart from the lane, if desired). The system is normally disabled if a turn signal is activated.

4.1.3 Blind Spot Information System

A blind spot information system (BLIS) uses radar and camera sensors to warn a driver that a vehicle is in a blind spot (an area around a vehicle where the driver cannot detect an object using his mirrors and must turn his head away from the road) if the driver signals a lane change using his turn signal. The warning is typically audible and/or visual. Some systems may intervene by increasing steering resistance to deter a driver from effecting the lane change if it is considered unsafe to do so.

4.1.4 Drowsiness Detection System

Drowsiness detection systems are designed to monitor a driver's state of alertness, and provide a suitable warning if the driver becomes drowsy or inattentive. Some systems use a charge-coupled device (CCD) camera and infrared (IR) light emitting diodes (LEDs), mounted forward

of the driver, to track head pose or blink rate. Some systems use externally mounted cameras and radar sensors to detect erratic vehicle movements, while other systems monitor sensor data such as steering angle, braking, acceleration, and time of day to ascertain driver alertness. The warning is typically audible, but if the driver doesn't respond to audible alerts, the system may apply a brake pulse or some other haptic warning, or increase the intensity of the audible alarm.

4.1.5 Pre-Crash Systems

Pre-crash systems are generally categorized as collision warning systems (CWS) or collision avoidance systems (CAS), depending upon the level of automatic intervention. They typically use a radar sensor, often coupled with one or more cameras, to sense when the vehicle ahead is slowing or stopped. They alert the driver to the risk of a possible crash, and may prepare for the crash by pre-charging the brakes, adjusting the seats, and/or tensioning the seatbelts. If a crash is imminent, the system may take action to avoid or mitigate the severity of the crash by applying the brakes. The warning is typically audible and/or visual, and it may vary in intensity depending upon the threat.

4.1.6 Predictive Cruise Control

A predictive cruise control (PCC) system enhances and works in combination with an existing cruise control (or ACC) system to optimize fuel consumption. Using information from a three-dimensional map, current location data from a global positioning system (GPS) receiver, and a predictive algorithm, the optimal vehicle speed is calculated according to the road profile. While keeping within a set speed range, the vehicle accelerates before it begins to climb a hill, and its speed is permitted to drop before it reaches a downhill slope. The increase in speed on the downhill compensates for the drop in speed on the uphill climb. [7] Such a system could be particularly useful for CTPS, facilitating maintaining a desired gap on hills despite differences in hill climbing ability.

4.1.7 Global Positioning System

Many operators use a GPS to provide map directions and to locate points of interest, as well as to identify the current location of the vehicle. When coupled with a communication means, a GPS can automatically report the current location of a vehicle, with a potential accuracy of less than 1 m. This information could facilitate coordinating the formation of platoons, or providing relevant and timely information regarding road conditions, accidents, etc.

4.1.8 Cooperative Adaptive Cruise Control

The ADAS listed above, especially ACC, are key enabling technologies for CTPS. However, the synergy resulting from the introduction of V2V communication, as detailed in Section 4.3, is ultimately what makes CTPS possible.

ACC systems, in order to be effective, must filter and process the sensor data before causing the system to respond. These delays prevent the system from responding quickly to speed changes of the preceding vehicle, which limits the potential for ACC to permit close following distances, or enhance traffic flow capacity and stability. A typical commercially available system supports a default time headway of 2.8 seconds (equivalent to a gap of 78 m at 100 km/h).⁵

⁵ http://www.bendix.com/media/documents/products_1/acb_1/bw2807bendixwingmanacbfaq.pdf

A cooperative adaptive cruise control (CACC) system is achieved by adding a wireless V2V communication system and control logic to an ACC system, augmenting ACC sensor data with speed and acceleration and possibly braking capability data from preceding and following vehicles. This additional data provides much earlier indication of speed change requirements, which permits significantly closer following distances, and improves the stability of the speed of the vehicles in the platoon. Following vehicles react almost instantly, without having to wait for the preceding vehicle to act (and then detecting that action).

4.2 Surrounding Field Monitoring Technologies

Cooperative platooning is dependent upon vehicles being able to sense their surrounding environment, in order to control vehicle position and to operate safely. A summary of existing technologies and their typical application is shown in Figure 4. A description of the technologies is provided in the following sections.

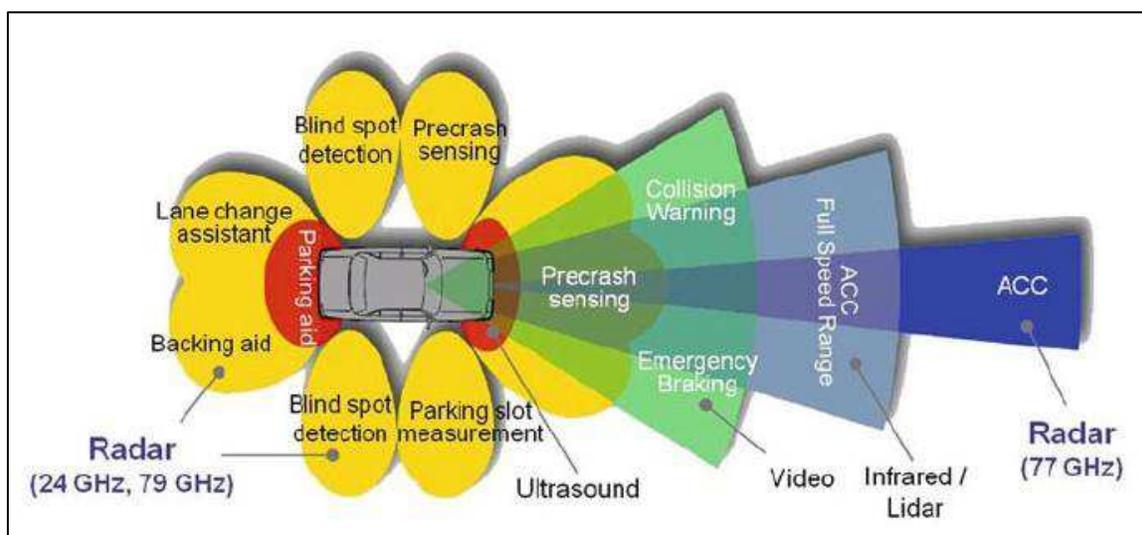


Figure 4: Surrounding Field Monitoring Technologies for Driver Assistance Systems [8]

4.2.1 Radar

The abbreviation *radar* stands for “radio detection and ranging”. It designates radio technology for the determination of distances to remote stationary or moving objects. [8]

Automotive radars are classified as long range radars (LRR) and short range radars (SRR). As shown in Figure 4, LRR (shown in blue) are used for long-distance sensing such as that required for ACC. SRR (shown in yellow) are used for wide-angle local sensing, for capabilities such as pre-crash sensing, blind spot detection and lane change assist. The two primary automotive radar bands in use today are 22-29 GHz (referred to as the 24 GHz band) and 76-81 GHz (referred to as the 77 GHz band) [9]. The 77 GHz band is typically used for LRR applications, whereas the 24 GHz band has traditionally been used for SRR applications. The 77 GHz band is currently allocated for ITS use in Europe, North America and Japan, and as technology advances, it is becoming the preferred band for both SRR and LRR applications.

To operate at higher frequencies, 77 GHz radars have historically been constructed using relatively expensive gallium arsenide-based chips. Recent advancements have permitted the use of special silicon-based chips, which are not only less expensive but also offer significantly better performance (four times the coverage, and four times the accuracy) and lower noise levels [10]. An example of a system employing this technology is shown in Figure 5, where the minimum radar detection range has been reduced to 0.5 m, and the maximum range has been increased to 250 m. The detection field of view was increased to 30 degrees, and the radar could be packaged in a compact size (74 x 70 x 58 mm).



Figure 5: Example LRR Sensor Using Silicon-Based Chips⁶

A 76 GHz SRR system has been developed for rear and side detection, offering better Doppler discrimination, wider bandwidth and a smaller radio frequency (RF) window than 24 GHz systems. The system supports blind spot detection, lane change assist, rear cross traffic alert, and rear pre-crash sensing. An illustration of the coverage areas is shown in Figure 6.

⁶ <http://johndayautomotiveelectronics.com/bosch-radar-and-stability-technologies-are-finalists-for-2010-automotive-news-pace%E2%84%A2-awards/>

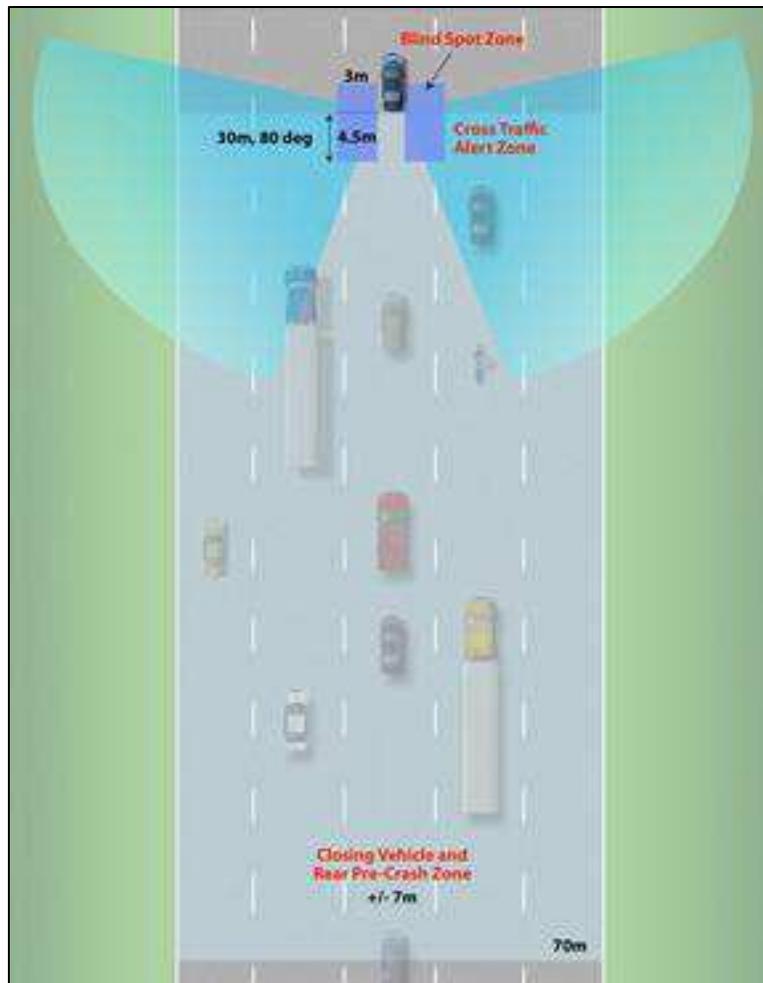


Figure 6: Sensor Coverage from 76 GHz SRR Rear and Side Detection System⁷

The advantages of radar over other sensing technologies, like video, LiDAR and ultrasound, come from its unique combination of properties that include the direct measurement of range as well as velocity information, good performance in poor weather conditions, and the ability to be mounted behind typical (non-metallic) automotive fascia. Also, where multiple technologies are employed, the radar data is heavily relied upon to improve the probability of detection and eliminate false alarms [9].

Some of the limitations of radar technology include limited azimuth resolution and height discrimination. For example, monopulse radars may present symmetrical infrastructure objects on narrow streets as a single object in the path of the vehicle, resulting in a false alert or an unwanted braking event. Similarly, low-profile objects on the ground or overhead structures may be seen as obstacles which present a hazard. Proliferation of automotive radars could lead to mutual interference, which would raise the signal-to-noise ratio and reduce accuracy. Coding and multiplexing schemes are required to address this issue. Radars would also have to be able to detect blockage of their field of view (e.g. due to snow or mud) and provide a notification to the driver of their reduced capability. [9]

⁷ <http://delphi.com/manufacturers/auto/safety/active/sds/>

4.2.2 Light Detection and Ranging

Light detection and ranging (LiDAR), also sometimes referred to as laser imaging detection and ranging or “laser radar”, is similar to radar but it is based on the reflection of laser pulses from objects rather than radio signals. A LiDAR sensor has a one-dimensional scanning ability which can accurately measure the relative distance from a preceding vehicle by scanning the horizontal plane with laser beams. The sensor uses a high-power laser diode to transmit IR light pulses with a wavelength in the range of 850 to 950 nm. A high-speed photodiode receives the light reflected by the preceding vehicle and determines the relative distance and speed. LiDAR sensors do not require special alignment during vehicle assembly since they can automatically align during operation. LiDAR-based ACC systems offer simple assembly, high reliability and a low-cost solution for proliferation across automotive platforms. [11]

A LiDAR sensor can sense both long and short ranges, and it provides a high angular resolution, making it a suitable technology for ACC and pre-crash systems. Unlike radar, LiDAR sensors are also able to interpret the size of an object. Since LiDAR is based on light, its effectiveness is reduced by fog, rain and snow. However, these same conditions limit the visibility of a driver, and ought to demand greater following distances. LiDAR systems can be used to calculate the actual visibility under such conditions, and determine a suitable following distance. [12] A LiDAR sensor is often coupled with a camera system to aid coverage and discrimination.

4.2.3 Camera

Cameras are often used to capture and process video images for use in pre-crash systems or LDWS. A forward-looking monocular camera is usually mounted inside the vehicle near the top centre of the windshield. The camera based pre-crash system identifies the closest object in the vehicle’s path and determines its scale change. Whenever size and optical growth of an object indicate a potential collision, a warning is given to the driver. Cameras are also frequently used to perform lane marking recognition to facilitate LDWS or automatic lane keeping, and for convenience features such as automatic high-beam control and speed limit sign recognition.

4.2.4 Ultrasonic Sensors

Ultrasonic sensors are based on sound waves being reflected by objects. The reflected sound waves can be used to detect distance and/or relative speed of objects at close ranges. As shown in Figure 4, ultrasonic sensors are often used in backing aid and parking assist systems.

4.3 Vehicle-to-Vehicle Communication

Safe and effective platooning requires cooperation between vehicles, which is facilitated by V2V communication. Wireless V2V communication presents unique challenges, though. Unlike a controlled infrastructure network, the environment and participants in a vehicular ad-hoc network are uncontrolled and change rapidly. The network must be flexible to accommodate both the addition of new vehicles and the withdrawal of existing vehicles, and permit efficient connection setup. For vehicle control scenarios like platooning, real-time and reliable data transmission are essential.

Various media (frequency bands) have been used for V2V communication in platooning trials, such as ultra-high frequency (UHF), microwave, millimetre wave and IR. Their relative location on the electromagnetic spectrum is shown in Figure 7. Specific UHF and microwave frequency bands have included 800-900 MHz, 2.4 GHz, 5.8 GHz, and 5.9 GHz [13]. While each of these media and frequency bands has its own advantages and limitations, 5.9 GHz Dedicated Short Range Communication (DSRC) has evolved as the “standard” V2V communication medium, as detailed in Section 4.3.1.

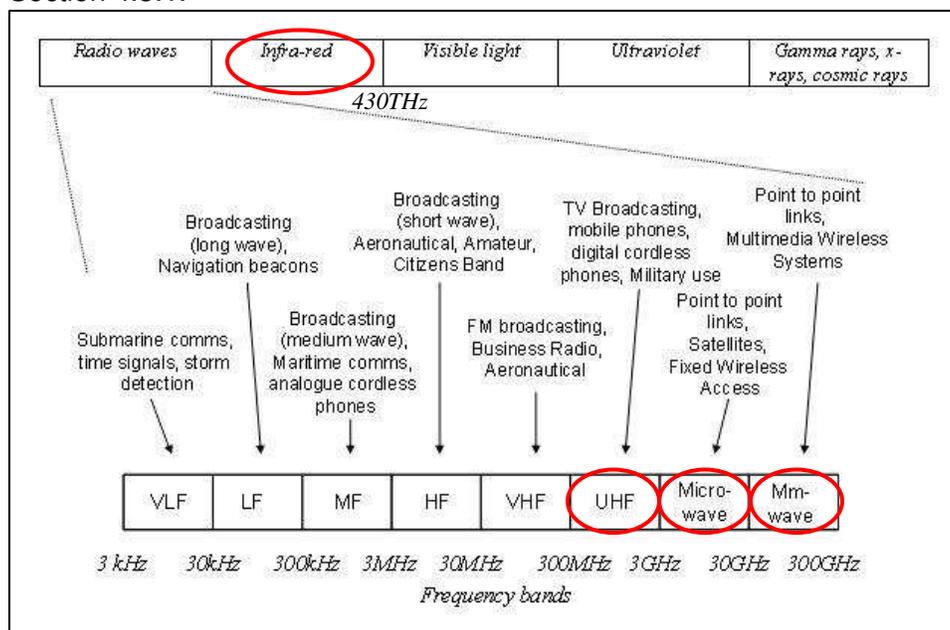


Figure 7: Vehicle-to-Vehicle Frequency Bands⁸

4.3.1 5.9 GHz Dedicated Short Range Communication

In order to ensure ample radio frequency spectrum and interoperability for future ITS safety applications, in 1999 the United States (U.S.) Federal Communications Commission (FCC) allocated 75 MHz in the 5.9 GHz band for licensed ITS use. Other licensed users of this frequency band include military radar and satellite communication systems. In 2003, the American Society for Testing and Materials (ASTM) and the Institute of Electrical and Electronics Engineers (IEEE) adopted the DSRC standard ASTM E2213-03, *Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems – 5 GHz DSRC Medium Access Control and Physical Layer Specifications*. The aim of this standard, which incorporated IEEE 802.11a, was to provide wireless communication capabilities for transportation applications within a 1000 m range at highway speeds up to 160 km/h. Note that in 2008, the central 30 MHz of the U.S. ITS frequency band was also allocated for ITS use in Europe.

The 802.11a medium access control protocol could not provide predictable quality of service, so 802.11p was subsequently introduced as an amendment to the IEEE 802.11 standard to add Wireless Access in Vehicular Environments (WAVE). 802.11p sets up to eight priority levels for different applications, such that every packet gets access to the medium based on the priority level of the application that generated it. [14]

⁸ http://www.comreg.ie/_fileupload/Image/RadioSpectrum/FrequencyBands.jpg

The DSRC spectrum provides seven non-overlapping 10 MHz channels at the 5.9 GHz licensed band, with the option to combine two channels into a single 20 MHz channel. The channel allocation and frequency bands defined by the FCC for the U.S. are shown in Figure 8. All safety messages are transmitted over a single channel, which is monitored by all vehicles. DSRC radios with a single transceiver must switch channels to monitor the safety channel and communicate non-safety messages on the service channels. Such channel switching can typically be performed in less than 1 ms. DSRC supports a high data transfer rate of 6-27 Mbps, with a low latency of less than 50 ms.

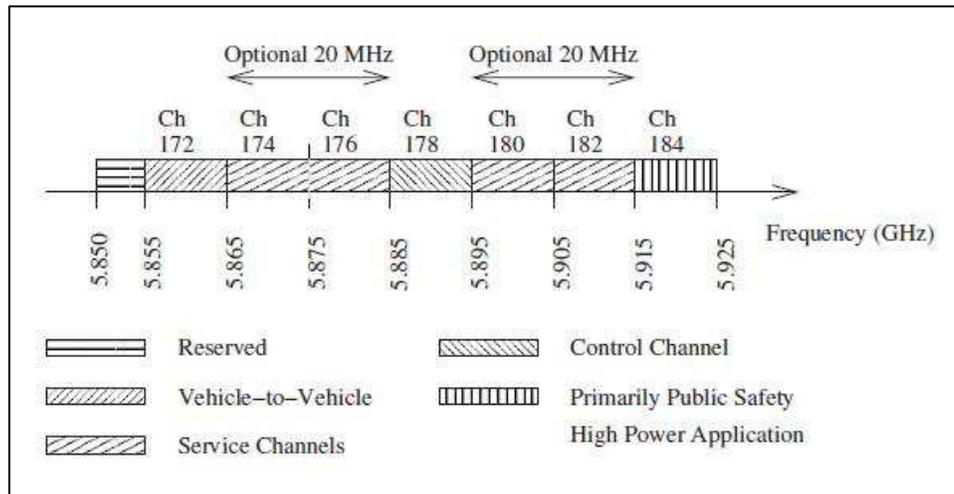


Figure 8: DSRC Channel Allocation and Frequency Bands [15]

The relatively narrow radio spectrum and the competing nature of wireless communication creates limitations which must be managed. Cooperative platooning requires that each vehicle track its neighbouring vehicles in real time, and adjust its driving parameters based on that data. The uncontrolled transmission of state information by each vehicle could easily generate excessive data traffic that could choke the vehicular wireless network and cause all applications to fail [16]. Furthermore, in an ad-hoc network, different stations may unknowingly send data at the same time, resulting in data collisions and communication failure.

Various performance optimization strategies to mitigate these shortcomings have been proposed and tested, with numerous technical papers produced. For example, Zhou et al. [17] developed a predictive control method algorithm for longitudinal control of a platoon in an unreliable wireless communication environment. The approach combines a statistical prediction model with an optimization algorithm to determine optimal control action for each time step. They performed successful simulation tests with a worst-case delay of 0.9 seconds. Similarly, various time division multiple access (TDMA)-based protocols have been explored [18], which dynamically allocate transmission time slots to individual vehicles within a platoon. Such solutions require accurate time synchronization, potentially using onboard GPS receivers. Fernandes [19] also proposed reducing message traffic by employing event-driven versus periodic messaging.

The U.S. Department of Transportation (DOT) Intelligent Transportation Systems Joint Program Office (ITS JPO) is responsible for conducting research to advance transportation safety, mobility, and environmental sustainability through electronic and information technology

applications. The Vehicle Infrastructure Integration (VII) program, later renamed IntelliDrive, was initiated to provide an infrastructure where vehicles can identify threats and hazards on the roadway and communicate this information over wireless networks to alert and warn drivers. At the core of VII is a networked environment facilitating high-speed communication among vehicles, and between vehicles and infrastructure or hand-held devices. [14] Security issues are addressed through authentication protocols, randomized vehicle addressing, and the use of public key infrastructure (PKI) encryption. The OmniAir Consortium and OmniAir Certification Services, both non-profit organizations, were formed to advance the deployment of standards-based, interoperable wireless transport technologies that improve mobility, safety and efficiency on U.S. ground transportation networks.⁹ Based on the results of the Connected Vehicle Safety Pilot program (detailed in Section 5.8.1), the U.S. DOT may mandate that every new vehicle be equipped with DSRC. These activities could further enable CTPS, as trucks may be required to have a DSRC radio, and receive safety messages from surrounding vehicles and the infrastructure.

4.3.2 Other Wireless Technologies

4.3.2.1 Optical

Optical communication systems, including lasers and IR, are well-suited for direct line-of-sight and relatively short communication, such as that between following vehicles. They support very high data exchange rates, offer a high level of security, and do not require licensing. The technologies can also be used for distance measurement. However, as the distance between the transmitter and receiver increases, the bit error rate also increases, making communication less reliable. Conversely, as the distance is reduced, the reliability of communication increases and the data transmission rate can be increased. This characteristic may be particularly useful in platooning where more precise control is required as the gap between vehicles is reduced. It would also be necessary to clean and align the optical transmitters and receivers regularly in order to achieve optimal signal strength and quality.

4.3.2.2 Cellular

Cellular communication technology has evolved quickly and significantly in recent years, with dramatic increases in data capacity and transfer rate. The latest cellular technology, long term evolution (LTE) – advanced, is capable of speeds approaching 1 Gbps, with a typical range greater than 1 km. However, cellular communication is indirect and relies on fixed infrastructure, such that V2V communication is conducted via a cellular network and service provider. This overhead results in V2V communication delays of approximately 500 ms, which may not be able to fulfil the safety requirements of extremely time critical control messages required for platooning [20].

The availability of a cellular network for V2V communication is code limited, in that the maximum number of users that can be served depends on the number of available codes in the network. As the number of concurrent users increases, the availability of the network for V2V communication is reduced. This limits the suitability of cellular technology for platooning, which requires dedicated communication between all vehicles in the platoon. Furthermore, cellular communication requires that the vehicles are within communicating range of a cellular network,

⁹ <http://www.omniaircertified.org/learn-about-omni-air-certification-services>

which may not be the case in some remote locations. The cellular network must also be operational, which requires uninterrupted grid power and functioning network equipment.

4.3.3 Hybrid Systems

V2V communication serves several purposes, and the best solution will likely incorporate more than one technology. Zang et al. [20] proposed a combination of the DSRC and the LTE technologies, noting that DSRC is well suited for cooperative road safety applications (e.g. cooperative collision avoidance and platooning), while LTE is well suited for cooperative traffic efficiency applications. Such a hybrid system would relieve DSRC of non-time-critical communication, and similarly relieve LTE of high-priority control and safety communication.

Fernandes and Nunes [19] proposed adding IR communication to a DSRC-based system to improve V2V reliability. The IR component can exchange high-bandwidth data between following vehicles, which could duplicate the DSRC control messages (for redundancy), and also facilitate the passage of video from the lead vehicle, for example. Note that an IR transceiver would have to be mounted on the rear of the trailer of a tractor/ trailer combination, and integrated with the V2V system in the tractor. As noted in Section 4.3.2.1, it would be necessary to clean and align the transceivers on the tractors and trailers in order to achieve optimal signal strength and quality. The performance of the transceivers would also be affected by precipitation, snow and ice build-up, etc.

Manufacturers are currently producing low-cost, compact, hybrid DSRC units which facilitate integration of V2V capability. Such units are being used for the large-scale connected vehicle Safety Pilot program in Ann Arbor, MI (detailed in Section 5.8.1). One example combines 5.9 GHz DSRC, GPS and Bluetooth¹⁰. It is designed to be integrated with a smartphone, which adds a user interface, cellular and WiFi capabilities. Another example includes an embedded GPS receiver and processor, and controller area network (CAN) bus and universal serial bus (USB) interfaces¹¹. It can also be easily paired to provide a two-radio solution.

4.3.4 Vehicle-to-Infrastructure

The preceding sections have addressed direct V2V communications, which is the minimum communication capability required for cooperative platooning. However, developments in ITS and connected vehicles will likely introduce V2I capabilities in the near future, where vehicles will broadcast information such as location, speed, acceleration and direction to roadside units. This data may be used to determine traffic density, which could then be used to establish variable speed limits, or actively manage traffic flow. It could also be used to identify hazardous conditions or accidents, which could be broadcast to nearby vehicles to provide traffic alerts, recommend alternate routes, and so on. V2I could also support electronic tolling and other efficiencies. While a thorough discussion of V2I is beyond the scope of this report, it should be noted that such capabilities would enhance the feasibility, effectiveness and safety of platooning.

¹⁰ <http://www.aradasystems.com/locomate-mini-obu/>

¹¹ <http://www.cohdawireless.com/product/mk2.html>

4.4 Vehicle Control

Modern vehicles are equipped with electronic vehicle control and actuation systems, which are important enabling technologies for the automation required for cooperative platooning. A platooning controller installed on the vehicle could generate and send the required control messages to the existing electronic control unit (ECU), using the CAN bus, and thereby cause the desired response (e.g. throttle control, steering, braking). An electronically-shifted automatic transmission will maintain the appropriate gear selection, electronic braking and the anti-lock brake system (ABS) will ensure controlled and effective braking, the electronic stability control (ESC) and/or roll stability control (RSC) system will ensure safe emergency manoeuvres, etc. Electric power steering (EPS) is becoming more popular, and this enables lateral control for higher levels of automation.

4.5 Human-Machine Interface

Modern instrument clusters and dash displays are interactive and configurable, providing excellent, relevant information to the driver. Such displays could be used to provide additional CTPS information as required. Vehicle-to-Device (V2D) integration could also support platooning, as powerful device (e.g. smart phone) applications could be integrated into the vehicle via a docking station. The device would offer portable processing and display capability which could be part of the platooning hardware solution.

4.6 Integration of Technologies

Integration of systems and components has the potential to reduce size and power requirements, reduce cost, and ease installation (for retrofit). Sensors are often combined and integrated to exploit the features of the different technologies, using “sensor fusion” to gain a more accurate picture of the surrounding environment. The combined system typically requires fewer modules, and can reduce latency associated with the exchange of sensor data between devices – an important factor for systems where real-time functionality is critical. Combining sensor data can also reduce the frequency of false alarms and inappropriate responses.

An example of integrated sensors combines radar sensing, vision sensing and data fusion in a single module, as shown in Figure 9. The technology integration enables a suite of active safety features that includes ACC, LDWS, and CWS. The small package size simplifies vehicle integration, allowing for application on the windshield, forward of the rear view mirror (on passenger cars). The system uses a compact 76-GHz radar sensor to provide superior long- and short-range performance, target discrimination, and more accurate range calculations compared to that of conventional automotive 24-GHz units [10].



Figure 9: Integrated Radar and Camera System¹²

¹² <http://articles.sae.org/12489/>

5 TESTS AND DEMONSTRATIONS

Automated driving and platooning of heavy trucks have been studied for decades, with major projects undertaken in the U.S., Europe and Asia. While improved traffic efficiency and safety are attractive potential benefits, the key motivation in Europe and Asia has been an improvement in energy efficiency to help countries meet their CO₂ emissions reduction commitments detailed in the Kyoto protocol.

Steven Shladover, from the California PATH Program, released a literature review and subsequent report entitled “Recent International Activity in Cooperative Vehicle-Highway Automation Systems”, in December 2012 [21]. The comprehensive report covers current activities related to developing, testing and deploying cooperative vehicle-highway automation systems in Europe and Asia, based on meetings, demonstrations, site visits, and his literature review.

An overview of platooning systems was also presented at the 19th ITS World Congress in Vienna in October, 2012. The paper, “Overview of Platooning Systems” [22], was prepared by key representatives from several of the significant platooning projects.

The most significant tests and demonstrations related to CTPS are described in the following sections.

5.1 Partners for Advanced Transportation Technology

California Partners for Advanced Transit and Highways (PATH) was founded in 1986 as a research entity focused on large-scale technical innovations for transportation. It was first the U.S. research centre dedicated specifically to ITS, located at the University of California, Berkeley, and it was initiated with funding from the California Department of Transportation (Caltrans). As announced in a press release on January 18, 2011, the California Center for Innovative Transportation, also a centre within the Institute of Transportation Studies at the University of California, Berkeley, was merged with California PATH. The new centre retained the PATH acronym; however, in the new organization, the letters now indicate the Partners for Advanced Transportation Technology (PATH). The centre has been conducting cutting-edge transportation research for 27 years, and has produced alumni – both students and faculty – who are transportation leaders and educators around the state, the U.S., and the world.

A Caltrans planning study for the Los Angeles region revealed that the only alternative to relieve congestion involved double-decking most major freeways, which was considered financially, politically, and environmentally unfeasible, and it was concluded that “building” will not solve the problem. [23] So it became a priority in California to determine how to achieve a highway capacity increase that is large enough to get ahead of the growth in population and economic activity. The PATH Program emphasizes research directions that offer potentially large improvements in the operations of the transportation system, relative to those that can make only incremental improvements. It also addresses the evolutionary steps that will be necessary to get to the long-term solutions.

The PATH Program research included some platooning activities, which are described herein. In 1994, a four-car platoon capability was demonstrated on the I-15 high occupancy vehicle (HOV) lanes in San Diego, CA, employing longitudinal control via throttle and brake actuators,

forward ranging radars, wireless local area network (LAN) communication systems, as well as control computers and software to implement cooperative vehicle following at close separations.

In August 1997, PATH demonstrated an eight-car fully-automated platoon of cars following each other in close formation. During the demonstration, one car changed lanes and shifted its position in the platoon formation while the “drivers” waved their hands to show that they were not steering, as shown in Figure 10. The gaps between the vehicles were maintained with a 0.2 m RMS error, which is small enough that vehicle occupants felt as if they had a mechanical coupling to the preceding car, while also maintaining a smooth ride quality for comfort [22].



Figure 10: PATH Program Eight-Car Fully-Automated Platoon Demonstration (1997) [23]

Several key conclusions were drawn from this platooning experience, including:

- automated platoons of passenger cars could increase capacity per lane by a factor of 2-3 (when conventional vehicles are excluded from the automated lane)
- automatic steering control can be accurate enough to permit significant reduction in lane widths for passenger cars
- the precise longitudinal control needed for safe driving within a close-formation automated platoon can be provided with smooth, comfortable ride quality
- vehicles can be driven at highway speeds and at very short gaps without exposing passengers to excessive exhaust gases or denying sufficient cooling air to vehicle radiators
- automated (platoon) operations require minimal electronic infrastructure on the roadway, with most of the additional equipment being required on the vehicles. Improvements in vehicle design are already implementing many of the capabilities that will be required.

In 2003, PATH purchased three class-8 tractors and equipped two of them for automated driving. They conducted two-truck platoon tests on a 2.2 km long unused runway at the former Crows Landing Naval Air Station near Patterson, California. Testing was successfully completed at gaps of 10, 8, 6, 4 and 3 m. During steady cruising at 90 km/h, fuel consumption reductions of up to 13 percent for the tail truck and 10 percent for the lead truck were achieved. [24] The two truck platoon is shown in Figure 11.



Figure 11: PATH Program Two-Truck Platoon [25]

In 2010, a three-truck platoon trial was conducted in order to demonstrate that string stability can be achieved within the default DSRC communication update rate of 10 Hz [24]. A schematic view of the fully-equipped truck is shown in Figure 12.

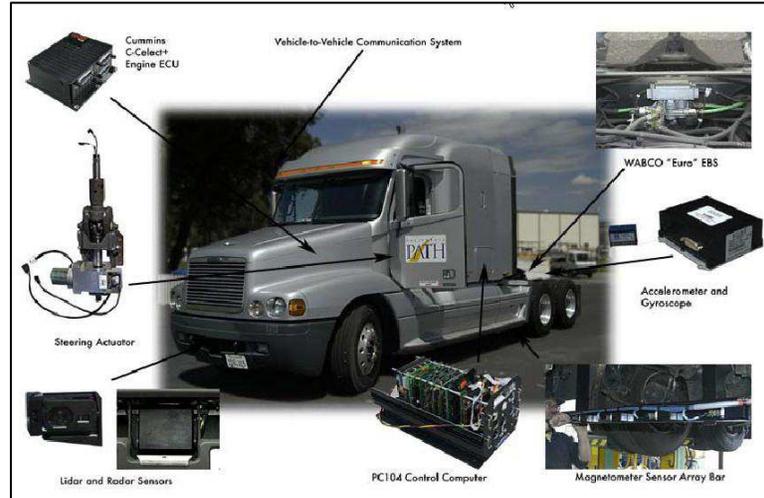


Figure 12: Schematic View of Automation Equipment for Platooning Trials [24]

Testing was performed on an 8 km section of Nevada State Route 722, a lightly travelled two-lane highway which was temporarily closed to the public. The trucks were steered manually, but accurate longitudinal control was automated. RMS gap variations of less than 0.25 m at 90 km/h were achieved. Data was collected at gaps of 10, 8, 6 and 4 m. Good platoon performance was observed at various speeds and road grades. Direct fuel consumption measurements were obtained, showing an average fuel savings of approximately 10 percent. It was noted that since testing was conducted at 1800 m elevation, and there was some intentional offset of the vehicles to guarantee line of sight for communication as well as some cross-wind conditions, fuel savings would likely be higher at sea level with better vehicle alignment. It was also noted that truck automation is significantly more difficult than automation of cars, due to inherent power limitations and resulting slow responses to commanded speed changes.

Further information on the PATH program can be found at the following website:
<http://www.path.berkeley.edu/Default.htm>

5.2 PROMOTE-CHAUFFEUR

The PROMOTE-CHAUFFEUR project was sponsored by the European Commission, and it was conducted in two phases between 1996 and 2004. PROMOTE-CHAUFFEUR I measured the fuel consumption benefits of an “electronic towbar” system, designed by DaimlerChrysler, to electronically couple two heavy-duty trucks, as shown in Figure 13. The system consisted of a V2V controller, a towbar vehicle controller, and an image processing system. A special pattern of IR lights was attached to the rear of the lead truck to enable the image processing system to measure distance and position. Field trials were conducted on a 12 km oval test track in Papenburg, Germany. The lead truck was driven manually and the trailing truck was completely operated by the electronic towbar system that automatically maintained following distances and position. Testing was conducted at speeds of 60 km/h and 80 km/h, at following distances ranging from 6 to 16 m.



Figure 13: PROMOTE-CHAUFFEUR Project Electronic Towbar¹³

At a speed of 80 km/h and a spacing of 10 m, the measured fuel consumption reduction for the tail vehicle, which weighed 28 tonnes, was approximately 21 percent. The full results are shown in Figure 14. Note that at this speed, the greatest fuel consumption savings occurs at a vehicle spacing of 8 m.

¹³ <http://www.commercialmotor.com/big-lorry-blog/robot-driver-less-truck-convoy>

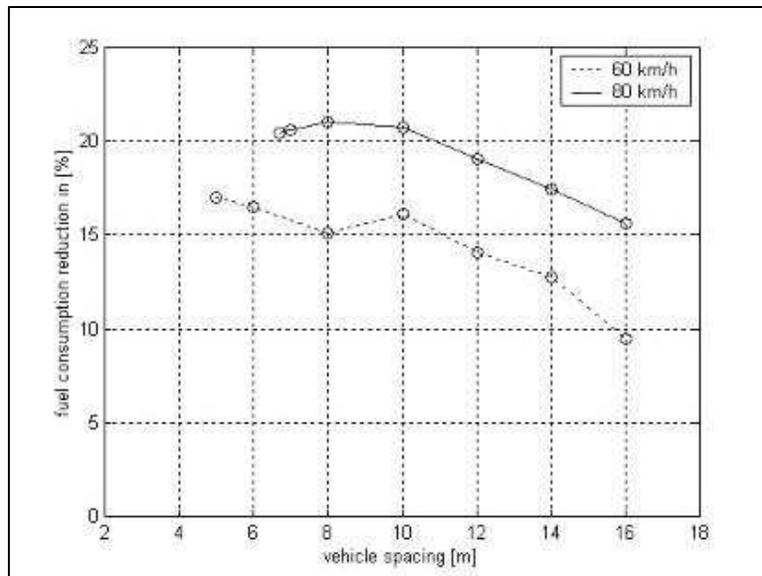


Figure 14: Fuel Consumption Reduction – Tail Vehicle [3]

An extrapolation of the results (at a test speed of 80 km/h) for other vehicle weights is presented in Figure 15. Note that as the vehicle weight increases, the proportion of drag force compared to the rolling resistance decreases, and therefore the fuel consumption reduction (expressed as a percentage of the total fuel consumption) decreases as well. No extrapolation was performed for higher speeds, but it is expected that the fuel consumption reduction would be higher (since the drag force is proportional to the square of the speed).

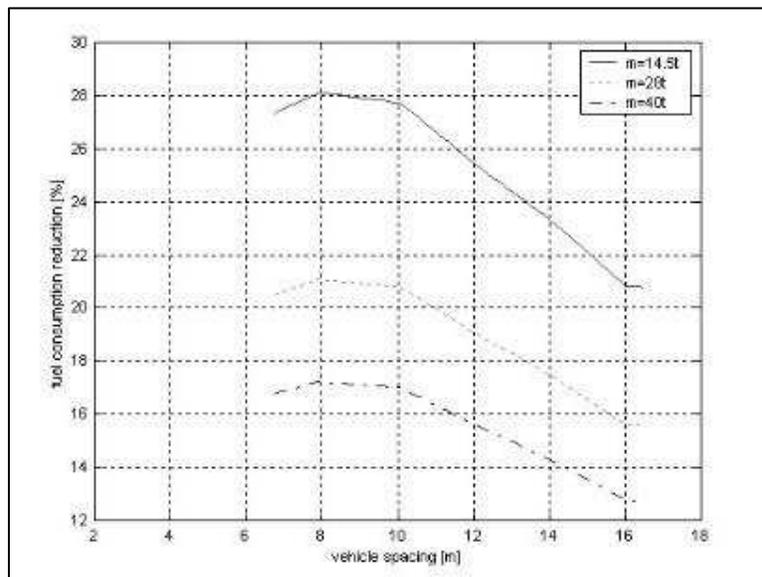


Figure 15: Fuel Consumption Reduction @ 80 km/h – Tail Vehicle (extrapolated mass) [3]

The fuel consumption reduction for the lead vehicle, which weighed 14.5 tonnes, at a speed of 80 km/h and a spacing of 10 m, was approximately 6 percent. This reduction is due to reduced

pressure drag on the rear of the trailer. The fuel consumption reduction increases as the vehicle spacing is reduced. The full results are shown in Figure 16.

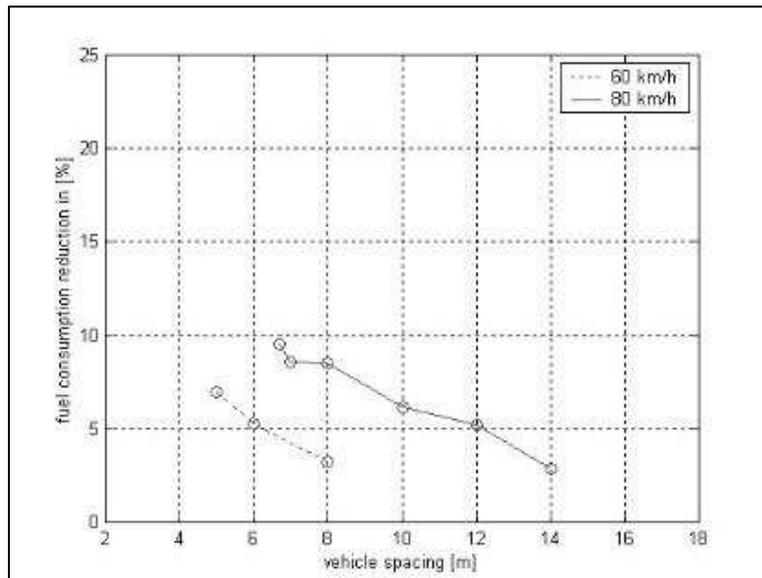


Figure 16: Fuel Consumption Reduction – Lead Vehicle [3]

Based on interest and feedback from freight forwarders and professional drivers regarding PROMOTE-CHAUFFEUR I, a second phase was launched in 2000 with the following objectives:

- demonstration of a three-truck platoon, including typical platooning manoeuvres
- development of an extension of the electronic towbar system, where an equipped truck could automatically follow any other truck (referred to as CHAUFFEUR Assistant)

The CHAUFFEUR Assistant was essentially a combination of ACC and a lane keeping system (LKS), where sensor fusion was used to combine radar and camera information to determine vehicle size and acceleration data. Using vehicle size data it deduced brake performance, allowing it to optimize following distance. Testing was performed on test tracks and in real life environments to demonstrate the effectiveness of the system, as well as the potential benefits of platooning. [26]

5.3 KONVOI

The KONVOI project was sponsored by Germany's Federal Ministry of Economics and Technology, and it was conducted between 2005 and 2009. Its purpose was to investigate the benefits and deployment issues associated with truck platooning, operating in mixed traffic on autobahns. It was assumed that there was no prospect for dedicated lanes or new infrastructure. Since the technical feasibility of such automated systems had already been proven, the project focused on quantifying the impact of automated systems on traffic, and on the interaction between humans and machines [27]. It also studied the legal aspects of vehicle automation systems in an effort to determine required legal changes. There are few technical papers available in the English language.

The concept for KONVOI was a platoon of up to four trucks that would operate in mixed traffic on the highway, with the driver of the first truck making the strategic manoeuvring decisions for the platoon. The lead truck was equipped with driver assistance systems to provide warnings about potential hazards in the driving environment. The drivers of the following trucks were not actively engaged in driving, but they were required to continuously monitor the operation of their trucks to identify problems, and remain prepared to intervene if necessary by taking control in the event of a failure or emergency. It was noted that the drivers of the following trucks expressed a strong interest in having a live video feed of the forward view from the front truck, so that they would know what was happening up ahead.

Lateral control of the following trucks was accomplished by using a wide-angle, multi-beam laser sensor at the front of each truck, which detected existing lane striping. The laser sensor also measured distance to the forward vehicle. A minimum gap of 10 m was maintained in order to accommodate expected cut-ins at highway entrance ramps (and avoid heavy braking). The platoon control system was designed to split the platoon as soon as a cut-in was detected.

A central server was used to coordinate joining and splitting from the platoon, considering location and destination of the platoon and the trucks, as well as truck suitability for joining the platoon. The driver was presented with options, from which a selection was made. Coupling was performed automatically when a joining truck was within 60 m. The KONVOI concept and its components are shown in Figure 17.

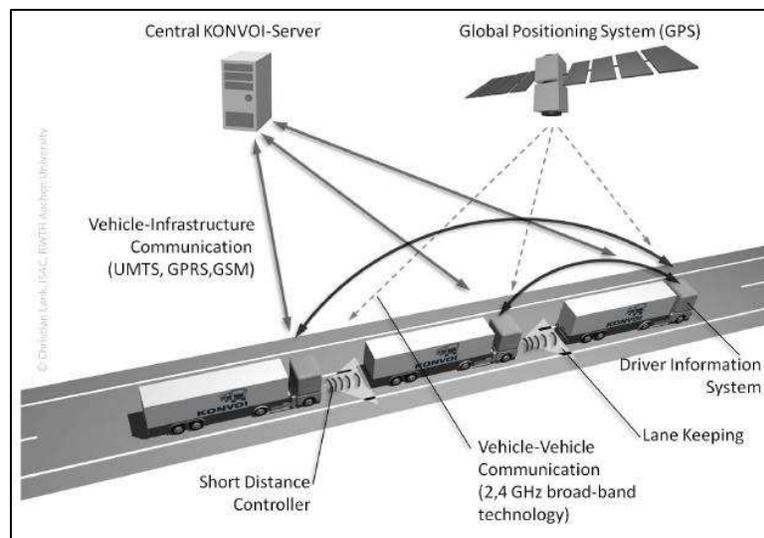


Figure 17: The KONVOI Concept and its Components [27]

The KONVOI project included the first trial of an automated system in real traffic in Europe. While some fuel consumption savings were realized on the test track with a 10 m gap, it was noted that there was no fuel consumption savings in the tests on the public highway. It was concluded that this occurred because the trucks had to vary their speeds continually to respond to traffic conditions and other vehicles on the road. The longitudinal control system was designed to emphasize accuracy of the gap between the trucks, which meant that the system was required to make frequent corrections. This was not a concern, since it was recognized that the control system could be optimized for better fuel efficiency.

The project concluded that the truck platoon had little impact on the surrounding traffic. The average speed of the platoon was 80 km/h, while the average speed of the surrounding traffic was 118 km/h, so it was relatively easy for other motorists to overtake the platoon. It was noted that the platoon had a positive impact on traffic efficiency. However, despite signage indicating the existence of the platoon, plus a police escort, cut-ins occurred regularly which detracted from the effectiveness of the platoon since it had to split and re-join each time.

5.4 Safe Road Trains for the Environment

The Safe Road Trains for the Environment (SARTRE) project was sponsored by the European Commission, led by Ricardo with Volvo as an industry partner. It was conducted from September 2009 – September 2012. As the project name implies, the main motivations were safety and environmental-related, but there was also interest in reducing congestion and enhancing driver convenience. As detailed in a Volvo press release on January 17, 2011, the objectives of the SARTRE project may be summarized as follows:¹⁴

1. To define a set of acceptable platooning strategies that will allow road trains to operate on public highways without changes to the road and roadside infrastructure.
2. To enhance, develop and integrate technologies for a prototype platooning system such that the defined strategies can be assessed in real-world scenarios.
3. To demonstrate how the use of platoons can lead to environmental, safety and congestion improvements.
4. To illustrate how a new business model can be used to encourage the use of platoons with benefits to both lead vehicle operators and platoon subscribers.

The long-term vision was to create a transport system where joining the road train would be more attractive and comfortable than leaving one's car behind and using public transportation on long-distance trips.

The concept for the SARTRE project was a mixed platoon operated in a public, mixed-traffic environment, led by a manually driven truck operated by a specially trained driver. Fully automated trucks and cars followed close behind. A four-vehicle platoon comprised of a truck and three passenger cars is shown in Figure 18. Lateral control of the following vehicles was performed by following the trajectory of the lead vehicle, without reference to any roadway markings. Vehicles entering and leaving the platoon were steered manually by their drivers, but their longitudinal control was automated. In all cases the drivers were easily able to override the automated systems.

¹⁴ <http://www.volvotrucks.com/trucks/global/en-gb/newsmedia/pressreleases/Pages/pressreleases.aspx?pubid=10054>



Figure 18: SARTRE Project Four-Vehicle Platoon¹⁵

The driver of the lead truck was provided with technologies to assist in driving as safely, smoothly and efficiently as possible, and maximum use was made of available sensor technologies in the test vehicles. The lead truck was equipped with ESC, LKS, driver alert support, lane change support, and ACC, as well as HAVEit (see Section 5.8.2) and Intersafe2 (a cooperative intersection safety system). The Volvo production cars were already equipped with a very comprehensive suite of sensors for collision warning and avoidance.

Each of the vehicles was equipped with one 5.9 GHz DSRC radio for V2V coordination, which provided updates of vehicle data at 40 Hz. It was noted that this update frequency is high and required considerable bandwidth, and that it could likely be reduced significantly. It was also noted that the magnitude and frequency of steering corrections made by the automated control system were comparable to or less than those made by the driver.

The SARTRE project also included a simulation study using the Program for the Development of Longitudinal Traffic Processes in System Relevant Environment (PELOPS) simulation tool, to investigate the impact of platooning on traffic flow efficiency [28]. Different traffic scenarios, with and without platoons, were simulated, analyzed and compared to each other. It was concluded that the number of vehicles in a platoon and the number of platoons both influence the flow of traffic. A larger platoon improves string stability and thus leads to higher capacity; however, the length of a platoon has to be bounded to avoid traffic jams on the acceleration lanes at highway entrances.

Further information on the SARTRE project can be found at the following website:
<http://www.sartre-project.eu/en/Sidor/default.aspx>

5.5 Energy ITS

The Energy ITS project was established by the New Energy and Industrial Technology Development Organization in Japan, sponsored by the Japanese Ministry of Economy, Trade and Industry. The work was conducted by researchers at multiple universities, with coordination

¹⁵ <http://www.techradar.com/news/car-tech/self-driving-cars-the-future-of-transport-explained-1137921>

and management by the Japan Automobile Research Institute, between 2008 and 2012. The project investigated energy savings and CO₂ emission reduction for road transportation, including research and development of automated heavy truck platooning. It also explored methods to evaluate the effectiveness of ITS on energy saving and CO₂ emission reduction. It was anticipated that significant energy savings would be achieved by operating trucks in an electronically-coupled platoon at reduced spacing, with additional benefits of improved highway traffic flow and safety.

The concept for the Energy ITS truck platooning effort was a platoon of three identical 25-tonne single unit trucks, all of which (including the lead vehicle) would be controlled automatically while in the platoon. The cargo compartment of each of the trucks was equipped as a mobile office, so it is unlikely that they were heavily loaded. The drivers would be responsible for the lane-changing manoeuvres associated with joining and leaving the platoon. The project initially focused on a dedicated-lane approach, and subsequently was directed by the sponsors to focus on mixed-traffic only. A key requirement was a highly reliable solution in order to facilitate potential near-term introduction. This led to significant redundancy of components and technologies, and high bandwidth communication. The Energy ITS three-truck platoon is shown in Figure 19.



Figure 19: Energy ITS Project Three-Truck Platoon [29]

Each truck was equipped with a 76 GHz radar and a 2-dimensional LiDAR, used for obstacle detection on the first truck in the platoon, and for both gap measurement and obstacle detection on the second and third trucks. The resulting wide field-of-view was also able to detect vehicle cut-in manoeuvres relatively early. Lane-position detection was performed by two identical downward-facing vision systems, one at the front and one at the rear of the truck, so that the two separate measurements could be used to identify both lateral displacement and yaw angle relative to the solid lane marking on the left side of the truck. The vision systems were comprised of both a passive CCD camera, and an active laser scanner and receiver. Lateral control was performed by a redundant pair of steering actuators. A schematic view of the equipment installed in each Energy ITS truck is shown in Figure 20.

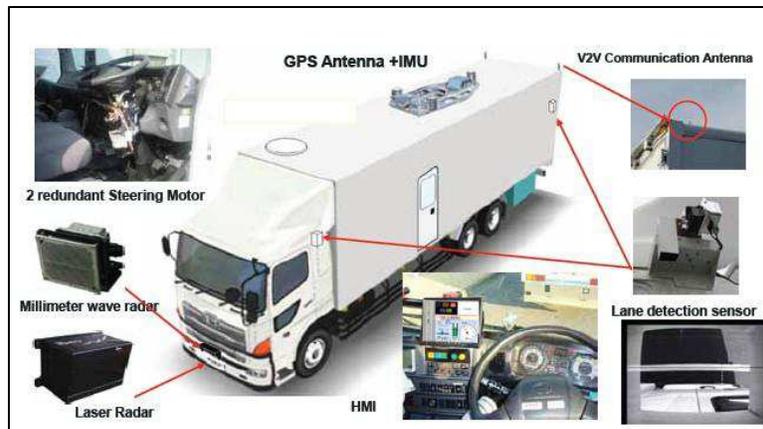


Figure 20: Schematic View of Energy ITS Automation Equipment [21]

V2V communication was effected using a redundant pair of 5.8 GHz DSRC radios installed in each truck. The data shared between the trucks included the reference velocity, the reference acceleration, the velocity of each truck, the braking signal, platoon management data such as platoon ID and truck position in the platoon, obstacle location (as required), and the position of each truck. This information was sent by each radio every 3 ms (333 Hz). Platoon control information was calculated and sent to the communications unit (for each truck) every 10 ms (100 Hz).

In addition to the display screen in the truck, the driver of the following vehicle was also required to monitor three information displays at the rear of the preceding trailer. The three coloured lights at the lower centre of the trailer were used to represent a large number of different operating conditions, using different colour and flash patterns. A reflective strip was also installed to improve the sensitivity of the forward-looking sensors. The information displayed on the rear of the trailers is shown in Figure 21.

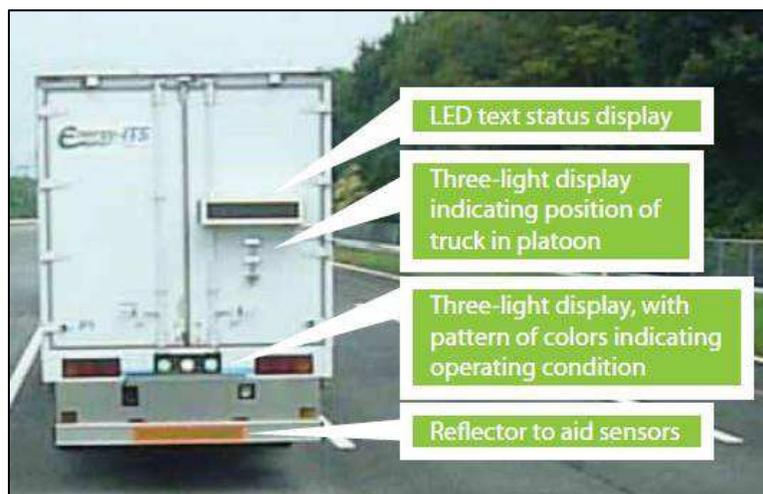


Figure 21: Information Displayed on Rear of Energy ITS Trucks [21]

To further improve the safety for the following trucks, the braking rate of the first truck was limited to substantially less than the braking capability of the following trucks. The drivers of the

following trucks were also provided with a live video feed of the forward view of the lead truck (as requested) to provide an awareness of the situation in front of the platoon.

In March 2010, a platoon of three trucks operating at 80 km/h with a 10 m gap was successfully demonstrated. A join manoeuvre was performed with the third truck entering the gap between the other two trucks. A subsequent demonstration with three heavy trucks and one light truck travelling at 80 km/h with a 4 m gap was conducted in February 2013.

The platoon of three trucks was operated for approximately 100 km on an oval test track, and 24 km on an expressway. The fuel consumption reduction varied slightly, but in both cases the greatest reduction was experienced by the middle truck, followed by the tail truck and then the lead truck. In both cases the average fuel consumption reduction for the platoon was 14 percent, with results ranging from 7.5 to 18 percent for the individual trucks. The project goals were generally achieved, but it was noted that algorithms for platoon forming and lane changing need improvement. The measures that were implemented to maximize safety will likely need to be revisited to reduce cost, complexity, and communication bandwidth without jeopardizing reliability (and safety). Regarding reduction of emissions, microscopic vs macroscopic benefits were delineated. At the individual vehicle and platoon level, emissions reduction would be achieved due to fuel consumption reduction. However, the operation of platoons is expected to improve traffic efficiency and reduce congestion, which will further contribute to fuel savings and a potentially significant reduction of emissions.

5.6 Scania

According to a Scania news release on April 4, 2012¹⁶, Scania, in collaboration with the Swedish National Road and Transport Research Institute, was preparing to start platooning trials on the 520-kilometre route between the Swedish cities of Södertälje and Helsingborg. At the time, four to five tractor and trailer units departed twice daily from Södertälje enroute to Scania's production facility in Zwolle, The Netherlands, loaded with engines, gearboxes and axles. These trucks were operated by the Scania Transport Laboratory, which tests and evaluates vehicle characteristics and performance in commercial road haulage. The plan was to coordinate the departure of these trucks and form a platoon as soon as they reached the motorway. The target gap was 10 m using ACC and V2V communication. It is unknown whether or not the trials were conducted as planned, but Scania continues to work with Stockholm's Royal Institute of Technology and Linköpings University to explore platooning technology. Scania recently announced that it will take the lead role in a three-year European research project to develop a system for implementing truck platooning on roads.¹⁷ A Scania truck platoon is shown in Figure 22.

¹⁶ <http://newsroom.scania.com/en-group/2012/04/04/scania-lines-up-for-platooning-trials>

¹⁷ <http://newsroom.scania.com/en-group/2013/12/11/scania-leads-european-research-project-on-vehicle-platooning/>



Figure 22: SCANIA Truck Platoon¹⁸

5.7 Peloton Technology Inc.

Peloton Technology Inc. was founded in 2011 in California, and it has proposed a platooning concept for two class 8 trucks. An analysis of fleet operations costs was performed, and it is suggested that the fuel savings due to platooning could triple fleet profits. The platooning system is based on the installation of commercial-off-the-shelf (COTS) components, including a forward-looking automotive radar, a 5.9 GHz DSRC radio, an electronic braking system, and a suitable display. A control module is used to link the installed components and interface with the truck. The proposal includes operation of a platoon network operations centre, where Peloton would coordinate linking opportunities and manage platoon activities to enforce safe platooning conditions. The commercial aspects of platooning would also be handled.

Peloton conducted a fuel economy test in November 2013, near Salt Lake City, Utah, which was overseen by the North American Council for Freight Efficiency. They demonstrated fuel savings of 4.5 percent for the lead truck and 10 percent for the tail truck, while travelling at 64 mph (102 km/h) with a 36 foot (11 m) gap. The test vehicles are shown in Figure 23. Peloton is actively seeking partners to advance the development and testing of the proposed system, and several tests and demonstrations are planned for 2014.

¹⁸ <http://newsroom.scania.com/en-group/2012/04/04/scania-lines-up-for-platooning-trials/>



Figure 23: Peloton Fuel Economy Test in November 2013 [30]

5.8 Other Studies, Tests and Simulations

Other studies, tests and simulations have been conducted, where the results directly impact the feasibility and practicality of CTPS. A summary of these tests are described in the following sections.

5.8.1 Connected Vehicle Safety Pilot Program

The Connected Vehicle Safety Pilot Program is a scientific research initiative sponsored by the U.S. DOT, with partnering from several vehicle manufacturers, public agencies and academia. The program includes driver clinics conducted at six sites dispersed across the U.S., and a large-scale model deployment conducted in Ann Arbor, MI, by the University of Michigan Transportation Research Institute (UMTRI). The driver clinics began in August 2011 and ran till early 2012. The model deployment was conducted from August 2012 to December 2013, and the results will be used by the National Highway Traffic Safety Administration (NHTSA) to decide whether to advance connected vehicle technology through regulatory proposals, additional research, or a combination of both.

The goals of the Safety Pilot program are:¹⁹

- To test the effectiveness of wireless connected vehicle technology in real-world, multimodal driving conditions
- To collect data about how ordinary drivers adapt to the use of connected vehicle technology
- To identify the potential safety benefits of connected vehicle technology

The safety clinics explored driver reactions to safety applications employing V2V technology, involving approximately 100 everyday drivers at each clinic site. The results were used to assess drivers' response to and benefits from in-vehicle alerts and warnings, and to determine whether the new applications create any unnecessary distractions for motorists, which may result in additional crashes.

¹⁹ http://www.its.dot.gov/safety_pilot/

The model deployment involved over 2800 vehicles, including cars, trucks and buses, each outfitted with a V2V device using 5.9 GHz DSRC. The majority of the vehicles used a vehicle awareness device, which emits a basic safety message at 10 Hz announcing position, speed and heading. Approximately 400 cars, trucks and buses were equipped with integrated or retrofitted safety devices which transmit, receive and process data. A limited set of V2I applications were also deployed, primarily at controlled intersections. The model deployment will assess the effectiveness of numerous safety applications.

Further information on the Safety Pilot program can be found at the following website:
<http://www.safetypilot.us/program-overview.html>

5.8.2 Highly Automated Vehicles for Intelligent Transport

The Highly Automated Vehicles for Intelligent Transport (HAVEit) project was sponsored by the European Commission, led by Continental with cost sharing from 17 partner organizations. The primary vehicle industry partners were Volkswagen for cars and Volvo Technology for trucks. It was conducted from February 2008 – June 2011. It was recognized that 95 percent of vehicle accidents are human-related, and therefore driver support on different levels offers high potential to achieve enhanced road traffic safety. The goal of HAVEit was to give the driver relief in monotonous driving situations, and appropriate assistance in demanding situations (such as driving in roadwork lanes and traffic jams). It was considered of utmost importance that the driver is always in the loop and always in control.

The three key objectives of the project were: [31]

- development and validation of next generation ADAS functions as a co-system
- optimum system joining and interaction between driver and co-system
- development and validation of failure tolerant, scalable, safe vehicle architecture

HAVEit explored how drivers interact with vehicles at different levels of automation, trying to avoid both underloading and overloading. Four modes of driver-vehicle interaction were defined:

1. Driver only – full manual control
2. Driver assisted, using a single existing driver assistance (warning) system, such as a LDWS or a CWS
3. Semi-automated, combining warning systems with a longitudinal control function such as ACC
4. Highly automated, combining lateral and longitudinal control (ACC plus LKS)

The solution was implemented on test vehicles primarily using existing commercially-available sensors and driver assistance systems. It employed vehicle-based sensors only – there was no cooperation between vehicles. A video camera was mounted inside the instrument cluster to observe the driver's face and monitor his alertness and attention to the driving task. If the driver's head or eyes were turned away from the forward view of the road for longer than a specified period, a video image processing system detected this as inattention and issued an increasingly urgent audio alert to the driver. If the driver did not return his eyes to the forward driving scene, the system assumed full control and safely brought the vehicle to a stop. The system effectively denied the driver the opportunity to perform other activities during automated driving.

Instead of just switching off an ADAS in the event of an impending potentially critical situation, a progressive step-by-step-approach was used to transfer the driving task back from the automated system to the driver. The interaction starts quite early in the event chain, i.e. a few seconds before a potentially critical situation occurs. It brings the driver back into the loop in advance of the critical situation and provides the driver with the optimum level of automation and assistance needed in critical situations.

The project identified the main challenges to deployment of these partially automated systems to be:

- affordable sensors with sufficient performance capabilities
- sensor fusion to achieve increased reliability and safety
- legal restrictions associated with the Vienna Convention on Road Traffic (in Europe), liability uncertainties, and the need for consistent regulations
- development of a human machine interface approach to maintain the driver's attention in the control loop without being annoying

Further information on the HAVEit project can be found at the following website:

<http://www.HAVEit-eu.org>

5.8.3 Computational Fluid Dynamics

Computational fluid dynamics (CFD) and scale model tests are used increasingly in vehicle development to evaluate aerodynamic performance. Rajamani [32] conducted research to investigate the use of CFD for understanding platoon aerodynamics and the airflow interaction between vehicles. Experiments were conducted in the Royal Melbourne Institute of Technology industrial wind tunnel to analyze the effects of drafting on drag coefficients using two different scales of Ahmed car models. The CFD proved to be a useful technique since its results compared reasonably well to wind tunnel results and previous test results.

5.8.4 Wind Tunnel Testing

Browand and Hammache [33] conducted wind tunnel testing using two simple truck models, approximately 1/16th scale, arranged in tandem. They concluded that the degree of drag reduction depends strongly upon the drag coefficients of the truck models in isolation, and upon how the two trucks are arranged. Therefore the expectation is that the wind tunnel drag results for tandem truck operation will be comparable to that for full-scale trucks exhibiting similar drag coefficients in isolation. They noted that the Reynolds numbers for full-scale trucks and scale truck models can differ by a factor of 15, which means that the flow about a full-scale truck and a truck model may be different. They concluded that the drag coefficient is the parameter of defining interest rather than the shape of the truck. The drag exhibited by a simple shape can be increased by using one or more add-ons such as thin surface netting over the cab, "collars" installed near the front of the trailer to increase boundary layer thickness (and the momentum deficit), and/or increasing the gap between the cab and trailer. The models in the wind tunnel are shown in Figure 24.

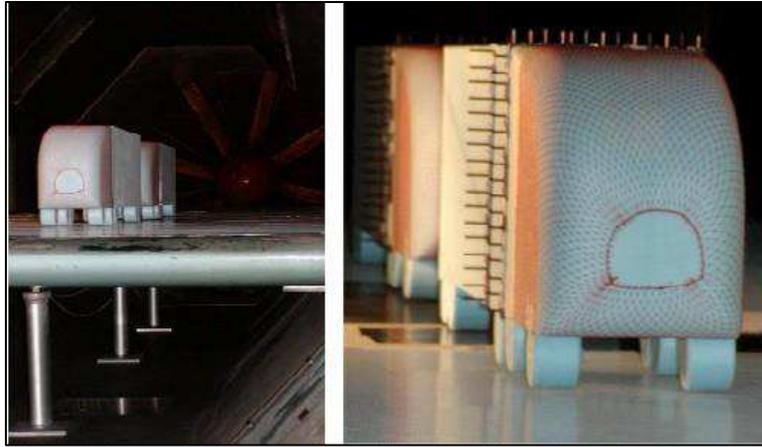


Figure 24: Browand and Hammache Truck Models in Wind Tunnel [33]

6 FACTORS AFFECTING SAFETY

While CTPS has the potential to improve road safety, there are many factors which affect platoon safety, as described in the following sections.

6.1 Equipment Reliability

For vehicles to operate safely at highway speeds with short spacing, equipment reliability is paramount. As detailed in Section 5.5, the Energy ITS project emphasized high reliability in order to facilitate potential near-term introduction of a platooning system. To achieve this, most components were redundant, and overlapping technologies were employed. Data was exchanged between vehicles at a very high frequency to reduce the risk of communication errors. These strategies were acceptable to facilitate the Energy ITS trials, but they added significant cost and complexity to the solution which reduces the practicality and feasibility for public adoption. The high bandwidth required for the V2V communication would lead to saturation of the DSRC channels as more equipped vehicles are fielded.

The system design must incorporate a high level of health monitoring (e.g. diagnostics, built-in test), and employ fail-safe modes to mitigate the danger associated with an equipment failure. The driver (if present) must be able to assume control and override the system at any time. Robust control algorithms which address all potential failure and hazard scenarios must be developed. Any breakdown in communication or system fault will require the platoon to immediately dissolve by increasing spacing, requiring the driver to assume control. If the driver fails to assume control, the vehicle should stop safely. The higher the level of automation, the higher the importance of reliability and system response in the event of failure.

Failure modes, effects and criticality analysis (FMECA) should be performed to quantify reliability requirements, and mean time between failure (MTBF) data should be gathered for components and assemblies which make up the platooning system.

Additional maintenance may be required to verify the fitness and functionality of the platooning systems. It may be necessary for drivers to inspect, clean and/or test sensors regularly to ensure optimal performance. It may also be necessary for maintainers to align or calibrate sensors as required.

Public acceptance of automated systems will require near-perfect performance. It is accepted that humans are responsible for most traffic accidents, but failure of an automated system resulting in a crash will not likely be viewed the same as a human error.²⁰

6.2 Vehicle/ Platoon Spacing, Platoon Length

The minimum spacing between vehicles is established based on safety criterion, with the goal of achieving the shortest possible following distance while managing the risk of a collision. Time headway is typically used to specify a following distance, expressed in seconds. For example, a following distance of two seconds equates to 33.3 m at a speed of 60 km/h, or 55.6 m at a speed of 100 km/h. Platooning trials to date have typically specified the spacing between

²⁰ <http://www.sae.org/mags/sve/12028>

vehicles as a fixed distance, where a gap of 10 m equates to 0.60 seconds at a speed of 60 km/h, or 0.36 seconds at a speed of 100 km/h.

As the spacing between the vehicles in a platoon, or the spacing between platoons, is reduced, the available reaction time in the event of an emergency situation is also reduced. Driver reaction time (the period between when an event is observed and when the driver actually responds such as applying the brakes) typically ranges from 0.75 to 1.5 seconds [18]. The *brick wall safety criterion* requires that a following vehicle does not collide with the vehicle ahead, even if it stops instantaneously. This is an unrealistic scenario, and therefore a more lenient policy is normally applied. The *hard braking safety criterion* requires that a following vehicle does not collide with the vehicle ahead, when that vehicle applies maximum braking until it comes to a stop. This policy is normally used. The *low relative velocity safety criterion* specifies that if a vehicle applies maximum braking and the following vehicle collides with it, the relative velocity at initial impact should be low enough that injuries are avoided. This policy achieves the highest capacity while accepting the risk of minor collisions.

The maximum deceleration rate and minimum stopping distance are dependent upon the effective vehicle braking capability (considering vehicle weight, brake and tire design and condition, road-tire friction, etc.). If the brakes on the lead and following vehicles were applied simultaneously, and the effective braking performance were identical, the vehicles would all stop within the same stopping distance, and the gap between the vehicles would be maintained. This is not possible due to communication delays and system response times, but a collision will not occur until the gap becomes zero (before a vehicle is stopped). As noted in Section 3.3, assuming negligible communication delay, a suitable braking response can typically be applied automatically within 20 ms. At a speed of 100 km/h, this response time equates to a distance of 0.56 m (i.e. the gap would be reduced by this amount during the system response period).

Assuming V2V messages are broadcast such that all vehicles in the platoon receive the messages simultaneously, the response time for all vehicles (assuming similar mechanical system response times) would be the same. Therefore the only gap which would be reduced in an emergency braking scenario is that between the lead and second vehicle due to the unavoidable communication delay. However, if communication between the vehicles failed, each vehicle would respond in succession once the braking action of the preceding vehicle was detected by the driver. The gap between successive vehicles in the platoon would be reduced by the distance travelled while each driver reacts. If the platoon is sufficiently long, a collision will eventually occur between vehicles, and a chain-reaction collision will follow. The smaller the gap and the longer the platoon, the higher the risk of collision in the event of a communication delay or failure.

The same logic applies for the gap between platoons. If the platoons are operating independently (i.e. no communication between them), a typical “safe” headway should be maintained. However, if the platoons are operating in a cooperative manner, the gap may be reduced with the associated increase in risk of a collision due to a communication delay or failure.

In an advanced platooning system, the inertia of each of the vehicles could be calculated in real time, and the individual vehicle braking capability modulated, in order to carefully manage the spacing between the vehicles while braking to minimize the severity of any potential collisions within the platoon. The platooning system could also adjust vehicle spacing based on road conditions (automatically, or based on lead vehicle driver inputs).

Typical Canadian provincial regulations state that the driver of a motor vehicle shall not follow another vehicle more closely than is reasonable and prudent, having due regard for the speed of the vehicle and the traffic and highway conditions. However, for commercial motor vehicles, the minimum following distance is often specified. For example, in Ontario, the driver of a commercial motor vehicle, when driving on a highway at a speed exceeding 60 km/h, shall not follow within 60 m of another motor vehicle.²¹ A similar regulation exists for British Columbia. In Manitoba, two following trucks shall maintain a gap of 90 m (if conditions permit).²² So in Ontario, the legal time headway at a speed of 60 km/h is 3.6 seconds, or 2.2 seconds at a speed of 100 km/h. To permit CTPS at close following distances, the existing regulations would require revision.

6.3 Platoon Speed, Composition

As the platoon speed increases, so does the risk of collision due to reduced reaction time (assuming a consistent gap). The potential severity of a collision is also increased. Furthermore, communication between vehicles and infrastructure may be less reliable at higher speeds.

Platoon composition has a significant impact on the safety of individual vehicles within the platoon. Ideally a platoon would consist of identical vehicles with similar loads, therefore exhibiting similar performance characteristics and responses to inputs. However, this is not a realistic constraint for the future of platooning. Therefore platoons should be strategically designed to minimize safety concerns related to vehicle size and weight, and performance characteristics.

Mixed platoons of cars and trucks present the greatest safety concern, but for this report, discussion is limited to platoons consisting of heavy-duty trucks. The most significant variable for a truck is weight, which affects braking, acceleration, and handling. Under normal circumstances, the platoon control system should be able to regulate acceleration and braking so that the platoon remains synchronized as a single unit. But during emergency manoeuvres, the trucks may behave differently due to performance and handling characteristics, and this behaviour must be managed.

Platooning is expected to make use of commercially-available ADAS technologies, which will likely differ between truck manufacturers and models. Differences in the capabilities and behaviour of these systems will also have to be managed to ensure the safety of the platoon is not compromised.

To further enhance platoon safety, the braking capability of a preceding vehicle could be limited so that it does not exceed the effective braking capability of any of the following vehicles. In a similar fashion, the gap could be automatically adjusted to account for reduced effective braking capability due to environmental conditions.

²¹ http://www.e-laws.gov.on.ca/html/statutes/english/elaws_statutes_90h08_e.htm#BK236

²² [http://web2.gov.mb.ca/laws/statutes/ccsm/h060e.php#117\(2\)](http://web2.gov.mb.ca/laws/statutes/ccsm/h060e.php#117(2))

6.4 Platoon Formation/ Dissolution, Joining/ Splitting

Forming and dissolving a platoon, as well as joining and splitting manoeuvres, are transient conditions which present higher safety risks than steady-state operation of the platoon. Speeds must vary to achieve the correct positioning, and there must be a handover of control between manual driving and automated (or semi-automated) driving.

For a formation or joining manoeuvre, the handover from manual to automatic control would typically occur at an early stage, so that the automated system would complete the manoeuvre safely and efficiently. Platoon formation is essentially a series of joining manoeuvres performed sequentially or simultaneously, with vehicles in the same lane at a safe following distance, joining from the rear. Depending on the design of the platoon control system, a joining manoeuvre (to an existing platoon) could occur at the rear, middle, or front of the platoon. Joining from the rear involves operation at a speed higher than that of the platoon to close in on the platoon from the rear. At a certain distance the platoon control system would take over the joining manoeuvre and manage the speed of the joining vehicle. Joining from the middle involves significantly increasing the gap at the desired position to create the necessary gap for joining. The joining vehicle then manoeuvres into the gap from an adjacent lane, and the platoon control system completes the manoeuvre by re-establishing the desired gap. Joining from the front implies assuming the lead vehicle position, and it requires the joining vehicle to manoeuvre in front of the platoon at a speed higher than that of the platoon, and then decelerate to achieve the desired gap and platoon speed.

Similarly, dissolution of a platoon, or splitting (leaving) a platoon, requires that the gap be significantly increased to a suitable gap for manual driving. Once that gap is achieved, control is handed over to the drivers. A single vehicle could leave the platoon from the rear, which simply requires deceleration to achieve the desired gap, and then the driver assuming full control. To leave from the middle, the gap in front of and behind the departing vehicle is significantly increased, and then control is handed over to the departing vehicle which performs a lane change to leave the platoon. To leave from the front, the departing vehicle accelerates to increase the gap between it and the platoon, and then control of the platoon is handed over to the new lead vehicle.

With heavy-duty trucks operating at highway speeds, these manoeuvres cannot take place quickly, as the speed and acceleration of a loaded truck is limited. Posted speed limits should be respected, and speed limiters may limit the maximum speed available to perform manoeuvres. There is always the risk that a non-platoon vehicle could interrupt the manoeuvre, requiring suitable corrective or evasive action. The platoon control system must accommodate these scenarios.

6.5 Level of Automation

Platooning can be performed at three levels of automation: longitudinal control only, longitudinal and lateral control, or fully automated (driverless) control. Because driver error or inattention is responsible for most accidents, and because automated systems could sense and respond more quickly than humans, there is certainly the potential to improve road safety by automating the driving function. But an alert driver can apply experience and instinct to choose evasive action that would not be possible through automation. Therefore, there are trade-offs at each level of automation.

The first level of automation, based on CACC, requires that the driver remain fully involved in the driving function by steering the vehicle. The platooning system simply facilitates maintaining a close following distance. If the driver is inattentive or drowsy, the driver might deviate laterally from his position and create an unsafe scenario. Driver assistance systems such as LKS and LDWS, as well as a drowsiness detection system, could reduce this risk.

The second level of automation effectively relieves the driver of driving duties while in the platoon. Assuming reliable system performance, lane positioning and hence level of safety could be improved. However, following the same trajectory of the lead vehicle raises concerns about the safety of followers if the lead truck runs off the road or is involved in an unsafe scenario. There are also safety concerns regarding the readiness of the driver to quickly assume control in an emergency, as detailed in Section 6.9.

Fully automated, driverless trucks introduce new safety concerns which are beyond the scope of this report.

6.6 Dedicated Lanes vs Mixed Traffic

The safety of platooning systems is certainly enhanced through the use of dedicated lanes. In a dedicated lane the behaviour of other vehicles can be reasonably predicted, and speed is much more consistent. Dedicated lanes could also employ more consistent or advanced lane markings, which could facilitate lateral control and safe operation at a higher level of automation.

Conversely, mixed lanes present the most significant obstacle to safe platooning. The behaviour of other drivers cannot be managed or predicted, and a platooning system must be designed to accommodate such unpredictable interaction. With existing infrastructure, platoons could interfere with efficient and safe merging onto highways. On mixed lanes, platoon length would likely be limited to no more than a few trucks, and the duration of effective platooning may be relatively short due to continual interference from other traffic. It may also be necessary to regulate when and where platooning is permitted.

Managed lanes may present opportunities to realize some of the safety benefits of dedicated lanes, and they are further discussed in Section 8.5.

6.7 Adverse Weather Performance

Adverse weather can affect the feasibility, effectiveness and safety of platooning in many ways. First, enhanced vision systems and V2V communication may mitigate safety concerns associated with platooning at night or in foggy conditions; however, on wet or snow-covered roads, effective braking capability may be significantly reduced such that the platooning gap should be increased to maintain a safe following distance. The reduction in effective braking capability may also vary significantly between trucks due to performance characteristics of different tires, so these differences must be considered when determining a suitable gap.

If lateral control relies on a clear view of lane markings, this level of automation may not be possible in dark or foggy conditions, or on snow-covered roads. However, it may be possible to continue platooning at a lower level of automation.

For LiDAR, optical and IR components to function properly, they must have an unobstructed view. Road spray, including mud, snow and salt, could block that view and render the system inoperable. There may be conditions when safe platooning simply is not possible, and the vehicles would have to operate independently. In this case the potential benefits of platooning would not be realized, but there is no penalty incurred due to operating the vehicles independently.

The platooning tests and demonstrations to date have been performed under ideal conditions in temperate climates, and the literature review did not reveal any test data regarding the impact of adverse weather conditions on platooning.

6.8 Data Security

A network of cooperating vehicles should immediately create safer and more efficient roadways. However, the ease of access to the inter-vehicle communications network (e.g. CAN bus), which inherently has no network infrastructure, presents a weak link that exposes the system to potential security threats. Denial-of-service attacks, and fabrication, impersonation or alteration attacks on legitimate network traffic, could actually increase the likelihood of collisions. Ironically, attackers could exploit ITS to create a new roadway danger with severe consequences – “intelligent collisions” [34]. Countermeasures must be implemented to address this threat.

6.9 Human Factors

Cooperative platooning requires that a driver relinquish some or all of the vehicle control to the automated system, but the driver is required to re-establish that control on relatively short notice in the event of an emergency. So while one of the potential advantages of platooning is some relief of the driver workload, the driver cannot completely disengage from the driving task, and hand-over of control must be effected in a safe and efficient manner. The HAVEit program detailed in Section 5.8.2 explored this issue in depth, and developed a system to maintain driver attention and facilitate progressive re-engagement of the driver.

The KONVOI project assessed driver workload, subjectively via questionnaires, and objectively via measured physiological parameters. Both methods confirmed that the KONVOI system did not create a high workload during platooning manoeuvres, nor was the workload too low to cause driver disengagement during automated phases. However, it was noted that drivers might become underloaded once they are more familiar with the system, which could present a concern regarding driver inattention. The trial also noted that following distances tended to be shorter after platoon driving, which would support the use of ACC to maintain a suitable distance.

NHTSA conducted a field operational test in 2009 to assess driver acceptance of integrated vehicle-based safety systems [35]. The system included CWS, lane change/merge warning system, LDWS, and blind spot monitoring. Sensor fusion was employed to provide alert arbitration. Ease of use and perceived usefulness was assessed based on subjective feedback from 18 professional drivers who drove the ten instrumented trucks on their normal work route for ten months. A data acquisition system collected performance data from drivers driving both with and without the system. Most drivers felt that the system provided a positive safety benefit and was easy to use. It was noted that drivers experienced positive changes in their driving behaviour when driving with the integrated system, including increased turn signal use, and a

decrease in the rate of lane excursions. These results indicate that the integrated safety system reinforces good driving habits and helps drivers maintain better lane position. The only negative comment was the frequency of invalid warnings, which occurred at an average rate of five per 100 miles. The drivers did not become overly reliant on the system, or increase the frequency of secondary tasks. In cases where multiple threats were presented, the first warning was usually sufficient to solicit the appropriate driver response. After the conclusion of the field test, Con-way Freight invested over \$5M to equip almost 1,300 tractors with an integrated safety system.

During the KONVOI trials, the interaction of the platoon with other drivers was assessed. It was noted that other drivers did not normally enter gaps of 10 m or less at any of the interchanges, and that a minimum gap of 20 m is preferred. However, the accepted gaps while entering and exiting traffic tended to decrease with increasing traffic volume. Therefore it might be necessary to dissolve a platoon before interchanges with high traffic volume. It was also noted that drivers expect a level of courtesy while merging (i.e. accelerating or decelerating slightly to offer a suitable gap for merging), and that courtesy cannot be extended while in a platoon formation. Familiarity with platoons, and adapting of driving habits, will be required.

7 FACTORS AFFECTING FUEL CONSUMPTION

The reduction of fuel consumption and emissions that can be achieved by CTPS is affected by several factors, as described in the following sections.

7.1 Vehicle Size, Type, Weight

Large vehicles such as heavy trucks have large, blunt front and rear cross-sectional areas, which result in a high drag coefficient. Platooning at close following distances can significantly reduce the aerodynamic drag, leading to a reduction of fuel consumption (and emissions). The larger and more aerodynamically “inefficient” the vehicle, the greater the potential reduction. A large vehicle following a small vehicle will not experience the same fuel savings as a small vehicle following a large vehicle. The most significant reduction in the drag coefficient results from similar vehicles following one another.

Rolling resistance is proportional to vehicle mass, so the greater the vehicle mass, the lower the percentage of fuel savings due to platooning since the percentage contribution of fuel consumption due to aerodynamic drag is smaller. It should also be noted that trucks with significantly different mass would likely have significantly different power-to-weight ratios, which could affect their ability to maintain desired spacing (or operate efficiently to maintain that spacing). For example, a lighter weight lead truck might be able to maintain its speed on an uphill slope while a heavier following truck cannot, even at wide-open-throttle operation.

The tests and demonstrations detailed in Section 5 have typically involved trucks which are not heavily loaded, so the percentage fuel savings experienced due to platooning are likely higher than that which would be experienced in Canada with trucks loaded much closer to their capacity. The actual reduction in fuel consumption, however, (expressed in L/100 km), would be expected to be similar.

7.2 Vehicle/ Platoon Spacing, Platoon Length

Based on the results presented in Section 5.2, the potential fuel savings increase as the gap between vehicles is decreased, to a gap of approximately 8 m for heavy trucks hauling van body trailers (for level road, constant speed operation). The most significant fuel savings are experienced by those vehicles between the lead and tail vehicle, so the longer the platoon, the greater the net savings. Similarly, the shorter the gap and the longer the platoon, the greater the traffic density and therefore the road capacity. The greater the number of vehicles operating in a cooperative platoon, the fewer the traffic oscillations, and hence the greater the average speed and traffic flow efficiency. The length of the platoon is bounded by the V2V communication speed and reliability required in order to maintain string stability. In mixed traffic on existing roadways, the length of the platoon is also limited due to potential bottlenecks at highway access ramps.

The ideal spacing between trucks for optimum fuel savings is dependent upon several factors including individual vehicle aerodynamic features, platoon speed, road grade, and transient conditions such as acceleration or deceleration. Hills and traffic interference demand throttle adjustments for the lead truck, which require similar adjustments for all of the following trucks in the platoon. The response of following trucks is slightly delayed due to communication latency and inherent delays in mechanical systems, such that more significant adjustments tend to be

required. Aggressive speed adjustments to maintain a desired gap may negate the potential fuel savings from platooning, as was experienced in the KONVOI trial detailed in Section 5.3. The gap tolerance should be sufficiently large to permit gentle speed adjustments. During the 3-truck platoon trials conducted by the PATH program in 2010, RMS gap variations of less than 0.25 m were maintained while still achieving fuel savings [24]. As detailed in Section 7.3, the desired gap could be adjusted dynamically to optimize the fuel savings as conditions change.

7.3 Platoon Speed

For a single vehicle on a level road, optimal fuel efficiency is achieved if a constant velocity is maintained – i.e. any speed variations result in an increase in fuel consumption. Anticipating speed changes permits more gentle acceleration and deceleration, maximizing fuel efficiency. A sophisticated platoon control system could vary the speed of the platoon and the gap between individual vehicles to maximize overall fuel efficiency [1]. It could also adjust the speed of the platoon to match that of the slowest vehicle (while climbing a hill, for example), in order to maintain platoon integrity. A PCC system such as Volvo’s I-See cruise control, which “learns” the road topography, could also be used to vary the platoon speed to optimize fuel efficiency while travelling over hilly terrain.

If it is possible to reduce the maximum platoon speed (e.g. 90 km/h versus 100 km/h), further fuel savings and emissions reduction could be achieved due to reduced aerodynamic drag (due to the reduced speed, rather than platooning). If congestion is reduced and traffic flow is improved as a result of platooning, the total travel time (at a reduced maximum speed) may be unchanged.

7.4 Lateral Alignment

The potential fuel savings that can be achieved by platooning are sensitive to the lateral alignment of the vehicles in the platoon, and it is generally assumed that the vehicles are perfectly aligned. If lateral control is automated, variations in lateral alignment due to driver inattention can be reduced or eliminated. However, since heavy trucks use most of the width of a typical highway lane, professional drivers tend to be experienced in keeping their trucks in the centre of their lane, thereby maintaining very good lateral alignment with the preceding truck. The sensitivity of fuel savings to lateral alignment was not addressed in the tests detailed in Section 5.

7.5 Crosswinds

While road tests are more realistic than wind tunnel tests or simulations, variable wind conditions often make fuel consumption test results questionable. Prevailing winds parallel to the direction of travel of the platoon, and air movement due to neighbouring lanes of traffic, impact the potential fuel savings of platooning by effectively modifying the platoon speed. However, crosswinds tend to increase the aerodynamic drag experienced by all vehicles in a platoon, thereby reducing the potential fuel savings due to platooning.

As noted in Section 2.1, the air-wake behind a vehicle is convected in the direction of the crosswind, such that the following vehicle may not be fully enveloped in the wake. However, it may be possible to intentionally “misalign” (i.e. offset) following vehicles in such a way that they more closely follow the centre of a crosswind-directed wake, and they may thereby experience a greater reduction in fuel consumption compared to those that are aligned with the leading

vehicle. The potential misalignment is limited due to lane width (and platoon length). The sensitivity of fuel savings to crosswinds was not addressed in the tests detailed in Section 5.

7.6 Duration of Established Platoon

The benefits that can be realized by platooning are dependent upon the length of time that the platoon is established. In mixed traffic, cut-ins by non-platoon traffic present the biggest obstacle to maintaining platoon integrity. When a vehicle cuts in, the following vehicle must decelerate to increase the gap behind the non-platoon vehicle to establish a safe following distance. When the non-platoon vehicle changes lanes, the platoon can re-establish assuming another non-platoon vehicle does not move into the existing large gap. The acceleration required by all following vehicles to close the gap and re-establish the platoon is inefficient, undermining the potential savings from platooning. Maintaining a gap which discourages cut-ins, even though it might not significantly increase fuel savings due to platooning, contributes to extending the platoon duration. As noted in Section 6.9, during the KONVOI trials, other drivers were reluctant to enter a 10 m gap, but the accepted gap while entering and exiting traffic tended to decrease with increasing traffic volume. It may be practical to reduce the gap as traffic volume increases.

Reliable and possibly redundant V2V communication systems would reduce the occurrence of loss of communication, which force the platoon to dissolve. Also, careful organization of platoons could minimize the occurrence of platoon dissolution due to vehicles leaving the platoon from the middle (requiring the platoon to re-establish, similar to a cut-in). For example, a vehicle joining a platoon could join somewhere in the middle, at a position where it would eventually be the last vehicle in the platoon when it reaches its destination. This planning would avoid the acceleration required to close the gap left by a departed vehicle, and create the gap for joining by gentle deceleration of vehicles behind the position of the joining vehicle.

7.7 Cold Climate Performance

Since aerodynamic drag varies with air density, fuel consumption is greater at colder ambient temperatures. In cold Canadian climates, the aerodynamic drag in winter can be nearly 20% greater than at standard conditions. [2] The reduction in the drag coefficient due to platooning is independent of temperature, so the reduction in fuel consumption due to CTPS should be greater at colder temperatures. Although the sensitivity of fuel savings to cold climate was not addressed in the tests detailed in Section 5, the effects of cold climate can be reasonably extrapolated from test results at standard conditions.

8 OTHER CONSIDERATIONS

While CTPS may offer several potential benefits, there are some challenges and obstacles which would have to be addressed in order for CTPS to be possible.

8.1 Coordination

In order to form a cooperative truck platoon, coordination is required to “organize” the platoon and assemble the participating trucks. Factors such as truck type, weight, performance parameters, installed equipment, current location, destination, etc. all need to be considered. If a platoon is comprised of trucks from a single carrier, the coordination is greatly simplified as it is performed exclusively by the carrier, who already has all of the necessary information and can coordinate the assembly of the trucks into platoon formation. The Scania platoon described in Section 5.6 is an example of such a platoon.

For a platoon of trucks that are not affiliated with each other, communication and cooperation between carriers or a third party coordinating agency is required. The availability of trucks to participate in a platoon must be advertised, and proposals to participate in a platoon must be communicated and considered. Ad-hoc platoon formation while trucks are operating on a highway requires that the trucks are already very close to each other, and that the coordination is performed in real-time.

A practical alternative to forming ad-hoc platoons with neighbouring trucks on the highway might be to coordinate platoons at specific access points (e.g. truck stops) along a highway. A carrier with a potential lead truck could offer the opportunity for carriers with suitable trucks to join a platoon, departing the access point at a specified time. Once the platoon is formed, trucks could withdraw from the platoon on the highway as required.

8.2 Licensing, Permits, Fees

Safe platooning on public roads will likely require that regulations be developed by provincial regulating authorities. Existing roadways were not designed to support platooning, so while some portions of some highways might be able to accommodate platoons, others might not. Regulations would likely specify when and where platooning is allowed, and place restrictions on the platoon composition, speed, length, etc. Initially, permits may be used to specifically authorize platoons, similar to the manner in which LCVs are currently regulated (as detailed in Section 9). Issues related to borders and jurisdictions will also have to be addressed. However, since dissolving a platoon is a simple and natural occurrence, platooning only when and where permitted does not present a challenge.

To ensure that vehicles are appropriately equipped, compatible, and fit for platooning, inspection and licensing will be required. Different capabilities may be required for vehicles to function as lead and following vehicles. Standards will need to be developed, and agencies trained and authorized to perform the necessary inspections. Drivers would also likely require training and certification to operate either lead or following vehicles, so training packages and qualification standards will also need to be developed.

The benefits to individual vehicles within a platoon are dependent upon the vehicle position. The driver of the lead vehicle assumes additional responsibility for the safe journey of the

following vehicles, while the drivers of the following vehicles are relieved of some of the driving duties, yet they experience the greatest fuel savings. Therefore a system to assess appropriate fees and facilitate billing and funds transfer will be required. This could possibly be a service developed and provided by a third party. Again, if a platoon is comprised of trucks from a single carrier, this is not an issue.

Some governments have encouraged and facilitated the development and introduction of autonomous vehicle operation, which could include platooning. For example, in 2012, the Nevada Legislature and the Department of Motor Vehicles enacted legislation and regulations to enable the testing and operation of autonomous vehicles on state highways. In this case, an autonomous vehicle is defined as a motor vehicle that uses artificial intelligence, sensors and GPS coordinates to drive itself without the active intervention of a human operator.²³ The regulations require a vehicle certificate of compliance, special license plates, and a driver's license endorsement to operate an autonomous vehicle in autonomous mode. The operator is deemed to be the driver, even if the driver is not physically present in the vehicle. There are specific clauses to facilitate testing of autonomous vehicles, including the requirement that at least two persons be physically present in the vehicle during testing. The State is currently accepting applications for testing only, and a license was issued to Google in May 2012. Once the feasibility and benefits of platooning have been proven in real-life scenarios, incentives could be offered to promote its growth.

8.3 Privacy

The ability of vehicles to communicate with other vehicles and infrastructure raises privacy concerns. It is feared that collected data could be used by insurers to manage insurance rates, or courts to determine fault, or law enforcement agencies to prosecute drivers, or employers to monitor employee performance, for example. Security measures such as authentication, encryption and random addressing help to alleviate these concerns. Further study is required to determine privacy implications, and develop strategies to manage privacy issues.

8.4 Legal Liability

Autonomous control of vehicles for platooning employs sensors, actuators, communication devices, processors and algorithms, any of which could fail or perform inappropriately and possibly lead to an accident. In such a case, the question of legal liability arises: suppliers of failed components could be named as potential defendants in accident litigation. [36]. There are also challenges related to law enforcement, such as determining who is responsible for driving infractions like speeding, since the vehicle occupants could have slowed the vehicle, the software provider's control software could have prevented the infraction, and the platoon lead vehicle driver could have respected the speed limit in the first place. Vehicle manufacturers are reluctant to provide functions that could remove the driver from the vehicle control loop without some assurance about their liability exposure in the event of a crash. A government-supported insurance pool has been suggested to encourage initial adoption of automation technologies until there is a substantial body of actuarial data about the safety of the systems. It is certainly easier to address liability for platooning operations conducted by a single fleet operator, where there would be a business relationship directly between the owner and insurer.

²³ [http://www.leg.state.nv.us/register/RegsReviewed/\\$DIGEST_REG_084-11.pdf](http://www.leg.state.nv.us/register/RegsReviewed/$DIGEST_REG_084-11.pdf)

The German Federal Highway Research Institute, BASt, has been leading a study of the legal implications of road transport automation under German law. This study combines technical factors, human factors, and legal expertise to make explicit determinations about what aspects of automation systems are clearly legal, clearly illegal, or in the grey area in between – identifying what research is required to resolve the ambiguities. The most important initial contribution of this study was a carefully developed definition of five different levels of vehicle automation, as shown in Figure 25, which was an essential prerequisite to addressing legal issues.

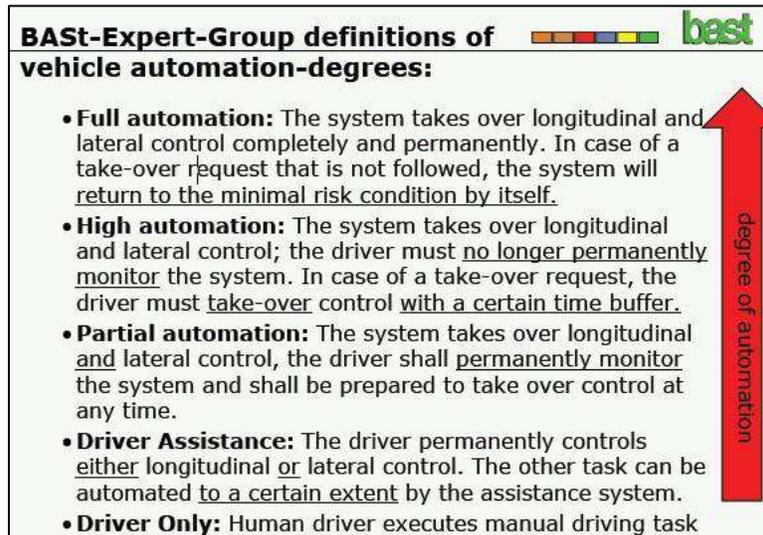


Figure 25: Degrees of Automation (defined by BASt) [21]

In general, the manufacturer would be liable for crashes that occur at the two higher levels of automation, unless the crash could be determined to be solely the fault of the other vehicle or driver. BASt also distinguished between product liability and road traffic liability in an attempt to separate manufacturer responsibility from driver responsibility. Terms such as *defectiveness*, *reasonably foreseeable misuse* and *abuse* were defined, where it was suggested that the manufacturer would be responsible for reasonably foreseeable misuse, but not abuse. Some identified areas for continued research include:

- determining human ability to interact with automation systems in real road traffic
- determining performance and reliability of driver-state-monitoring systems that may be needed to determine driver condition in real time
- defining functional safety of automation systems at the two higher levels of automation
- determining human capabilities to take control over automation under fault or emergency conditions
- determining driver skill loss from use of automation
- identifying any new driver skills or training that would be needed to use automation systems safely
- identifying demands of automated systems on road infrastructure (e.g. quality of road markings)

8.5 Infrastructure

CTPS has the potential to increase the safety and efficiency of existing roadways, which may be facilitated by the use of managed lanes. HOV lanes are the most prevalent form of managed lanes, where access is restricted to vehicles with a minimum occupancy. Most HOV lanes employ a buffer with limited access, and they may operate continuously or part-time, or may be reversible, depending on traffic patterns. High occupancy toll (HOT) lanes employ tolling technology to improve HOV lane utilization by “selling” excess capacity, where variable pricing may be used to regulate the demand and maintain speeds. The most efficient use of existing roadways will employ priced and dynamically operated lanes, customized to meet local area needs [37].

Lane access could also be restricted to vehicles with specified equipment and performance characteristics, and traffic density could be managed to avoid congestion. Controlling lane access has the potential to simplify the driving environment by minimizing variable traffic conditions. A customer service business model could be created, where users pay for an enhanced transportation service. Access and egress could be managed to further optimize traffic density and limit interference of merging traffic. V2V capability required for platooning could be used to communicate with the infrastructure to facilitate access and tolling, and hazard warning. Physical lane separation could also significantly enhance traffic safety by separating platoons and automated vehicles from manual traffic.

Establishing dedicated truck lanes, where CTPS is permitted, facilitates the introduction of CTPS with minimal impact to the existing infrastructure, while enhancing highway safety and efficiency. Separating trucks from light duty vehicles is attractive to the general public. As well, educating professional drivers to adapt their driving skills to accommodate platoons is easier than educating the general public.

It is assumed that platooning, even at following distances as close as 4 m, will not result in damage to existing infrastructure. However, the U.S. bridge formula²⁴, which links allowable weights to the number and spacing of axles, was intended to be used for single vehicles. It may be necessary to revisit axle weights and spacing between successive vehicles, which might limit the minimum platooning gap.

8.6 Driver Acceptance

Drivers must appreciate and welcome CTPS in order for truck platooning to take place. Modern ADAS, as detailed in Section 4.1, contribute to relieving some of the driver workload and enhancing safety. CTPS may further enhance driving comfort and safety since trucks communicate and operate cooperatively. Improvements in road efficiency and reduced traffic congestion are also appealing to drivers, potentially reducing travel times and easing the driving task. Finally, reduced fuel consumption may motivate drivers to pursue CTPS.

²⁴ http://ops.fhwa.dot.gov/freight/publications/brdg_frm_wghts/bridge_formula_all.pdf

9 COMPARISON WITH LONG COMBINATION VEHICLES

An LCV consists of one tractor and two or three full length trailers, where either the number of trailers or the combined length of the configuration exceeds normal limits.²⁵ LCVs are highly regulated, operating by special permit in most Canadian provinces. An A-train LCV permitted to operate in Ontario is shown in Figure 26. For this configuration, the maximum length is 40 m, and the maximum weight is 63,500 kg.

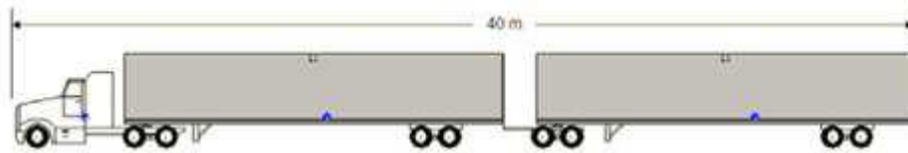


Figure 26: Illustration of an A-Train LCV in Ontario²⁶

LCVs allow carriers to haul a greater volume of freight using one tractor, and therefore only one driver. This alone can result in a significant reduction in operating costs (tractor ownership and operating costs, and human resources). However, the maximum weight is limited such that the trailers in an LCV are much lighter than two separate trailers loaded to their maximum allowable weight. LCVs are most suitable for hauling lightweight goods which fill the volumetric capacity of each of the trailers with lower density freight (i.e. “cube out”) rather than by maximum mass. Conversely, a truck platoon could consist of many trucks, all loaded to their maximum allowable weight. Even if LCV weight limits were increased, their usefulness would still be limited since the current tractor may be power-limited and might not be powerful enough to move the LCV effectively, particularly in areas with steeper grades.

LCVs can contribute to reducing traffic congestion since every LCV is shorter than the equivalent two or three tractor-trailer combinations it replaces (by the length of the additional tractors and the distance between the trucks). The fuel consumption and GHG emissions are significantly reduced due to the elimination of one or two tractors, plus the reduction of aerodynamic drag between the trailers due to the close spacing. Natural Resources Canada (NRCan) quotes possible fuel savings of up to 39 percent with the use of two-trailer LCVs compared to two tractor-trailer combinations when used on flat terrain²⁷.

CTPS also has the potential to reduce fuel consumption and GHG emissions due to reduced aerodynamic drag, but there is no reduction in the number of tractors, so the potential reduction is not as great as it is with LCVs. Similarly, CTPS also has the potential to improve traffic efficiency by reducing the distance between trucks. Two trucks in a platoon could not follow as closely as the two joined trailers in an LCV, plus the combination would be longer since it would include a second tractor. However, a platoon of four trucks may be shorter than two two-trailer LCVs following at a safe following distance (depending upon the spacing within the platoon).

LCV permits specify the conditions under which the vehicles may operate, such as highways on which they can be driven, time of day, time of year, weather conditions and driver experience. There are also speed restrictions. In Alberta, for example, the speed of LCVs is limited to 100

²⁵ <http://canadasafetycouncil.org/traffic-safety/safety-long-combination-vehicles>

²⁶ <http://www.mto.gov.on.ca/english/trucks/programs/cvos/module-11-4.shtml>

²⁷ <http://www.nrcan.gc.ca/publications/energy-efficiency/council-energy-ministers/822>

km/h even where the general speed limit is 110 km/h. Driver qualifications are stringent.²⁸ Similar restrictions may be relevant for CTPS, but since platoons can be dissolved as required, such restrictions simply eliminate the potential benefits of platooning (while eliminating any negative impacts of platooning).

An LCV must travel as a complete combination vehicle at all times, forcing the operator to carefully plan his route and schedule. The trailers are typically owned by the same carrier, filled with similar goods, headed to the same destination. They normally operate between two fixed depots designed to handle LCVs. If the LCV is comprised of conventional van semi-trailers, the rear trailer(s) must be decoupled in order to access the front trailer to permit loading and unloading.

Platoons, on the other hand, offer greater flexibility since trucks can join a platoon when appropriate, and split from the platoon at any time (e.g. to exit the highway for a destination that differs from that of the lead truck). The weight capacity of each truck in a platoon is unaffected by its participation in the platoon.

In summary, the use of LCVs results in decreased fuel consumption and improved traffic efficiency, while trading off flexibility due to size, weight and operational constraints. CTPS has the potential to achieve decreased fuel consumption and improved traffic efficiency, depending upon platoon spacing, length, speed, alignment, duration, etc. But flexibility is maintained since the platoon can dissolve and re-establish at any time as required, and the trucks can operate independently. The locations where platooning could be permitted could be more specifically-defined and shorter duration. For example, a long stretch of highway might not be suitable for LCVs because of a particular section that is unsuitable (perhaps due to construction or typical congestion); however, that same stretch of highway might be suitable for CTPS before and after the unsuitable section, meaning that the platoon would simply have to dissolve before the unsuitable section, and then re-establish afterwards.

²⁸ <http://canadasafetycouncil.org/traffic-safety/safety-long-combination-vehicles>

10 SUMMARY

Potential Benefits of CTPS

CTPS may present an opportunity to significantly reduce fuel consumption and emissions, while potentially improving road safety and efficiency. Reducing the spacing between vehicles reduces the aerodynamic drag experienced by all vehicles in a platoon, and maintaining a consistent speed reduces the frequency of acceleration and deceleration, thereby reducing fuel consumption. The actual reduction in fuel consumption (expressed in L/100 km) is independent of the vehicle weight; however, the percentage reduction in fuel consumption is reduced as the weight increases, since a heavier vehicle consumes more fuel (due to higher rolling resistance). CO₂ emissions, which are the leading contributor to global warming, are also reduced as fuel consumption is reduced. Since long-haul trucks accumulate high annual mileage, most of which is at highway speed, the savings could be substantial.

Through the use of sensors, V2V communication, and some automated vehicle control, it may be possible to reduce or eliminate chain collisions, which often result from an inability of drivers to react quickly in emergency situations. A cooperative truck platoon would likely be led by a professional driver with a proven driving record, operating a truck equipped with modern ADAS to further enhance the driver's ability to drive safely. The requirement for speed changes or manoeuvres are communicated automatically throughout the platoon in real time such that the platoon operates as a synchronized unit, smoothing traffic flow and improving traffic efficiency. Furthermore, as the gap between vehicles is reduced, traffic density is increased such that roadways are used more efficiently. NHTSA determined that highway capacity essentially doubled using 3-truck platoons travelling at 65 mph (104 km/h), and the capacity was essentially tripled using 10-truck platoons.

Enabling Technologies

CTPS is enabled by the emergence of several complementary technologies, including various ADAS (such as ACC, LDWS, BLIS, CWS, GPS, etc.), V2V communication, and modern vehicle control methods and human-machine interfaces. Adding V2V communication to ACC, known as CACC, is ultimately what makes CTPS possible.

Technologies used to monitor the field surrounding a vehicle include long-range and short-range Radar, LiDAR, cameras and ultrasonic sensors. Sensors are often combined and integrated to exploit the features of the different technologies, using "sensor fusion" to gain a more accurate picture of the surrounding environment, and to reduce integration complexity. Electronic vehicle control and actuation systems, permitting remote throttle control, steering and braking, are also important technologies for the automation required for CTPS. Modern instrument clusters and dash displays are intuitive and interactive, and may be configured to provide additional information required for platooning.

V2V communication has been accomplished using various UHF, microwave, millimetre wave and IR media, but in recent years 5.9 GHz DSRC has been adopted as the "standard" V2V (and V2I) medium. The U.S. FCC has allocated 75 MHz in the 5.9 GHz band for licensed ITS use for safety applications. The IEEE 802.11p standard was developed as an amendment to 802.11 to optimize communication in a vehicular environment. Based on the results of the Connected

Vehicle Safety Pilot program, the U.S. DOT may mandate that every new vehicle be equipped with DSRC.

Studies, Tests and Demonstrations

Major projects have been undertaken in the U.S., Europe and Asia to evaluate the benefits and feasibility of platooning. PATH has been operating in California since 1986, and has conducted several platooning trials including a four-car platoon with automated longitudinal control, a fully automated eight-car platoon, and two- and three-truck platoons. They demonstrated fuel consumption reductions of up to 13 percent for the tail truck and 10 percent for the lead truck. They also demonstrated that string stability can be achieved within the default DSRC communication update rate of 10 Hz, maintaining RMS gap variations of less than 0.25 m at 90 km/h.

The European PROMOTE-CHAUFFEUR project was one of the earlier demonstrations of CTPS with two trucks, using an “electronic towbar” system. IR lights were used to control following distance and position, and the following truck automatically followed the lead truck. A second phase demonstrated the feasibility of a three-truck platoon operating in real world environments. At a speed of 80 km/h and a spacing of 10m, the fuel consumption reduction for the tail vehicle was approximately 21 percent, and that for the lead vehicle was approximately six percent.

The German KONVOI project investigated the benefits and deployment issues associated with truck platooning, operating in mixed traffic on autobahns. It focused on quantifying the impact of automated systems on traffic, and on the interaction between humans and machines. The project concluded that the truck platoon had little impact on the surrounding traffic.

The European SARTRE project demonstrated a mixed platoon of cars and trucks operated in a public, mixed-traffic environment. The platoon was led by a manually-driven truck followed by automated vehicles. Lateral control of the following vehicles was performed by following the trajectory of the lead vehicle, without reference to any roadway markings. It was noted that the frequency and magnitude of steering corrections made by the automated control system were comparable to or less than those made by a driver.

The Japanese Energy ITS project investigated energy savings and CO₂ emission reduction for road transportation, including research and development of automated heavy truck platooning. The CTPS concept was a platoon of three identical 25-tonne single unit trucks, all of which (including the lead vehicle) were controlled automatically while in the platoon. A key requirement was a highly reliable solution in order to facilitate potential near-term introduction, which led to significant redundancy of components and technologies, and high bandwidth communication. In March 2010, a platoon of three trucks operating at 80 km/h with a 10 m gap was successfully demonstrated.

Scania was preparing to start platooning trials between the Swedish cities of Södertälje and Helsingborg, coordinating the daily departure of several trucks loaded with engines, gearboxes and axles, such that they would form a platoon as soon as they reached the motorway. It is unknown whether or not the trials were conducted as planned, but Scania continues to work with Stockholm’s Royal Institute of Technology and Linköpings University to explore platooning technology.

Peloton has proposed a platooning concept for two class 8 trucks based on the installation of COTS components. The proposal includes operation of a platoon network operations centre, where Peloton would coordinate linking opportunities and manage platoon activities to enforce safe platooning conditions. Peloton conducted a fuel economy test in November 2013, and several tests and demonstrations are planned for 2014. They are actively seeking partners to advance the development and testing of the proposed system.

The Connected Vehicle Safety Pilot Program includes driver clinics across the U.S., and a large-scale model deployment conducted in Ann Arbor, MI, from August 2012 to December 2013. Over 2800 vehicles, including cars, trucks and buses, have been outfitted with V2V devices using 5.9 GHz DSRC. The model deployment will assess the effectiveness of numerous safety applications, and driver clinics will be used to explore driver reactions to the technology and the safety applications. The results will be used by NHTSA to decide whether to advance the technology through regulatory proposals, additional research, or a combination of both.

The European HAVEit project involved 17 partner organizations, and its goal was to provide relief to the driver in monotonous driving situations, and appropriate assistance in demanding situations (such as driving in roadwork lanes and traffic jams). It explored how drivers interact with vehicles at different levels of automation, trying to avoid both underloading and overloading. Instead of just switching off an ADAS in the event of an impending potentially critical situation, a progressive step-by-step-approach was used to transfer the driving task back from the automated system to the driver, providing the driver with the optimum level of automation and assistance needed in critical situations.

CFD analysis proved to be a useful technique for evaluating aerodynamic performance, since its results compared reasonably well to wind tunnel results and previous test results. Wind tunnel testing involving two simple truck models, approximately 1/16th scale, arranged in tandem, concluded that the drag reduction is closely related to the drag coefficients of the truck models in isolation, and upon how the two trucks are arranged. So it is expected that wind tunnel results will be comparable to that for full-scale trucks exhibiting similar drag coefficients in isolation.

Factors Affecting Safety

CTPS safety is dependent upon several factors, including equipment reliability; vehicle and platoon spacing; platoon length, speed and composition; platooning manoeuvres; the level of automation; surrounding traffic; weather conditions; data security; and human factors.

The system design must incorporate a high level of health monitoring (e.g. diagnostics, built-in test), and employ fail-safe modes to mitigate the danger associated with an equipment failure. The driver (if present) must be able to assume control and override the system at any time. Any communication failure or system fault will require the platoon to immediately dissolve by increasing spacing (decreasing speed), and requiring the driver to assume control.

As the spacing between the vehicles in a platoon, or the spacing between platoons, is reduced, the available reaction time in the event of an emergency situation is also reduced. As the number of vehicles in a platoon increases, the potential for a collision is increased due to the accumulated reaction times. Similarly, as the speed of a platoon is increased, the available reaction time is reduced (assuming a constant gap between vehicles). The potential severity of

a collision is also increased. Communication delays and system response times must be considered in determining minimum safe following distances. Existing regulations specifying minimum following distances would require revision.

Platoon composition has a significant impact on the safety of individual vehicles within the platoon, due to differences in vehicle mass and handling characteristics. This issue is less significant in CTPS, where all of the vehicles are heavy trucks, ideally loaded to a similar weight, and exhibiting similar handling characteristics. Platooning manoeuvres such as joining and splitting introduce dynamic behaviour which also increases risk, since speed and gap are varied during the manoeuvres.

Because driver error or inattention is responsible for most accidents, and because automated systems can typically sense and respond more quickly than humans, there is the potential to improve road safety by automating the driving function. But an alert driver can apply experience and instinct to choose evasive action that would not be possible through automation. Therefore, there are trade-offs at each level of automation.

The safety of platooning systems is enhanced through the use of dedicated lanes, where the behaviour of other vehicles can be reasonably predicted, and speed is much more consistent. Conversely, in mixed lanes, the behaviour of other drivers cannot be managed or predicted, and a platooning system must be designed to accommodate such unpredictable interaction.

Adverse weather can affect the feasibility, effectiveness and safety of platooning, in that it may hamper V2V communication, obstruct necessary markings used for vehicle control, reduce braking performance, etc. There may be conditions when safe platooning simply is not possible, and the vehicles would have to operate independently. In this case the potential benefits of platooning would not be realized, but there is no penalty incurred due to operating the vehicles independently.

The inherent ease of access to the vehicle communications network (i.e. CAN bus) through wireless V2V communication, presents a weak link that exposes the system to potential security threats. Denial-of-service attacks, and fabrication, impersonation or alteration attacks on legitimate network traffic, could actually increase the likelihood of collisions, so countermeasures must be developed to address this threat.

While one of the potential benefits of platooning is some relief of the driver workload, the driver cannot completely disengage from the driving task. The driver must be able to resume control on short notice, and hand-over of control must be effected in a safe and efficient manner.

Factors Affecting Fuel Consumption

The reduction in fuel consumption and CO₂ emissions that can be achieved by CTPS is affected by several factors, including vehicle size, type and weight; vehicle and platoon spacing; platoon length and speed; lateral alignment of platoon vehicles, and cross winds; and the duration of effective platooning.

Heavy trucks have large, blunt front and rear cross-sectional areas, which result in a high drag coefficient. Platooning at close following distances can significantly reduce the aerodynamic drag, leading to a reduction of fuel consumption (and emissions). Rolling resistance is proportional to vehicle mass, so the greater the vehicle mass, the lower the percentage of fuel

savings due to platooning, since the percentage contribution of fuel consumption due to aerodynamic drag is smaller. However, the actual reduction in fuel consumption, expressed in L/100 km, is independent of the vehicle weight.

The potential fuel savings increase as the gap between vehicles is decreased, to a gap of approximately 8 m for heavy trucks. The most significant fuel savings are experienced by those vehicles between the lead and tail vehicle, so the longer the platoon, the greater the net savings. Similarly, the shorter the gap and the longer the platoon, the greater the traffic density and therefore the road capacity. The ideal spacing between trucks for optimum fuel savings is dependent upon several factors, and ideally the gap could be adjusted dynamically to optimize the fuel savings as conditions change.

The longer the platoon, the fewer the traffic oscillations, and hence the greater the average speed and traffic flow efficiency. The length of the platoon is bounded by the V2V communication speed and reliability required in order to maintain string stability. The length must also be limited to avoid bottlenecks at highway entrances and exits.

While the potential fuel savings are greater at higher speeds due to the associated higher aerodynamic drag, fuel efficiency decreases as highway speed increases. Therefore the platoon speed should be optimized to achieve the greatest fuel economy for the individual vehicles. A PCC system could be used to vary the speed to optimize fuel economy over hilly terrain.

The potential fuel savings that can be achieved by platooning are sensitive to the lateral alignment of the vehicles in the platoon. For heavy trucks operated by experienced (and alert) drivers, it is reasonable to assume that lateral alignment will be very good. Crosswinds tend to increase the aerodynamic drag experienced by all vehicles in a platoon, thereby reducing the potential fuel savings due to platooning.

The duration of an established platoon determines the fuel savings that can be achieved due to platooning. In mixed traffic, cut-ins by non-platoon traffic present the biggest obstacle to maintaining platoon integrity. The acceleration required by all following vehicles to close the gap and re-establish the platoon following a cut-in is inefficient. Dissolving the platoon due to heavy traffic, adverse weather, platooning system faults, etc. foregoes the potential benefits of platooning.

Since aerodynamic drag varies with air density, fuel consumption is greater at colder ambient temperatures. The reduction in the drag coefficient due to platooning should be similar at all ambient temperatures, so the reduction in fuel consumption should be greater at colder temperatures. The effects of cold climate can be reasonably extrapolated from test results at standard conditions.

Other Considerations

In order to conduct CTPS, coordination is required to design and establish the platoon. Factors such as truck type, weight, performance parameters, installed equipment, current location, destination, etc. all need to be considered. This coordination is greatly simplified if the platoon is comprised of trucks from a single carrier. For a platoon of trucks that are not affiliated with each other, communication and cooperation between carriers is required, including financial arrangements based on platoon position, duration, etc.

Regulations will be required to authorize and control platooning, perhaps similar to those developed for LCVs. An advantage of platooning, though, is that platoon vehicles must be able to operate independently, so platooning only when and where permitted does not present a challenge. Specifications must be developed, and inspecting agencies established, to verify vehicle configuration and fitness for platooning. Driver training and certification must also be developed and implemented.

There is the potential that the data exchanged between vehicles to facilitate platooning could be used by insurers, law enforcement agencies, employers, or others. Further study is required to determine privacy implications, and develop strategies to manage privacy issues. Automated control also raises liability issues, determining who is at fault in the event of a crash.

Existing infrastructure, which was not designed to support platooning, may be improved through the implementation of managed lanes. Lane access could be restricted to vehicles with specified equipment and performance characteristics, and traffic density could be managed to avoid congestion. Controlling lane access has the potential to simplify the driving environment by minimizing variable traffic conditions. Establishing dedicated truck lanes, where cooperative truck platooning is permitted, could facilitate the introduction of CTPS with minimal impact to the existing infrastructure, while enhancing highway safety and efficiency.

In order for CTPS to become popular, drivers must demonstrate an interest in it. Enhanced driving comfort, safety, and efficiency, as well as reduced fuel consumption, would likely influence driver acceptance.

Comparison with LCVs

LCVs are single vehicles comprised of one tractor and two or three full length trailers, which are well suited for hauling lightweight goods which tend to “cube out”. The fuel consumption and GHG emissions are significantly reduced due to the elimination of one or two tractors, plus the reduction of aerodynamic drag between the trailers due to the close spacing. Restrictions typically include where and when LCVs can operate, as well as the maximum speed and weight. Since an LCV only uses one tractor, it must travel as a complete combination vehicle at all times, usually between terminals designed to accommodate LCVs.

Platoons, on the other hand, can be easily formed and dissolved as required. They offer more flexibility because each trailer is physically hitched to a suitably sized tractor, so the tractor-trailer combinations can operate independently. However, there is no reduction of the number of tractors (or drivers), and the minimum gap is greater than that possible with LCVs; therefore, the potential fuel savings are considerably less.

11 NEXT STEPS

CTPS, enabled by modern technologies, presents an opportunity to reduce fuel consumption and emissions, while potentially improving road safety and efficiency. However, further investigations, testing and evaluations in various operating environments and conditions are required in order to have the empirical evidence needed to be able to draw sound conclusions and recommendations.

The purpose of this section is to provide guidance on developing a targeted workplan that will create and facilitate a test and evaluation campaign for CTPS, identifying questions that federal and provincial regulators will need to answer in order to support the development of future safety and environmental regulations, non-regulatory codes and standards, and energy efficiency programs. The goal of follow-on work would be to identify and benchmark the safety and environmental limits and performance characteristics of CTPS, including consideration for both human factors and driver/user acceptance, and the costs and benefits of CTPS. Specific emphasis will be placed on conditions and constraints unique to Canada (e.g. geography, climate, infrastructure, social-political issues, etc.). Various government agencies are key stakeholders, including federal regulators (e.g., TC, Environment Canada, NRCan, Industry Canada), and provincial transportation regulators, who should be consulted for input to the workplan. Other stakeholders that should be consulted for input to the work plan would be industry and the trucking companies. Important knowledge gaps related to environmental benefits, safety aspects, and feasibility of CTPS are identified below.

Environmental Benefits

The following areas should be investigated to facilitate an assessment of the fuel savings and emissions reduction that could be achieved with CTPS:

- sensitivity of the overall drag coefficient of a platoon to tractor-trailer geometry, spacing between trucks, lateral alignment, crosswinds, ambient temperature, and surrounding traffic
- impact of aerodynamic devices such as side skirts, boat-tails, and gap reduction devices
- typical ACC duty cycle on equipped Class 8 trucks on highways that might be suitable for CTPS, and variation in speed during ACC use. (Such information could provide an indication of the potential opportunity for CTPS in current mixed traffic conditions.)
- fuel consumption of a heavy truck while accelerating to close the gap to establish a platoon (or re-establish a platoon following a cut-in), how long it takes to perform such a manoeuvre, and the likelihood that the manoeuvre is successful without another cut-in occurring before the gap is reduced
- effectiveness of PCC in reducing platoon fuel consumption, when used by the lead truck of a platoon
- technologies or techniques that could improve the effectiveness of CTPS, and how to evaluate or quantify the improvement

Safety Aspects

The following areas should be investigated to identify and define the safety aspects associated with CTPS:

- minimum safe following distance between trucks operating in a platoon, and impact of cut-ins
- ease and accuracy of predicting braking distance, and sensitivity of effective braking distance to factors such as tractor-trailer weight, tire and brake condition, and road conditions
- reliability and effectiveness of ACC and V2V in inclement weather, and sensitivity of sensor performance to precipitation, road dirt, ice and snow; identification of minimum performance levels
- undesirable consequences of CTPS, such as driver inattention and disengagement, or a tendency to follow too closely when not actively participating in a platoon
- impact of CTPS on the smooth flow of traffic at highway entrances and exits, and the response of other drivers to the presence of truck platoons; assessment of markings required to identify a truck platoon
- driver training and qualifications for participation in CTPS
- response of truck drivers to closely following a lead truck at highway speeds (with limited view of the road ahead)
- parameters that should be used to establish safety requirements, including minimum performance levels

Feasibility

The following areas should be investigated to assess both the feasibility and level of interest of CTPS:

- minimum fuel savings, safety benefits and/or efficiency returns which must be achieved in order for carriers to be interested in CTPS
- determination of where CTPS would be possible in Canada, and what restrictions would be required; evaluation of highway design changes that might facilitate CTPS, such as extended passing lanes, modified on ramp acceleration lanes, revised markings, etc.
- public acceptance of CTPS (i.e. tolerance of other motorists)
- risk of infrastructure damage due to dynamic loading of close-following laden trucks
- opportunity for managed lanes to reduce the interaction between trucks operating in a platoon and other drivers
- legal barriers to CTPS, and challenges of operating truck platoons across provincial borders
- response of insurers to CTPS
- opportunities or locations where CTPS trials could be conducted (in Canada)
- competing technologies which might negate the potential benefits of CTPS

ACRONYMS AND ABBREVIATIONS

ABS	Anti-Lock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
ASTM	American Society for Testing and Materials
BLIS	Blind Spot Information System
CACC	Cooperative Adaptive Cruise Control
Caltrans	California Department of Transportation
CAN	Controller Area Network
CAS	Collision Avoidance System
CCD	Charge-Coupled Device
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COTS	Commercial-off-the-Shelf
CTPS	Cooperative Truck Platooning System
CWS	Collision Warning System
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communication
ECU	Electronic Control Unit
EPS	Electric Power Steering
ESC	Electronic Stability Control
eTV	ecoTECHNOLOGY for Vehicles
FCC	Federal Communication Commission
FMECA	Failure Modes, Effects and Criticality Analysis
Gbps	gigabits per second
GHG	Greenhouse Gas
GHz	gigahertz
GPS	Global Positioning System
HAVEit	Highly Automated Vehicles for Intelligent Transport
HC	Hydrocarbons
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
Hz	hertz
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
ITS	Intelligent Transportation Systems
ITS JPO	Intelligent Transportation Systems Joint Program Office
kg	kilogram
km	kilometre
km/h	kilometres per hour
L	litre
LAN	Local Area Network
LCV	Long Combination Vehicle
LDWS	Lane Departure Warning System
LED	Light Emitting Diode
LiDAR	Light Detection and Ranging (Laser Imaging Detection and Ranging)

LKS	Lane Keeping System
LRR	Long Range Radar
LTE	Long Term Evolution
m	metre
m/s	metres per second
Mbps	megabits per second
MHz	megahertz
mm	millimetre
mph	miles per hour
ms	milliseconds
MTBF	Mean Time Between Failure
NAHSC	National Automated Highway Systems Consortium
NHTSA	National Highway Traffic Safety Administration
nm	nanometre
NO _x	Nitrogen Oxides
NRCan	Natural Resources Canada
NRC-AST	National Research Council – Automotive and Surface Transportation
PATH	Partners for Advanced Transportation Technology (formerly Partners for Advanced Transit and Highways)
PCC	Predictive Cruise Control
PELOPS	Program for the Development of Longitudinal Traffic Processes in System Relevant Environment
PKI	Public Key Infrastructure
PM	Particulate Matter
RF	Radio Frequency
RMS	Root Mean Square
RSC	Roll Stability Control
SARTRE	Safe Road Trains for the Environment
SPITS	Strategic Platform for Intelligent Transport Systems
SRR	Short Range Radar
TC	Transport Canada
TDMA	Time Division Multiple Access
THz	terahertz
U.S.	United States
UHF	Ultra High Frequency
UMTRI	University of Michigan Transportation Research Institute
USB	Universal Serial Bus
V2D	Vehicle-to-Device
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VII	Vehicle Infrastructure Integration
WAVE	Wireless Access in Vehicular Environments

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