

# DEVELOPMENT OF PRE-CRASH SAFETY SYSTEM WITH PEDESTRIAN COLLISION AVOIDANCE ASSIST

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## ABSTRACT

A new pre-crash safety (PCS) system with pedestrian collision avoidance assist has been developed. This system is capable of detecting both vehicles and pedestrians, and helps the driver to avoid a collision by automatically braking the vehicle by up to 40 km/h, one of the highest rates of deceleration for a PCS system in the world. Pedestrian detection is enabled by a sensing system that combines millimeter wave radar and a stereo camera. This system is capable of stable object detection regardless of day or night. At night, the system uses near infrared projectors to enhance the detection performance of the camera.

This paper describes the core technology for achieving this system, including brake control technology for decelerating the vehicle by up to 40 km/h to help avoid a collision, and recognition technology capable of detecting pedestrians walking quickly across a road. The collision avoidance brake control technology achieves higher and more accurate deceleration than conventional systems, and is robust against variations in brake effectiveness. These variations are suppressed by the control algorithm, which uses the distance to the object and the deceleration as feedback parameters. As a result, the target deceleration performance may be achieved even under certain conditions of brake effectiveness variation. In addition, the timing of braking start was designed not to interfere with collision avoidance operations performed by the driver. The deceleration and jerk (i.e., the deceleration gradient) were also determined considering the risk of the driver becoming dependent on or over-confident in the system.

An effective recognition technology that helps to prevent a wider range of accidents should be capable of detecting pedestrians quickly crossing a road. To further this goal, the response of the position detection filter of the millimeter wave radar was enhanced, and

new algorithms were developed for collision judgment as well as the fusion between the millimeter wave radar and stereo camera. These measures enable highly accurate collision judgment for pedestrians crossing a road.

## 1. INTRODUCTION

PCS systems judge the probability of a collision based on the position and relative speed of the driver's vehicle with respect to an object, and either help the driver to avoid the collision or help to mitigate collision damage by activating devices such as warnings, brake assist, automatic braking, and the like. Since Toyota developed the first commercial PCS system in February 2003, the technology has advanced to include detected pedestrian as well as frontal collisions at intersections [1-2]. In contrast, most conventional automatic braking systems were designed to activate only when a collision is unavoidable, help mitigate the damage caused by the collision. However, new systems have since been developed that are capable of avoiding some types of collisions automatically [3].

This paper describes a newly developed PCS system with pedestrian collision avoidance assist. This system is capable of detecting both vehicles and pedestrians, and helps the driver to avoid a collision by automatically braking the vehicle by up to 40 km/h. This is one of the highest rates of deceleration for a PCS system in the world, however, the system cannot fully replace driver attention to surround.

The following sections detail the aims of the system, the development issues, and the core brake control and recognition technologies that were developed to resolve these issues. This system was installed on the Lexus LS launched in September 2012.

## 2. SYSTEM OUTLINE

This section describes how the aims of the PCS system with pedestrian collision avoidance assist were determined based on the analysis of real-world accidents, the development items to achieve these aims, and the system configuration.

### 2.1 System Aims and Development Items

According to traffic accident statistics in Japan, rear-end collisions are the most frequent type of accident, and accidents between vehicles and pedestrians account for the highest proportion of fatal accidents [4]. Furthermore, the relative speed distribution data of these accidents shows that more than 80% of rear-end collisions and more than 90% of vehicle-pedestrian accidents occur at a relative speed of 40 km/h or less (Figure 1).

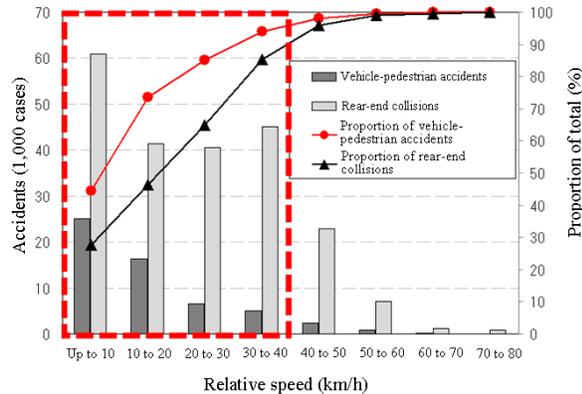


Figure 1. Relative speed distribution of rear-end collisions and vehicle-pedestrian accidents (source: Institute of Traffic Accident Research and Data Analysis (ITARDA) 2010 Report).

The same traffic accident statistics show that most (76%) accidents between vehicles and pedestrians occur when the pedestrian is crossing a road (Figure 2).

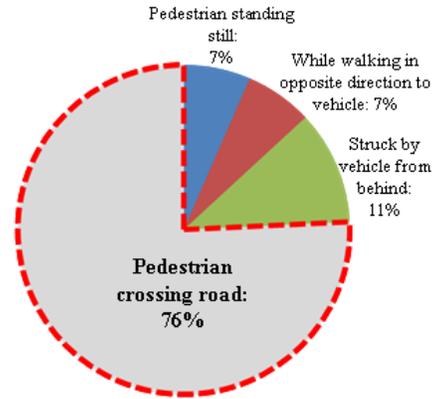


Figure 2. Distribution of vehicle-pedestrian accident types (source: ITARDA 2010 Report).

In addition, time distribution statistics of fatal accidents between vehicles and pedestrians indicate that most such cases occur at night (Figure 3).

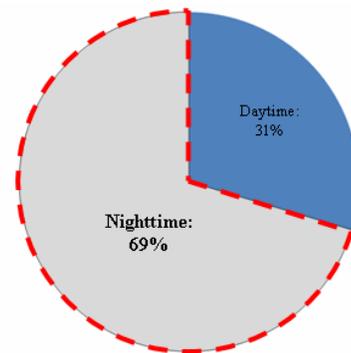


Figure 3. Daytime/nighttime distribution of fatal vehicle-pedestrian accidents (source: “Details of Fatal Traffic Accidents and Results of Road Traffic Law Enforcement in 2011” (in Japanese), Traffic Bureau of the National Police Agency of Japan).

Based on these statistics, this development aimed to achieve a system capable of detecting both vehicles and pedestrians walking quickly across a road regardless of day or night. The speed reduction target was set to 40 km/h.

The following two development items were identified to achieve these aims.

- Automatic brake control technology with high deceleration
  - Early collision probability judgment and recognition technology for pedestrians crossing a road
- The following sections describe the development of these technologies in more detail.

## 2.2 System Configuration

Figure 4 shows the configuration of the system. It consists of a pre-crash sensor system, which judges the probability of a collision, and collision avoidance assist devices. The pre-crash sensor system includes various peripheral monitoring sensors such as a millimeter wave radar, stereo camera, and the like, and a PCS ECU. This system is capable of stable recognition of objects regardless of day or night. At night, the system uses near infrared projectors to enhance the detection performance of the camera.

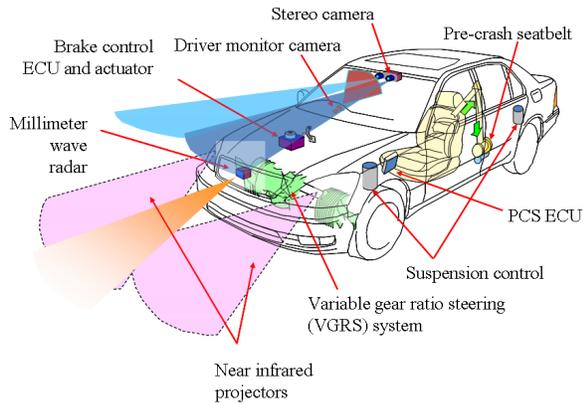


Figure 4. Configuration of PCS system with pedestrian collision avoidance assist.

The pre-crash sensor system detects vehicles, pedestrians, and other objects, judges the collision probability using parameters such as the position, speed, and predictive courses of the driver's vehicle and object, and then activates the collision avoidance assist devices based on this probability. Figure 5 shows the operation sequence of each device. If the system detects a danger of a collision, it urges the driver to take evasive action through a warning buzzer and meter display. In this case, if the driver monitor camera detects that the driver is not paying sufficient attention to the road ahead due to distraction or drowsiness, an earlier warning is given and warning braking is performed to attract the driver's attention. If there is a higher danger of a collision, the system acts to assist evasive action by the driver. For example, the variable gear ratio steering (VGRS) system sets the appropriate steering gear ratio to help the driver steer around the object, the suspension control activates to help prevent the nose of the car diving forward, and the pre-crash brake assist increases the emergency braking force when the driver presses the brake pedal. Then, if a collision is unavoidable, the pre-crash seatbelt is operated so as to retract the seat belt automatically, and the pre-crash brake is operated to assist the driver avoid the collision.

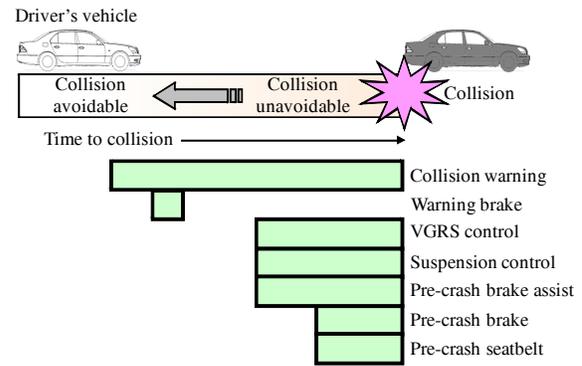


Figure 5. Operation sequence of collision avoidance assist devices.

## 3. HIGH-DECELERATION AUTOMATIC BRAKE CONTROL TECHNOLOGY

This system aims to help mitigate collision damage by reducing the vehicle speed by up to 40 km/h, the brakes must be capable of achieving high deceleration. In addition, to help avoid an object, the brake control must generate the required deceleration accurately so that the vehicle does not stop in front of the object unless necessary (Fig. 6). To achieve these aims, a new deceleration feedback control algorithm was developed. The braking start timing, deceleration, and jerk were determined considering the risk of the driver becoming dependent or over-confident in the system. These points are described in the following sections.

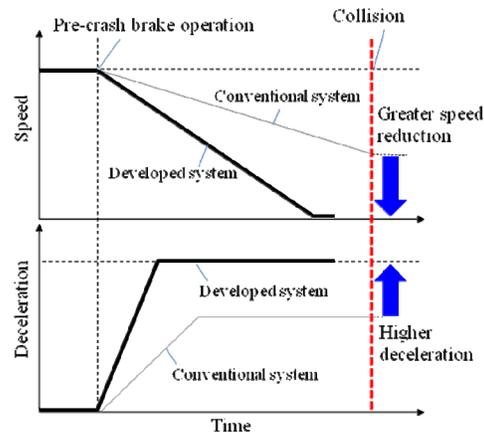


Figure 6. Expansion of automatic braking effect.

### 3.1 Deceleration Feedback Control Algorithm

Figure 7 shows the flow from judgment that a collision is probable to activation of the automatic braking system.

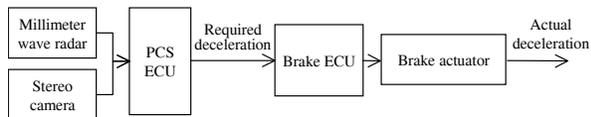


Figure7. Flow of deceleration controlled by automatic braking system.

First, the sensor detects an object and the PCS ECU judges the collision probability. If the probability is higher, the PCS ECU sends the required deceleration signal to the brake ECU. The vehicle is then decelerated via the brake actuator. However, the actual deceleration varies in accordance with a large number of factors, such as the state of the brake pads, vehicle weight, road surface friction ( $\mu$ ), and the like. Figure 8 shows the difference between the actual deceleration and the deceleration required to avoid an object at a relative speed of 40 km/h. The figure shows actual deceleration results from tests performed under two different conditions for the brake pad state, vehicle weight, and the like.

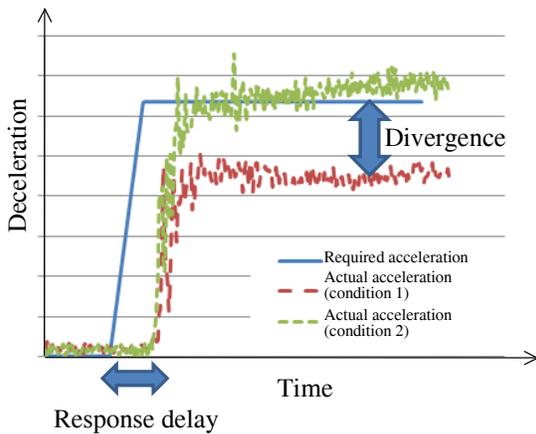


Figure8. Difference between required and actual deceleration (stationary object, relative speed: 40 km/h).

Figure 8 indicates that a response delay occurred before the actual deceleration is generated. In addition, the final deceleration diverged from the required deceleration depending on the test conditions. Consequently, a new deceleration feedback control algorithm was developed to stably reduce the relative speed of the vehicle by up to 40 km/h under various conditions that cause actual deceleration to fluctuate. Figure 9 shows a block diagram of this feedback control.

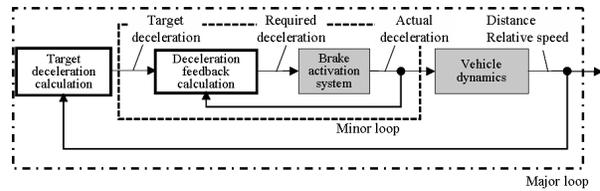


Figure9. Deceleration feedback control.

First, the target deceleration calculation module in the major loop feeds back the distance, relative speed, and the like detected by the sensors and calculates the target deceleration required to avoid the object. Next, the deceleration feedback calculation module in the minor loop feeds back the actual deceleration and calculates the required deceleration by correcting the target deceleration. These steps enable a brake control that is robust against variations in brake effectiveness by suppressing their impact.

### 3.2 Deceleration Control Considering System Dependence and Over-Confidence

The automatic brake may intervene depending on the collision probability judgment. However, if the timing of the intervention is too early, the driver may start to feel that objects can be avoided without manual brake operation; this is known as system dependence. Since the driver must always remain in control of the vehicle and be aware of the surrounding, PCS systems are designed simply to assist manual operation by the driver by helping to compensate for errors in cognition and decision making. Therefore, the brake control is designed to reduce the risk of the driver becoming dependent on or over-confident in the system. To achieve this, the braking start timing, deceleration, and jerk were designed not to interfere with collision avoidance operations performed by the driver, thereby reducing the livelihood of dependence and over-confidence.

**3.2.1 Braking start timing** There are two types of collision avoidance operations: avoidance by braking and avoidance by steering. Figure 10 shows the avoidance timing region of an ordinary driver in normal driving [5].

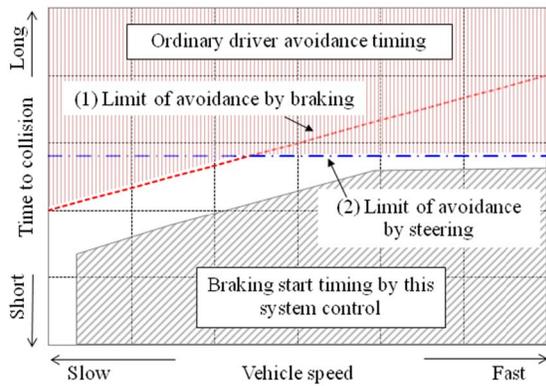


Figure 10. Braking start timing of developed system.

In Figure 10, the time to collision (TTC) is calculated by the relative distance and speed. An ordinary driver is capable of avoiding a collision in the region where the TTC is longer than indicated by lines (1) and (2). The braking start timing was set to the region in which the TTC is shorter than that avoidable by manual operation. This works to prevent interference with collision avoidance operations performed by the driver, reducing dependence or over-confidence in the system.

**3.2.2 Deceleration and jerk** A monitoring evaluation test was carried out under the conditions listed in Table 1 to confirm the deceleration and jerk during normal braking by an ordinary driver.

**Table 1.**  
**Evaluation Conditions**

Vehicle speed conditions	25 km/h, 45 km/h
Braking conditions	Avoidance of object by normal braking
Test samples	208

Figure 11 shows the distribution of deceleration and jerk in normal braking obtained by the monitoring evaluation and in automatic braking by this system.

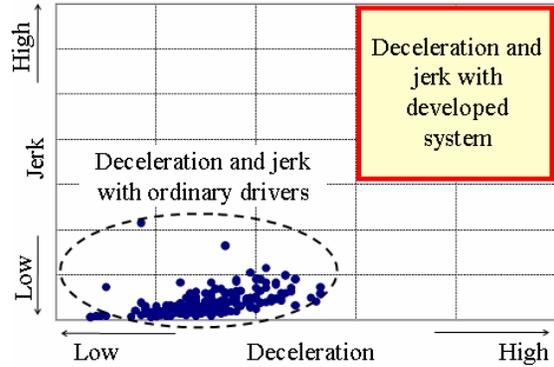


Figure 11. Deceleration and jerk during normal braking by ordinary drivers.

The deceleration and jerk of the automatic braking in this system were set substantially higher than the normal braking region. This clearly differentiates normal and emergency braking and helps prevent system dependence.

#### 4. EARLY COLLISION JUDGMENT AND RECOGNITION TECHNOLOGY FOR CROSSING PEDESTRIANS

As Figure 12 shows, braking to achieve a deceleration of up to 40 km/h when a pedestrian crosses a road requires an expanded PCS system operation region and earlier collision probability judgment. Therefore this system was designed to judge the probability of a collision with a pedestrian crossing a road and to operate the brakes at an earlier timing. This was accomplished by enhancing the horizontal position response of the millimeter wave radar, and developing new algorithms for collision judgment as well as the fusion between the millimeter wave radar and stereo camera for detecting pedestrians crossing a road. The details of these three items are described in the following sections.

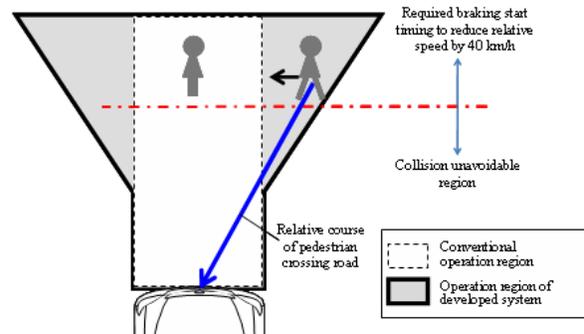


Figure 12. Outline of operation for pedestrian crossing road.

#### 4.1 Design of Millimeter Wave Radar Horizontal Position Filter

The horizontal position of an object detected by radar (i.e., the relative distance horizontally to the direction of travel) contains a certain response delay due to the filter processing within the radar ECU (Figure 13). Therefore, if a pedestrian is crossing a road quickly, the timing of entry into the collision probability judgment region is also delayed, making early collision probability judgment more difficult.

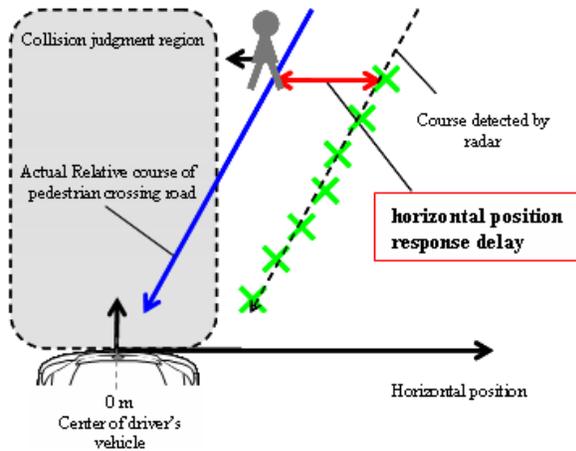


Figure 13. Issue of millimeter radar wave horizontal position response.

Therefore, a filter with a faster response was designed to detect pedestrians walking quickly across a road. The conventional filter process assumes the detection of both vehicles and pedestrians. In contrast, a new filter was designed that concentrates on the detection of pedestrians crossing a road by focusing on the differences in the amount of horizontal positional changes, travel speeds, and the like between vehicles and pedestrians. This approach helps to suppress variations and to enhance response. As shown in Figure 14, the developed system has an improved horizontal position response for pedestrians crossing a road and obtains results close to the actual course of a pedestrian.

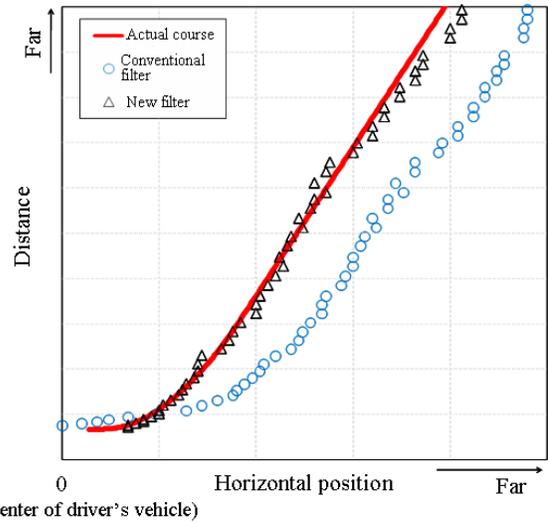


Figure 14. Results of millimeter wave radar horizontal position response comparison (speed of driver's vehicle: 30 km/h, crossing speed of pedestrian: 5 km/h).

#### 4.2 Fusion Algorithm

Since the level of radar reflection from a pedestrian is lower than a vehicle, pedestrians are detected by lowering the detection threshold value. Consequently, if only radar is used for collision judgment, it is possible that unwanted items such as metallic objects on the road may also be detected. Therefore, greater detection reliability is achieved by combining radar information with information from a stereo camera with excellent three-dimensional object recognition capabilities. Figure 15 outlines the fusion algorithm.

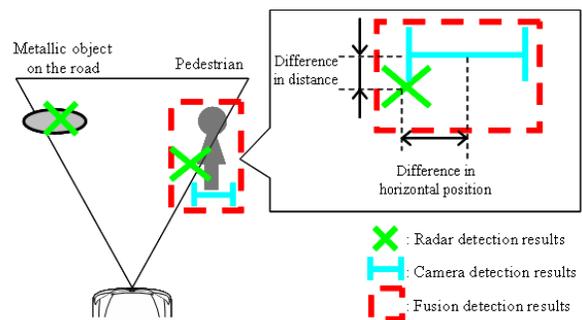


Figure 15. Outline of fusion algorithm.

Fusion information is created by combining radar and camera information within certain ranges based on the differences in distance and horizontal position. The fusion algorithm allows information that cannot be detected by radar alone, such as width, height, and the like, to be used in combination with radar information.

During the fusion process, the reliability weighting attributed to the respective information from the radar and camera is adjusted in accordance with factors such as distance. This allows short-range detection, which is difficult for radar to perform, to be interpolated by the camera, thereby enhancing the accuracy of pedestrian collision judgment.

The collision judgment algorithm described in Section 4.3 uses this fusion information.

### 4.3 Collision Judgment Algorithm

As shown in Figure 16, a conventional system can only judge collision probability within a range inside the driver's vehicle width. Therefore, to judge the probability of collision at an earlier timing, it is necessary to expand the collision probability judgment range outside the width of the driver's vehicle. A new algorithm was developed to reduce the vehicle speed by up to 40 km/h when an object is detected outside the driver's vehicle width by determining the point of intersection between the front of the driver's vehicle and the relative course of the pedestrian crossing the road. Figure 17 outlines this newly developed algorithm.

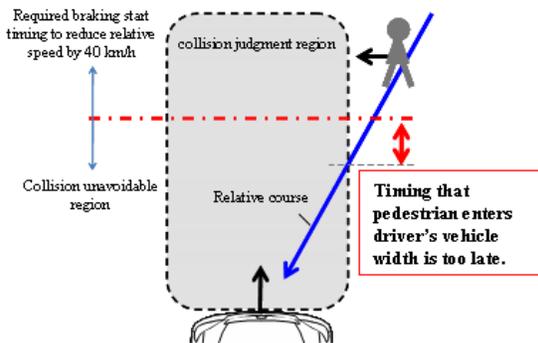


Figure 16. Issue of detecting pedestrian crossing road.

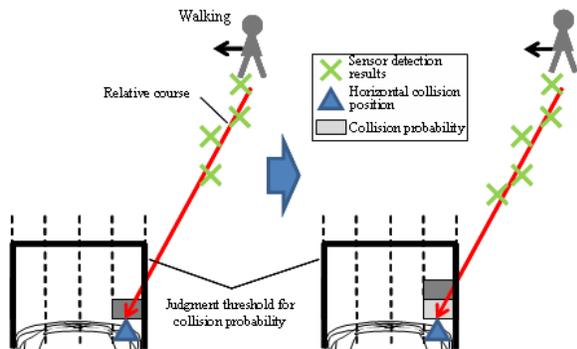


Figure 17. Outline of collision probability judgment algorithm.

First, the algorithm calculates the point of intersection between the front of the driver's vehicle and the relative courses of the vehicle and the pedestrian crossing the road (i.e., the horizontal position of collision). In this process, the relative course is calculated using position information over an elapsed period of time obtained from the sensors. However, the accuracy of the sensors may cause vector variations, resulting in an unstable horizontal collision position. Therefore, the front of the vehicle is divided into regular segments and the distribution of the horizontal collision position over a set period of time is calculated as the collision probability. If the probability of collision with the front of the vehicle exceeds a threshold value, the algorithm judges that a collision is probable. The left and right diagrams in Figure 17 show time-series detection histories. The probability of a collision within the same segment increases because the same horizontal collision position segment was calculated in two successive cycles. In this way, vector variations due to sensor accuracy are reduced by judging the horizontal collision position based on the distribution over set segment and time ranges, thereby improving judgment accuracy. Finally, the collision probability outside the vehicle width is judged by combining these results with the TTC and other collision probability judgment conditions calculated using the fusion results described in Section 4.2. As a result, the vehicle speed can be reduced by up to 40 km/h even with a pedestrian crossing a road.

In addition, Figure 18 shows a scenario in which a pedestrian suddenly stops outside potential collision zone while crossing a road as an example of a false positive that conflicts with the enlarged operation range of the system.

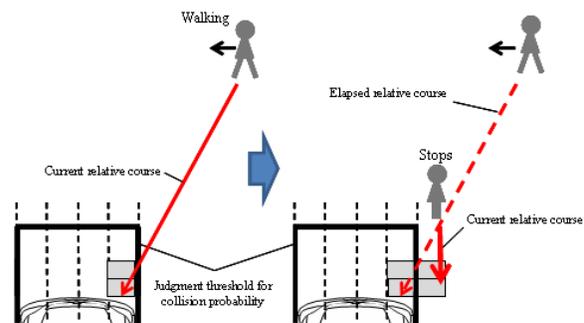


Figure 18. Collision probability distribution in false positive scenario.

In this type of scenario, the pedestrian should not be detected as a possible collision object. Therefore, factors such as the segment width, collision probability adjustment calculation, and the like were optimized so that the collision probability is scattered over multiple

segments rather than concentrating in one segment. This helps prevent the collision probability judgment threshold from being exceeded.

## **5. CONCLUSION**

PCS systems have previously been developed to help mitigate collision damage by reducing the speed of common accident patterns such as rear-end collisions and frontal collisions at intersections. This paper has described the development of a PCS system with pedestrian collision avoidance assist to help reduce traffic accident fatalities and injuries. This system aims to help further reduce the number of people killed or injured in traffic accidents by enabling automatic braking with one of the highest rates of deceleration for a PCS system in the world. Future goals include further enhancing the level of collision avoidance performance, developing technology to achieve omni-directional detection, and reducing costs to enable these systems to be adopted more widely. By these measures, technological development can help contribute to a safer and more comfortable mobile society.

## **REFERENCES**

- [1] Tsuchida, J. et al. 2007. "The advanced sensor fusion algorithm for Pre-Crash Safety system." SAE. Paper No.2007-01-0402
- [2] Kawasaki, T. et al. 2009. "Development of front-side pre-crash safety system for intersection collisions." 16<sup>th</sup> ITS World Congress and Exhibition on Intelligent Transport Systems and Services.
- [3] Noguchi, Y. et al. 2011. "Development of Driving Assist "System Eyesight Ver.2". Subaru Technical Review, 33-37
- [4] Institute for Traffic Accident Research and Data Analysis (ITARDA). 2010. "Traffic Statistics: 2012 Edition." (in Japanese)
- [5] Ministry of Land Infrastructure and Transport of Japan (Engineering Safety Department, Road Transport Bureau, Engineering Planning Division). 2008. "Technical Policy for Frontal Object Collision Mitigation Braking Devices (Proclamation No. 139)." (in Japanese)

# ENVIRONMENTAL, SAFETY, LEGAL AND SOCIETAL IMPLICATIONS OF AUTONOMOUS DRIVING SYSTEMS

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## ABSTRACT

The concept of autonomous driving opens up for many opportunities but, at the same time, raises concerns and issues for discussion that need to be analyzed and penetrated before a more broad roll-out of autonomously driven vehicles on public roads can be attempted.

Among the obvious potential benefits for the society is improved fuel economy, enhanced safety and reduced congestion. There are, however, also potential benefits in offering mobility to the physically challenged, reduced need for infrastructure investments, more efficient use of the urban landscape and individual benefits with more efficient use of the time spent in the car. Driving in autonomous mode opens up for using the time for other useful occupations, e.g. working, relaxing, eating, etc.

Many obstacles remain before autonomous driving can be a part of transportation on public roads. In Europe an intense debate is discussing the implications of the Vienna Convention, which governs the framework for the requirements on the driver, and the legality of not having the driver in control of the vehicle. In the US, activities within the states are opening up for autonomous driving testing on public roads under certain provisions, but there is an obvious risk of causing fragmentation by creating deviating requirements.

Sorting out the liability issues will be one of the major challenges before autonomous driving on public roads can be a reality. Present national laws in some countries do require a person in form of the driver to be liable in the case of an incident or a crash. For higher levels of autonomous driving, liability needs to rest with the manufacturers or another entity not in the form of a

person and should be reflected in national liability legislations.

## INTRODUCTION

During the last decades, driving a car in a modern urban area has, globally, turned into following a slow moving traffic for a considerable amount of time without neither the pleasures of maneuvering an advanced modern vehicle nor being able to use the time for a more useful activity. The concept of autonomously or semi-autonomously driven vehicles would potentially open up for a number of possibilities attractive to the future car buying customers and occupants. Being able to use the time in the car for other things than monitoring traffic and driving and instead being able to find the ride relaxing and efficient could potentially improve the work-life-balance for many people in densely populated areas. There is, however, a deep-rooted and, for many reasons, well justified concern among both governments, manufacturers and the public that there will be huge obstacles in the path of the technological development and in relation to the perception and behavior of humans that will efficiently prevent fully autonomous vehicles.

The development of various levels of driver assistance systems has been very rapid during the last decade. These systems also have various levels of autonomy, i.e. the vehicle assumes the responsibility from a driver, for a shorter or longer duration and can be viewed as necessary steps in the development towards semi- or partial autonomous systems and eventually fully autonomous systems.

It is generally accepted that, in about 90-95% of all incidents and crashes, human behavior is partially or fully responsible. In the push towards reaching the goal of zero serious injuries and fatalities there is a clear need in having the vehicle assuming more of the

responsibility from the drivers either in assisting or taking over the control of the car in a critical situation. The debate is currently running high on the legality and desirability of having the car fully or partially assuming the control, or if the driver should always be in control. For many of the involved parties, however, in assessing what is needed for reaching very low numbers of casualties, there is a shared view that more advanced assistance systems leading towards autonomous driving are desired or needed in reaching this goal.

The legal implications and constraints will have a major influence on the speed of the development, the applications and the directions of autonomous driving in different countries and on different continents. The legal framework affecting the development of autonomous driving concepts varies considerably between the US, Europe and the rest of the world. It even varies within Europe and within the US.

Autonomous driving also, potentially, opens up for possibilities for improved fuel economy, reduced problems with congestions in urban areas, more efficient use of land for city planning, reduced emissions and driving possibilities for the physically impaired.

It is clear to most safety stakeholders that autonomous driving, on some level, is very much part of the future. The technology level has already reached a stage where initial tests are possible. However, dealing with the legality, liability, infrastructure usage and driver acceptance issues will be critical in order to make this truly a part of the future.

## **DEFINITIONS OF AUTONOMOUS DRIVING CONCEPTS**

When discussing autonomous driving the different levels of automation can be identified as:

- Driver Assistance
- Partial Automation (or semi-automation)
- High Automation
- Full automation

### ***Driver Assistance Systems (DAS):***

Driver assistance systems are systems geared towards assisting drivers by giving information essential or useful for driving and, when a situation is beginning to become critical, giving clear and concise warnings. Examples of DAS are Lane Departure Warning (LDW), Forward Collision Warning (FCW) and Blind Spot Information Systems (BLIS).

### ***Partial automation systems:***

Partial automation systems are systems that autonomously intervene when the driver fails to act despite warnings. Examples of this are Automatic Emergency Braking (AEB) and Emergency Lane Assist (ELA).

### ***High automation systems:***

Systems that have the main focus on assuming the control from the driver for a shorter or longer time, but still with the driver supervising the driving.

### ***Full automation systems:***

Systems that do not need a driver but instead have all occupants in the vehicle performing other activities and not supervising the driving. This level of automation opens up for activities such as computer work, relaxing, different forms of entertainment, etc.

High automation, Full automation and to some extent Driver assistance Systems will have the possibility to offer clear advantages to reduce congestion and to improve safety, fuel economy and comfort.

Communication between vehicles, a.k.a. Vehicle-to-Vehicle communication (VtV) will be an important component for High automation and Full automation systems. VtV opens up for reducing the distance between the vehicles, and thus reducing congestion, since the vehicle behind will be aware of, e.g. braking actions, before when they occur. Braking can therefore occur simultaneously and with no added distance needed for reaction time.

VtV will also help to improve safety since the communication between vehicles will be essential in the decision making of the autonomous vehicle. VtV may also be used to link up vehicles in car trains (platooning) or in smaller units. Such road trains may potentially have a positive influence on improving fuel economy.

Another way of differentiating the levels of automation can be made focusing on the human participation. At the first level the human monitors constantly and is expected to immediately interact, which provides independency whether or not requests. At the second level a human is present and constantly monitoring the driving and when requested by the vehicle, after some time, the driver interacts and provides direction and input. In the third level, a human is present and provides input to the driving as and when desired and at the fourth level no human at all is present in the vehicle.

For the forth and third level, and partially also for the second level depending on the time allowed for the human to respond and provide input, the vehicle systems need to have redundancies so as to rectify and cover up for any malfunctions, misinterpretations or any mistakes made by the systems. This may also be performed in a way as to get the vehicle safely off the road (in a limp-home manner). Any deployment of such systems would require careful evaluations of Failure Mode Efficiency Analyses (FMEAs) before being deployed on public roads.

There are also other ways to differentiate autonomous systems. One way is between the level of automation, speed and length of time the autonomous system is active. The National Institute for Standards and Technology (NIST) describes 'contextual autonomy' according to three dimensions: the complexity of the mission assigned to the system, the complexity of the environment in which that system performs its mission, and the degree to which that performance is performed without human involvement.

In the discussions linked to the discussions on the upgrade of the Vienna Convention, The German auto makers' organization VDA (Verband der Automobilindustrie) has proposed, in addition to the groups for levels of automation: driver only, assisted, partially automated, highly automated and fully automated, two subgroups: driver assistance systems and driver authorization systems. The proposed definitions are:

#### ***Driver assistance systems***

A driver assistance system is a system integrated into the vehicle. It supports the driver in his driving task by providing information and warnings, and – if designed to do so – actively intervening in the driving process. The driver must specifically activate and deactivate the system. The driver can override the driver assistance system at any time.

#### ***Driving authorization systems***

A driving authorization system is either a passive or an active system integrated into the vehicle which, using one or more stages of authentication, either once or repeatedly grants fully, restricts or prevents access to the vehicle or to a function. A driving authorization system is designed such that the driver cannot override it.

The definition of the subsystem 'Driver Authorization systems' could open for various types of autonomous systems assisting in moving the vehicle and its

occupants to a safe haven in the case of the driver being incapacitated, e.g. intoxicated, excessive drowsiness, sudden severe illness, etc., and where it is not desirable for the ride to continue in spite of the intentions of the driver.

## **SAFETY IMPLICATIONS OF AUTONOMOUS DRIVING**

Many governments worldwide have adopted long-term safety goals and targets, eventually ending up in zero fatalities and serious injuries. Among those is Sweden who, in 1997, adopted its Vision Zero, which aimed at future goal of zero with respect to casualties in traffic. Governments have set up action plans for making the traffic system robust and forgiving, such as reducing the number of intersection and replacing them with roundabouts, separation of vehicles and vulnerable road users, preventing head-on collisions, etc.

Many manufacturers have also adopted targets and plans for reaching zero injuries and fatalities. Volvo Car Corporation has adopted a target of zero serious injuries and fatalities in a new Volvo vehicle by the year 2020. All of these are, of course, very ambitious and far-reaching goals. The big question then arises; can this be done only by relying of the Haddon Matrix approach, i.e. that traffic safety is depending on the interaction between drivers, the infrastructure and the vehicles?

It is an established fact that in about 90-95 % of all incidents and crashes human error is partly or fully responsible. Eliminating human error therefore offers the largest potential in reaching the target of zero casualties. The development of preventative or active safety, forming the basis for autonomous driven vehicles, has already proven the safety potential for supporting this important target. Since the launch of the first advanced active safety system (the Electronic Stability Control system) in the late 1990s, a whole set of systems, aiming at avoiding or mitigating crashes in a number of scenarios have been developed and launched. These systems reflect different levels of autonomy and are completely or partially taking over the responsibility of correcting a critical situation from the driver. The systems all depend on various sensor technologies for establishing the conditions around the vehicle in making the right decision. Examples of used technologies are laser systems, radar, cameras and positioning technologies separate or in combination.

Among the examples of proven benefits for active technologies is the effect on claim rates for the Volvo

City Safety system, installed on the Volvo XC60 since 2010 and on all Volvo models since 2012, a system that brakes automatically for rear impact at low speeds when the driver is not paying attention. The Insurance Institute for Highway Safety (IIHS) in the US evaluated the City Safety system in a study using data from about 80% of the insured vehicles in the US. The study showed a reduction of claims for the Volvo XC60, compared to other luxury SUVs by 22%. The reduction in bodily claims is about 51%. [1]

For other types of assistance systems similar effects on the reduction of the number of crashes or casualties have been proven or estimated. For instance, the reduction of the number of fatalities with a system detecting and braking autonomously for pedestrians has in a study [2] been estimated to 24% as compared to cars without the system.

During the last decade the issue of distracted driver, especially in connection to the use of devices brought into the vehicle, such as hand-held or hands-free cell phones, has been high up on the list of priorities for actions for reducing the number of traffic casualties. In the US, some studies indicate that the number of traffic fatalities related to drivers being distracted may be as high as 5,000 of a total of 33,000, i.e. about 15%. Measures discussed are including permanently shielding off the vehicle for incoming calls, not using cell phones, hand-held or hands-free, while driving and reducing the ability for manual-visual interaction with a nomadic device brought into the vehicle.

We know that being connected is very much part of the everyday life for modern people. Many of the young generation, the digital natives, may view the driving time, not being connected, as a distraction from the desire of being connected. Shielding off the time spent in the car from connections with the outside world would not appear to be a viable strategy. Having the car supporting the driver during heavy workloads and adapting the assistance to the driver accordingly would be a strategy in-line with a more realistic approach.

Some of the systems available today already point at possibilities to discover distraction or lower attention levels among drivers. E.g. in studies made of the Euro FOT data [3] about 56% of the drivers were distracted shortly before the warning from the alertness system, in about 20% of the cases the drivers were both tired and distracted and in about 20% the drivers were only tired. The development of systems detecting distraction and balancing the driver workload is anticipated to be part of the future for vehicle safety.

These systems can be a stepping-stone for a continuation into partially autonomous systems, systems that can temporarily assume the driving responsibility from the driver during a situation when the attention level of the driver is not considered to be sufficient. Building on these examples it is believed that the evolution of more efficient assistance and autonomously activated system have the potential of, in practice, eliminating traffic casualties.

Up to this point in time, assistance and autonomously activated systems have acted basically with only limited support from the infrastructure. Lane departure warning systems, lane keeping aid systems and some driver alertness systems use the lane markings for establishing movements within the lanes and correcting and warning when the car is deviating from the right path or that driver is showing signs of drowsiness. A number of projects are, however, under way to align the interface between the infrastructure and the vehicle assistance systems. Road signs, lane markings, vehicle-to-infrastructure communication systems (VtI), locations of obstacles, traffic lights and wild life fences, locations and shape of pedestrian and bicycle crossings, all play an important role in making it possible for the in-vehicle systems to make the right accessions and decisions.

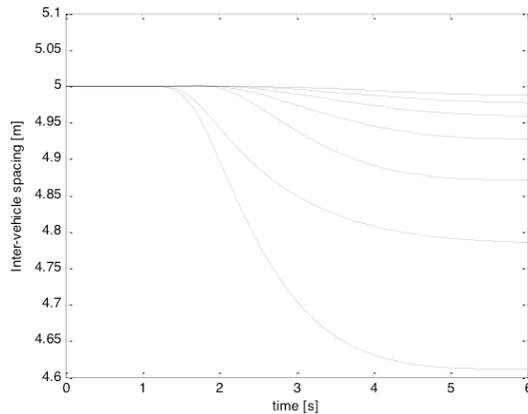
For some manufacturers and governments, there is a belief that Vehicle-to-Vehicle communication systems (VtV) will play a major part in reducing the number of crashes with the next couple of decades. However, the penetration of these systems is a major factor and issue. Unless the penetration becomes very high rather quickly, there is an obvious risk that real life benefits will take time to show effect.

#### ***Cooperative technologies***

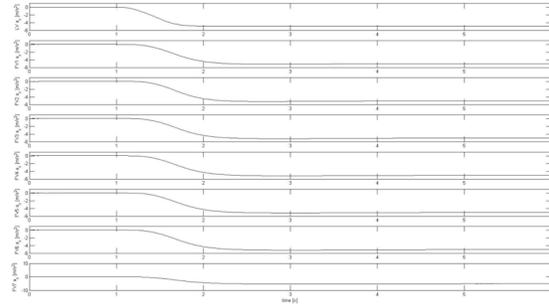
It is foreseeable that the technologies for communication between vehicles and infrastructure, Vehicle-to-Vehicle (VtV), Vehicle to Infrastructure, (VtI) and other applications called VtX, will have a large impact on the development and implementation of autonomous vehicles. These technologies will not only allow for distributed sensing, where information from different vehicles sensing platforms will be used in the own vehicle, but will also allow for cooperative decision making and control, where vehicles will act depending on other neighboring vehicles in order to reach a common goal. One such example is that of vehicle platoons, where cooperative control is necessary in order to keep short following distances.

A road train with cars equipped with automatic braking systems that communicates with other vehicles will always brake faster and more efficiently than a line of cars guided by normal drivers. This can be illustrated by the following example. If a road train with 8 vehicles is driving in 90 km/h with a gap of 5 meters the distance between the cars will be more or less the same after an emergency braking, as shown in Figure 1 and 2. This can be compared to the case of 8 vehicles in ordinary highway driving in 90 km/h, as shown in figure 3. Here the human driver is assumed using a time gap of 2 seconds, i.e. a 50 m following distance. All drivers respond quickly (reaction time less than 1 sec), however the last vehicle will stop 25 meters behind the vehicle in front. If someone in the line will have a less quick reaction time the cars will likely crash into each other.

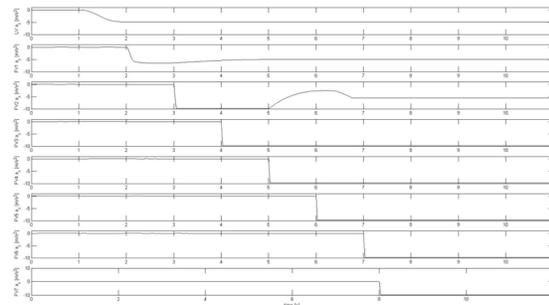
The controller shown in Figure 3 is tuned to resemble a responsive driver with a fast reaction. In the considered example the controller will lock the wheels to 1g, in the last vehicles in order to regulate to its desired gap, however this might not be possible if e.g. the road friction conditions are not optimal, resulting in the last vehicles crashing into each other.



**Figure 1.** Inter-vehicle spacing during automatic braking in a platoon. The inter-vehicle spacing is changing insignificantly during the braking. This is due to actuator delays. It is interesting to note that the intervehicle spacing error is decreasing downstream the platoon, i.e. the spacing error is greater between the lead vehicle and the first follow vehicle than between the last and next last follow vehicle. This property of comes from the controller algorithm and it is referred to as string stability.



**Figure 2.** A vehicle platoon with one lead vehicle LV, and 7 following vehicles FV is braking. The LV is initiating a manual braking, the FVs are braking almost instantaneously, resulting in similar deceleration amplitudes and profiles with almost no loss of inter-vehicle spacing.



**Figure 3.** Typical, human driver-like behaviour during braking on highway from an initial following distance corresponding to 2 s time gap. The first vehicle brakes with 5m/s<sup>2</sup>, the following vehicles brakes each after a reaction time of 1s. The controller simulating the human driver will lock the brakes in most vehicles avoiding an accident in case of a good road friction conditions, i.e. 1 g considered in the example above.

### Systems handling temporarily incapable drivers

In a not too long distant future it can be expected that there will be systems developed that can very accurately assess the state of the driver, whether being drowsy, intoxicated, subject to sudden illness or in some other way unfit to carry out the responsibilities of driving. For the automation systems where the driver is still in the loop, or for systems where the driver is able to switch off the autonomous driving mode, it will not be desired to allow the driver to keep on driving or assume control of the vehicle. Systems that can safely guide the vehicle off the road into a safe haven at the roadside will be a desired for avoiding misjudgements by incapable drivers. The development of such systems may, however, be impeded by legal restrictions requiring that the driver should always be able to make an override of

the autonomous system under all circumstances. In the discussions on the amendments to the Vienna Convention strong voices are raised that clarifications should be made that the driver should always be able to switch off the autonomous systems at all times. There are, however, amendments being proposed that overrides should not be possible when this endangers safety.

## LEGAL IMPLICATIONS

The existing legal framework for regulating the requirements on motor vehicles, on the driver and on the infrastructure offers many challenges on the way towards autonomous driving. When this framework and most of the base work for the regulations were created, autonomous driving was unheard of or something displayed in films and cartoons as visions for the future. Given the rapid technological development and the opportunities for developing and implementing technologies of various levels of autonomy, the legal framework needs to be restructured and revised in order not to be a hindering obstacle towards reaching the objectives envisioned by autonomous driving. In the analysis of the legal framework on different continents, obvious differences appear in the attitude of the lawmakers.

As a general statement, the US lawmakers, either on federal or state level, tend to be looking for removing obstacles for performing testing and field operations eventually leading up to the possibility of a broad roll-out of autonomous driving, whereas the European lawmakers struggle with the definitions and concepts of the level of autonomy that are to be allowed in the future.

The legal framework with implications for autonomous driving can be divided into four major parts:

1. The Vienna Convention
2. The Geneva Convention
3. US State Laws
4. National Rules and Regulations.
5. Product Safety
6. Product Liability

When analyzing the laws and regulations that have a bearing on autonomous driving a difference in approach is soon apparent. In some countries it is considered that everything is prohibited unless permitted by law. In most countries, however, everything is legal unless prohibited. This becomes an important fact when

analyzing the US state laws and the national rules and regulations.

### *1. The Vienna Convention*

The Vienna Convention or Convention on Road Traffic (8 November, 1968) was adopted by United Nations Economic Commission for Europe, UN-ECE under its Working Party on Road Safety (WP1). This working party focuses on preventing crashes by adopting international uniform traffic rules. These rules are focusing rules for the general behavior in traffic specifying the requirements on, among other things, sign and signals, traffic education, speed and distance between vehicles, instruction by officials and the drivers physical and mental condition and ability, skill and alertness.

In Article 8, Drivers, it is specified that:

1. Every moving vehicle or combination of vehicles shall have a driver.
2. It is recommended that domestic legislation should provide that pack, draught or saddle animals, and, except in such special areas as may be marked at the entry, cattle, singly or in herds, or flocks, shall have a driver.
3. Every driver shall possess the necessary physical and mental ability and be in a fit physical and mental condition to drive.
4. Every driver of a power-driven vehicle shall possess the knowledge and skill necessary for driving the vehicle; however, this requirement shall not be a bar to driving practice by learner/ drivers in conformity with domestic legislation.
5. Every driver shall at all times be able to control his vehicle or to guide his animals.

The last paragraph: 'every driver shall at all times be able to control his vehicle or his animals' is, at the moment, the subject for intense discussion within the regulatory community. How should the line 'be at all times being able to control his vehicle' be interpreted? In view of the fact that this convention is adopted by WP1 and its authority to regulate general rules for traffic and that it does not have the authority to specify requirements on vehicle performance, the most common view is that this paragraph only concerns the state of the driver and does not restrict how the control of the car can be handed over to the vehicle systems.

There is, however, an interpretation that this paragraph specifically restricts the possibility to hand over the

control of the vehicle from the driver to the in-vehicle systems. The consequence of the latter interpretation is that the Vienna Convention must be amended to accommodate for the already introduced driver assistance systems that do temporarily assume the control from the driver. This interpretation in practice also illegalizes Partial and Fully Autonomous Systems until an amendment has been made to this article.

The discussions on the interpretation of this article are being, at the moment, very intense in Geneva. Some governments, such as the Swedish and Belgian governments are supporting the first view, i.e. that Article 8 only makes specifications for the state of the driver, whereas the German government supports the latter view, i.e. that the driver must always be in control and that Highly Automated or Fully Automated system are violating this paragraph in the Vienna Convention.

Since no homologation is linked to this convention, it is up to each country that has ratified the Vienna convention to interpret the wording in Article 8 in relation to automated systems and their legality. This means that we can end up in a situation where the Highly or Fully Automated systems are legal in some countries but not in some others.

In line with the interpretation made by some countries, i.e. that the Vienna Convention does not allow for handing over the control to the vehicle and the fact that driver assistance systems already do this, the discussions in Geneva are now focusing on how to amend Article 8. The countries that see no conflict believe that the Vienna Convention does not need to be amended.

Proposals are now being put forward suggesting sub paragraphs for allowing a temporary hand-over to the vehicle. These sub paragraphs are specifically including requirements that the driver should always be able to over-ride the system. Similar requirements would efficiently prevent the introduction of future systems sensing that the driver is unfit to perform his or her task as a driver and direct the vehicle in a safe manner off the road into a sheltered spot near the roadway. This could then be the case for a very tired driver or an intoxicated driver where such pullover or limp-home function may be in contradiction to the intentions of the driver but clearly in line with traffic safety.

With all the proposals and amendments to the Vienna Convention that are being discussed there is a risk of imposing major restrictions for the future technological developments needed for reaching the levels of High Automation and Full Automation and consequently not achieving all the benefits from automated driving.

Restrictions for the development based on assessments and hesitations made when evaluating the progress of the present level of technology and all existing uncertainties can easily end up in the similar historical mistakes made in relation to other areas of technical progress, e.g. airplanes and computers. Regulators are therefore strongly urged not to, at this time, set limits for the development towards autonomous driving but rather regulate individual systems and set performance standards as needed as the technologies continue to be developed.



**Figure 4.** Countries that have ratified the Vienna Convention (dark green) and that have signed the Vienna Convention (light green) for Road Safety. [4]

Within the regulating community there exists a certain resistance towards the concept of not having the driver always in control of the vehicle. This resistance is not, however, compatible with the ambitions and targets of reaching zero fatalities and serious injuries. As explained in the safety chapter of this paper, for the vast majority of crashes, human error plays a role. This fact can never be eliminated purely by other measures such as driver education and infrastructure improvements. Having the technologies taking over the controls from the driver and guiding the vehicle will be necessary for reaching the low casualty levels.

## 2. The Geneva Convention

The Convention on Road Traffic signed at Geneva in 1949, a.k.a. ‘The Geneva Convention was established with the intention of establishing uniform rules for international traffic. 95. Visiting motorists would then be familiar with the basic rules for travelling in a foreign country.

Article 8 reads:

1. Every vehicle or combination of vehicles proceeding as a unit shall have a driver.
2. Draught, pack or saddle animals shall have a driver, and cattle shall be accompanied, except in special areas which shall be marked at the points of entry.

3. Convoys of vehicles and animals shall have the number of drivers prescribed by domestic regulations.
4. Convoys shall, if necessary, be divided into sections of moderate length, and be sufficiently spaced out for the convenience of traffic. This provision does not apply to regions where migration of nomads occurs.
5. Drivers shall at all times be able to control their vehicles or guide their animals. When approaching other road users, they shall take such precautions as may be required for the safety of the latter.

The commonly accepted interpretation of this based on the history behind the Geneva Convention is that this concerns unsupervised animals but not unsupervised cars. The conclusion will then be that the Geneva Convention does not restrict the use of automated vehicles.

### **3. US State laws**

Under the common law approach, as applied by the states in the US, anything is allowed unless prohibited by law. Since no specific state laws restrict the licensing of autonomous vehicles no principle barriers exist that would prevent automakers from receiving such licenses. However, in order to facilitate testing on public roads, state law- and rule makers have been very busy preparing and adopting laws and regulations specifying rules for licensing automated vehicles.

Among the states that have passed laws, as of February 2013, are Nevada, California and Florida. Bills for licensing of automated vehicles have been introduced in, among others, Arizona, Hawaii, Michigan, Washington state and Washington DC. Only Nevada has so far, however, adopted regulations specifying necessary verifications for receiving a license.

Automakers fear that this state activity, although commendable in its ambition, may lead to a patchwork of laws of regulations that may complicate the introduction of autonomous vehicles on a 50 state level in the US. It is therefore recommended that the National Highway Traffic Administration, the federal agency regulating the performance and equipment on a motor vehicle, gets involved in creating a national proposed standard to be adopted by the individual states.

### **4. National Rules and Regulations**

Many countries, states and provinces worldwide have restrictions in place regulating the general behavior of the driver in relation the road traffic circumstances. In addition to a general cautious and prudent behavior,

there are specifications on the minimum distances to the vehicle in front. This is specified in some states to be between 100 and 300 feet. These requirements will be significant in relation to some applications of autonomous driving, such as road trains or when cars link up with VtV communications systems where the distance between the vehicles may be and need to be shorter than the distance considered necessary for a safe normal driving.

### **5. Product Safety**

An automated vehicle, in full compliance with all applicable legal requirements and in compliance with the Vienna and Geneva Conventions, could, if it is considered that it, or its subsystems, presents an unreasonable risk of death or injury, be classified as 'defective'. The manufacturer of this vehicle would then be obligated to inform its customers and send out a notice of a recall. All recalls are very costly and could tarnish a manufacturer's reputation and brand image in addition to making its customers dissatisfied and lower their loyalty to the brand. A widely published recall of an autonomous vehicle could be devastating for the subsequent launches of similar vehicles.

The technological and behavioral challenges with autonomous driving entering, in many ways, uncharted territory will impose additional considerations in design and marketing. Any mistakes leading to crashes and subsequent recalls and bad publicity could seriously impede the progress of autonomous vehicles for years.

### **6. Liability**

There are a number of challenges dealing with product liability in relation to autonomous driven vehicles. How will it be possible for manufacturers to design for any foreseeable misuse? How to distinguish between foreseeable misuse and system abuse? Requirements on instructions, redundancies and the design of the Human Machine Interfaces will be excessive and demanding. Will it be enough to prove that the system is sufficiently safer than for the driver-guided situation?

It is clear that manufacturers will have to put more efforts into deeper Failure Mode Efficiency Analyses (FMEAs) and other additional analyses of the systems. In some countries in Europe, and also in some countries globally, the national liability legislations specify that the liability must rest with an individual and not with a manufacturer or a supplier. This fact does make the liability issue for autonomous driving very complex and it, in practice, prevents High and Full Autonomous driven vehicles being applied for public road use in those countries. For other countries, without the specific need to assign the liability to an individual, this can

instead be distributed according the individual proportions of responsibilities between the driver, manufacturer, suppliers and other entities liable.

As long as the driver is required to monitor the situation, e.g. for systems such Traffic Jam Assist where the system will be switched off if there is insufficient driver surveillance, liability will fully or partly rest with the driver. However, for systems not requiring a driver monitoring, the manufacturer will be liable for the time period when the driver is out of the loop (unless the accident is solely caused by a third party or an override by the driver). In conclusion, as today, liability will probably be decided on a case-by-case basis.

Some special liability issues may arise for the case of platooning. Where does the liability rest in an accident between a vehicle in the rear of the platoon and an outside vehicle? If the crash is caused by the platoon but it was not possible to foresee this by the platoon leader since the end of the platoon is not visible from the front. If then the vehicle in the tail is in a highly automated mode just following the leader assigning liability will be complicated.

## TECHNICAL ISSUES

A number of technical challenges remain before systems with higher levels of automation can be launched on public roads. Many issues remain that require more research and development of more advanced systems.

Among the challenges are how to properly assess to vehicle surroundings, the algorithms for the decision-making, how to consider actions from other road users, etc. Public acceptance levels for errors in decisions or for unmotivated activations, so called false positives, will be very low.

There is a common belief among manufacturers, governments, safety and policymakers that truly full automation will never be achieved. However, the only conclusion one may make from history is that technology very often exceeds the common conception of what is considered possible.

One area for concern linked to autonomous systems and also for driver assistance systems in general is what is commonly called Cyber security, i.e. the risk that external hostile sources penetrate the shield manufacturers are developing for advanced systems of autonomy. The integrity and protection of the systems

have to be safely secured before any system launch. Customers will have a very low understanding of systems malfunctioning or acting improperly in traffic endangering the safety of occupants or other road users. One way of safeguarding against both Cyber security attacks and system misjudgments is to create redundancies, i.e. have multiple sources of information in support of the decision-making. Information from external sources, e.g. from infrastructure or from other vehicles, adding to the information created by the in-vehicle systems will be needed for a reliable and robust decision-making.

In order to restrict the challenges linked to a large variety of traffic situations, systems for autonomy may be certified only to be allowed on special road sections adapted for certain systems, e.g. on highways or for special applications such as parking. Such certification may require some regulatory framework for setting the requirements to be met on each section of road or for each application.

One issue that has been raised for systems of high automation or full automation is how to safeguard that the driver is back in charge when the system goes from automation to driver back in control of the vehicle. What would be the reliable ways to reactivate the driver, e.g. for a sleeping driver and how to check the alertness of the driver before handing controls over? This area is in need of extensive human behavior research in order to support the proper decision-making.

## ENVIRONMENTAL IMPLICATIONS OF AUTONOMOUS DRIVING

### *The transport sector's impact on health and the environment*

The global burden of disease study 2010 [5] reveals that as many as 3.1 million deaths globally were caused by unhealthy air quality from air pollutions in 2010. To give a perspective, in the same study the number of traffic related fatalities were around 1.3 million globally.

The transport sector is one of the main causes of pollutants. In addition to the emissions contributing to the exceeding of air quality standards, carbon dioxide (CO<sub>2</sub>) is one of the key pollutants related to global warming. The transport sector represented approximately 22% of the global CO<sub>2</sub> emissions in 2008, out of which road traffic caused 73% [6]. In the United States, this fraction was higher than the global average and the transport sector represented

approximately 31.1% of the total amount of CO<sub>2</sub> emissions in 2008 [7]. After electricity and heat generation, transportation takes the position as the second largest cause of CO<sub>2</sub> emissions [6].

Despite the accomplishments of reducing the environmental impact per vehicle, greenhouse gases (GHG) from transport as a fraction of the total amount of emitted GHG in the European Union, did in fact increase by 34% (including international aviation and maritime transport) from 1990 to 2008 [8]. This is a undesirable trend, but the percentages above must, however, be interpreted with consideration not only to the change of amount of GHG, but also with respect to the achieved reductions of emissions within the transportation sector in comparison to the achievements of reduction of emission of other polluting sectors. The GBD 2010 study [5] further presents findings of “years of lost life” (YLL) and “years lived with disability” (YLD), which together is abbreviated to “DALY” (i.e. DALY = YLL + YLD). The study shows that particles in outdoor-air represented 76 million DALY in 2010, i.e. particles in the air take the position as ninth highest risk factor for DALY in 2010 globally [9]. This risk factor linked to particles is even higher in some regions, in particular in South East Asia. Overall, urban areas are most vulnerable and the emissions from local traffic as the main cause. This is worrying as the percentage of the population living in urban areas is estimated to increase, e.g. in Europe from 74% of the population in 2011 to approximately 85% of the population living in urban areas by 2050 [8].

#### ***The process of reducing the transport sector’s emissions***

The transport sector’s high level of impact on health and the environment, an increasing population and growing needs of transportation, verifies the need of improvement. However, while discussing reduction of emissions during the vehicle operation cycle, rolling resistance, aerodynamic resistance, weight and the internal combustion engine are areas often mentioned. Although the progress of improving the vehicle design, internal combustion and the exhaust cleaning processes have been successful and will continue (it is estimated that a up to 30% CO<sub>2</sub> reduction for passenger cars can be achieved with present technology [8]), more rewarding and cost effective reductions are sought after. This is one of the main reasons why manufacturers and researchers are developing alternative energy propulsion systems for the vehicles of tomorrow.

Regardless if the vehicle fleets are driven by fossil fuels or by other energy sources, the benefits of improving

the actual driving cycle are expected to have a significant potential in lowering energy economy, i.e. reduce emissions. Although educating drivers in “eco-driving” will help to improve fuel economy and reduce emissions, autonomous driving is expected to have a significant influence while reaching for a more energy efficient driving cycles. In addition, autonomous accident preventing systems could help to reduce emissions by avoiding accident related congestion and improving traffic flow.

#### ***Autonomous system’s direct and indirect environmental impact***

In 2012 the European field operational test project, Euro FOT published its report [10] verifying that driver assistance systems significantly improve fuel economy. The project was conducted by a partnership of 28 companies and organizations in Europe between May 2008 and June 2012. It involved both trucks and passenger cars, focusing on investigating a number of driver assistance systems. In total (trucks and cars) around 1200 drivers drove the test vehicles on a daily basis, resulting in data for about 35 million kilometers of driving. Volvo Car Corporation, which was one of the participating car manufactures, collected data from 100 vehicles driven by 263 drivers for a total of 3 million km. Subsequently, the study provides a large amount data available to be evaluated of for example system performance, driver behavior and user acceptance in an ordinary real traffic environment.

Among the findings of the Euro FOT study is the potential of improving the fuel economy by using the Adaptive Cruise Control system (ACC). The ACC is designed to automatically adjust the distance to the vehicle in front, which is a stepping-stone on the way towards autonomously driven vehicles. Overall, the ACC was used on about 50% of the kilometers driven on motorways (tested over 780 000 km [11]) and the average fuel economy while driving with the system was reduced by 2.1% for cars [10]. ACC further reduced the average speed with 0.4% [10] and the targeted crashes (rear-end crashes) with 16-42% [11].

With the high driver acceptance of 50%, the targeted usage area and the benefits of the ACC, promising potential is provided from the statistic that about 63% of the car emissions in the European Union are related to non-urban roads and motorways (73% of the total kilometers of car travel) and that non-urban road travel represents 61% of the fatalities [8].

With the assumption that all passenger cars in EU-27 were equipped with ACC, the Euro FOT study

estimates that a total of about 693.9 million liters of fuel per year could be saved, resulting in a reduction of about 1.7 million tons of CO<sub>2</sub>. Considering the total amount of the approximately 3.8 billion tons of CO<sub>2</sub> emissions in the EU27 in 2011, the one system could then potentially decrease the impact in EU27 with 0.0447%. [21]

The indirect traffic effects from the safety enhancement of the bundle of Forward Collision Warning (FCW) and ACC, i.e. the safety aspects contribution to reduction of subsequent congestion, is stated to be capable to lower the incidental delay with about 3 million lost vehicle hours in EU-27 [10].

A study of 437 urban areas in the United States, conducted by using measurements from 2005, presented a total congestion delay of 4.2 billion hours and 10.97 billion liters (2.9 billion gallons) fuel wasted due to congestion in those urban areas in 2005 [13].

The project, Safe Road Trains for the Environment, "SARTRE", was completed in 2012 and showed findings of promising benefits of taking the human driver partially out of the driving-loop. The project aimed at investigating the potential from vehicle platooning with respect to enhanced safety, comfort and reduced environmental impact on normal public highways. Being funded by the European Commission under the Framework 7 program, the project was carried out by a partnership between Ricardo UK Ltd., Kraftfahrwesen Aachen (IKA), SP Technical Research Institute of Sweden, Volvo Car Corporation and Volvo Technology of Sweden.

By using Vehicle-to-Vehicle (VtV) communication the distance between the platooning vehicles was reduced significantly, producing beneficial aerodynamic conditions. On the same instance, the VtV communication implied a high safety enhancement as a professional driver leads the platoon and the following vehicles are interacting seamlessly with each other. In addition to the safety benefits (predicted to be as high as 50% on highways) and the consequence of reduced indirect traffic effects, the direct improvement in fuel economy was estimated to be around 10% [14].

***Autonomous systems potential to increase traffic efficiency and lower the environmental impact while expanding the infrastructure***

A study presented on the IEEE Vehicular Technology Conference in 2011 [15] suggested that autonomous systems could increase the highway capacity by 273%, if all cars had such technology. This is derived from the

fact that just a few percentage of the road space is taken up by the car due to the safety distance required by the human driver.

To drive safely at a highway speed of 90km/h, a driver must hold a distance of around 75 meters to vehicle in front. In the SARTRE project platoons were safely driven in 90 km/h with just 6 meters of gap between the vehicles. This obviously proves the high traffic density and thus the traffic efficiency autonomous vehicle technology is capable of achieving.

Moreover, it is expected that road transportation will continue to be an important part of transportation in EU through 2050 (about 2/3 of total passenger transport) [8]. Without any changes, the traffic is predicted to increase with 34% by 2030 (51% by 2050) in the European Union and the cost of congestion will increase with approximately 50% in the European Union by 2050 (reaching almost €200 billion annually) [8]. With an increasing number of vehicles on the roads, a reduction of emissions-per-vehicle is required just to keep the same total amount of emissions from transport of today. The challenge of lower the total amount of emissions requires a multiplicity of technology enhancements.

The environmental benefit of autonomous systems goes beyond the driving cycle. With a higher traffic density, the required road space is less, thus less road infrastructure investments is needed to cope with the growing population and higher transport needs.

Although the environmental aspects of building roads are complex, less building implies environmental benefits, if the traffic efficiency and safety aspects are maintained (or improved). McKinsey & Co. have estimated that approximately \$16.6 trillion worldwide (€1.5 trillion between 2010-2030 in the European Union [8]) is needed to be invested in roads through 2030 to match the demand for transportation with the global growth [16]. Road investments is the single largest investment of the total estimated \$57 trillions needed to be invested in infrastructure all over the world through 2030. To give some perspective, \$57 trillions are nearly 60% more than the infrastructural investments the last 18 years [16]. The approach of improving the vehicles to more effectively use the roads in a complementary manner to reduce the need of expanding the road infrastructure would also result in more representative economically circumstances. The cost of the necessary technology to achieve such efficiency would be paid by the road users (or owners of the vehicles) and as a result would the cost of the road infrastructure investments be

reduced, otherwise paid by all of the society.

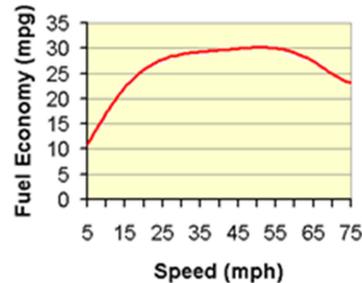
### ***Environmental effect of reduced number of traffic accidents***

Autonomous driving is expected to have an effect on reducing the environmental impact from traffic by avoiding or by a substantial reduction in the number of crashes, incidents and disturbances in traffic that already are being significantly reduced by e.g. automatic emergency braking systems. Autonomous driven vehicles will further enhance the efficiency.

In order to estimate the benefits the following calculation can be made. Assume that a moderate rear-end collision results in a 30 minute complete blockage of 1 out of 2 lanes on a highway during rush hour. Furthermore, assume that this will temporarily reduce the traffic flow to 1/6 of the capacity during 30 minutes, (blockage of one lane forces the traffic into one lane with a 1/3 which means that the total capacity is about 1/6 of the original capacity) which in turn will result in a traffic jam. Assume that, during rush hour, the average time gap between vehicles is 2 seconds. Then the 30 minute blockage will result in approximately  $30 \cdot 60 \cdot 2 \cdot \frac{1}{2} \cdot (1 - \frac{1}{6}) = 1500$  vehicles initially being involved in the traffic jam. Further assume that the average front-to-front distance between two vehicles is 7 meters in a low speed traffic jam. Then the traffic jam builds up to  $7 \cdot 1500 \cdot \frac{1}{2} = 5250$  meters during the 30-minute blockage. Since the accident occurred during rush hour, the traffic jam will remain for the entire duration of the rush hour, e.g. 2 hours (since flow in = flow out during rush hour). In 2 hours,  $120 \cdot 60 \cdot 2 \cdot \frac{1}{2} = 7200$  vehicles will endure the 5.25 km traffic jam before it is dissolved. Assume that the average fuel consumption for the vehicles increases with 1 L/10 km during the traffic jam. Each vehicle is thus consuming 0.525 L extra gasoline in the 5.25 km traffic jam, in comparison to driving with normal speed. In addition, all vehicles need to slow down and then accelerate again after the traffic jam. Assume that the average weight is 1500kg and the engine efficiency is 25%. The energy content of gasoline is 34.8MJ/L. The energy required to accelerate a 1500 kg vehicle from 0 to 72 km/h = 20 m/s is  $1500 \cdot 20^2 = 0.6$  MJ, which is equivalent to  $0.6 / (34.8 \cdot 0.25) = 0.07$  L of gasoline. In total, the 7200 vehicles involved in the 5.25km traffic jam will consume approximately  $(0.525 + 0.07) \cdot 7200 = 4300$  L of extra gasoline due to the rear-end collision in this example.

Furthermore, the traffic blockage in traffic is wasting excessive time for all occupants involved in this incident. Approximately 30 minutes per person is

wasted, giving a total of 5000 hours time lost. The traffic jam also increases the wear and tear on all vehicles, but this is harder to estimate. The same thing applies to stress-related health issues created by being stuck in a traffic jam.



**Figure 4.** Estimates for the effect of speed on MPG [55]

## **SOCIETAL IMPLICATIONS OF AUTONOMOUS DRIVING**

The path towards more advanced vehicle assisting systems and finally leading up to partially autonomous or fully autonomous driving will be challenging for all involved stakeholder including industry, governments, authorities, infrastructure developers, researchers, fleet owners and the general public. The deployment of the various level of autonomy will affect everything from urban and infrastructure planning and investments, legal adaption, technology developments, changing road user's conception of traffic and driver education.

### ***Investments in infrastructure***

Investments in infrastructure impose huge costs to society. In the US it is estimated that the cost per mile for an urban highway is about 8 to 12 million USD per mile. [17] Over the next ten years the investments in roadways in the US are estimated to be in the order of 1.5 trillion USD. [18]

The question then arises, will autonomous driving concepts need larger infrastructure investments or will the need for infrastructure investments be reduced with implementation of autonomously driven vehicles? What supports the need for major infrastructure investments is if special lanes are required for deploying autonomous driving, lanes that have to be built and linked to this are investments in property, planning, constructions, etc. There are, however, a number of ideas and concepts that can be used when deploying autonomous driving and that can help to reduce the need for investments rather than increasing them. Concepts such as directional devices built into the

infrastructure may be used to direct an autonomously driven vehicle and keep it more centered to the center of the lane, which in turn can open up the possibility to reduce the width of the lanes. Those concepts may also have a number other directional uses such as indicating a safe roadside emergency location.

By reducing the width of a lane it would potentially be possible to add more lanes on existing areas used for highways, which would significantly reduce investments and increase savings.

Autonomous driving in urban areas can also potentially open up improved possibilities for more optimized use of the city landscape by improving traffic flow, more dense parking, reduced lane widths, etc.

### ***Personal and societal benefits***

In the continuous development of various levels of assistance systems leading up to fully autonomous systems there are potentially a number of possibilities for societal benefits.

From an individual perspective the main benefit from autonomous driving would be to recapture the true freedom behind the wheel, the freedom that cars defined a century ago. At that time freedom was defined by the possibility to go wherever you wanted with your own car. Today true freedom is defined in further dimensions, such as being able to travel and spending time as desired. A vehicle with autonomous driving capabilities could potentially offer the freedom to use time as desired when on the road, on top of traditional freedom.

In the modern society time has become one of the most critical factors of wellbeing. An autonomous driving vehicle could open up possibilities for other activities such as leisure, work and social interaction. Improved health status due to more time available for personal use is also a factor that may be added to the benefits as stated above.

Wasted time in traffic can be linked to a financial loss, this both from individual point of view and from a societal point of view. Being able to use time more efficiently when commuting to and from work can add valuable time to read mails, book meetings, prepare speaker notes and presentations etc. This will free-up time at work for more useful meetings and discussions where personal presence is necessary. The time in the car can also more efficiently be used for private matters, such as reserving time with a dentist, arrange theater tickets etc. which can be handled behind the wheel

more efficiently, freeing up time away from work for social engagements.

Automated driving may have an equal opportunity factor by offering mobility to users that would normally not be able to drive. Blind, physically challenged or persons without driving licenses could potentially own and ride a car with autonomous driving features.

Clear benefits like time, and reduced fuel consumption, are required for a sustainable business case. The direct value of having vehicles with autonomous driving capabilities can be estimated based on time saved and reduced fuel consumption. The value for the driver is higher when adding comfort of travel and gained freedom.

Autonomous driving also could open up for benefits such as the possibility of using commuter lanes, bus lanes, reduced city tolls, access to certain restricted areas, using specially assigned parking areas, etc.

The event of a crash free society could open up for new opportunities for vehicle interiors and removing some restrictions for the occupants positioning in the interior compartment. If there is no crash risk occupants will not need to be belted and may have the possibility to move around freely inside the vehicle which would even further improve riding comfort.

If crashes and incidents can be avoided or reduced, the costs for insurance is likely to come down which if impact the total cost of owning a motor vehicle. Autonomous Driving systems will make it possible to utilize the available road space more efficiently. By coordinating traffic flow, i.e. speed and distance between vehicles, congestions can be reduced and the traffic flow through cities increased. With improved control of distance between vehicles the static distance can be reduced in slow moving traffic, but also reduced dynamic distance between vehicles in stop-start traffic scenarios. Traffic flow speed in congestion is often reduced by delays in stop start traffic, but also narrow sections and access points. If the speed can be increased by automated control in these sections an increased overall traffic flow can be reached. Reduced distances between cars and increased traffic flow speed require increased knowledge of the environment around the vehicle.

There are studies in the US indicating an efficiency increase for traffic with autonomous vehicles with up to 273% [17]. Although this figure appears to be on the

overestimated side it is clear that autonomously driven vehicles will help to improve traffic flow.

### ***Cost Savings from Avoiding Crashes***

It is evident that the societal savings from altogether avoiding crashes, as potentially being able to be delivered by the combination of autonomous driven vehicles and efficient driver assistant and automatic braking and steering systems, will be huge. The different studies of annual savings for road casualties fatality circle around a level in Europe of around 1.6 million EUR per avoided fatality, 70,000 EUR per avoided injury and efficiency benefits of avoided casualties (add on to road safety): 15,500 EUR per avoided fatality accident, 5,000 EUR per avoided injury accident [3]. In the US, in a study published 2011, the total cost for car crashes is estimated to be around 300 million USD with a cost per fatality of 6 million USD and 126,000 USD per injury [19]. In the same study the cost for road crashes per person in the US is estimated to be 1050 USD per year.

From the studies being released during the last couple of years, assistance systems have proven to yield a number of clear safety enhancements and reduction of both casualties and reduction of societal costs. In one of the studies [20] the British motor vehicle research institute Thatcham has estimated the saved repair costs if all vehicles in the UK were equipped with an automatic emergency braking system similar to the Volvo City Safety system to around 1.3 billion Euros annually. The saved societal costs for avoiding around 150,000 whiplash injuries per year would be nearly 2 billion Euros.

### ***Benefits and Business Opportunities from Road Trains***

As described earlier autonomous driving can be defined and is expected to be offered on different levels. These levels may offer different levels of business opportunities. For the level of high automation, one application possible is platooning, also known as road trains or platooning. The EU project called SARTRE, SAfe Road TRains for the Environment was finished in 2012 [14]. The target for this project was to investigate the technical, legal, environmental challenges and the business opportunities with road trains.

Results from the project indicated a fuel economy improvement of 14% for the following vehicles and 5% for the lead vehicle. Assuming add-on costs for necessary in-vehicle equipment at about 2,000 Euros, a small amount of administrative costs and a commuting distance of around 80 km per day, the break-even cost

per car in the train would be about 55 Euros per month or 3.5 Euros per 100 km. If the lead vehicle is a truck, being in the road train will immediately be paying off. If the lead vehicle is a passenger car, the level where the road train will be adding income to the car owner would be 4-8 cars in the road train depending on the business model of monthly subscriptions or charge rates per distance.

It is clear that in the initial phase, however, there will be too few trains on the road to make the leading car business be sustainable alone but instead only as a secondary business (taxi, delivery services, etc.). There are also a number of inherent issues with road trains that need to be resolved before a broad rollout on public roads. Among those are e.g. the use of commuter lanes and necessary infrastructure investments, liability issues for conflicts between external cars and cars in the road train, liability of the driver in the lead truck or car, etc.

## **DISCUSSION**

Systems with high levels of automation clearly have the possibility to offer many benefits both to individuals, the general public, and the transportation sector and to the society. At the same time it may profoundly alter the conception of driving and riding in an automobile, something that will be a major shift from a focus on the transportation as such to the usage of the time in the car. The question can then be asked, will the society be ready and will it adapt to the new possibilities? Will the expected business opportunities arise and in a timely manner? Will public skepticism overrule the possibilities opened up by automated systems?

The development of assistance systems and systems paving the way towards higher levels of automation is very rapid. Will this development be in tune with other developments such as infrastructure developments? Will the need for infrastructure investments to accommodate for autonomous systems be significantly higher than anticipated?

Given the obvious benefits from automated driving, can we expect governments and infrastructure authorities to step up to the challenge of supporting the development and progress of launching these systems on public roads? On key factor that may influence the development is the risk of failures on the way to highly automated systems that can seriously affect the trust and willingness by authorities and the general public to adopt the idea of the driver not being in control of the

vehicle. Cases of malfunctions and failures causing public distrust are well known in the automotive history. It is therefore paramount that manufacturers, suppliers and rulemaking bodies use caution and carefully examine each step on the way towards high or full automation.

## CONCLUSIONS

The event of automated driving offers a number of possible benefits both on an individual level as well as to the society, such as improved safety and fuel economy, reduced exhaust emissions, improved traffic flow and reduced problems with congestions, mobility for the physically challenged, etc. There are, however, many obstacles and challenges left before the systems for high or full automation can be launched on a wider scale. Additional research, further technological development, adaptations to the infrastructure and to interaction with other road users, sorting out the legal matters, establishing business cases are a few of the critical issues that need to be addressed. Given the potentials and clear advantages it is likely that the development towards high or full automation will continue and in an ever more rapid pace attaining levels and producing new concepts in a not too distant future.

## REFERENCES

- [1] Insurance Institute for Highway safety (IIHS), 2011. 'Status report: Avoid Crashes', July 2011.
- [2] Lindman et. al., (2010), 'Benefit Estimation Model for Pedestrian Auto Brake Functionality', ESAR 2010
- [3] Malta, L., Ljung Aust, M., Faber, F., Metz, B., Saint Pierre, G., Benmimoun, M., Schäfer, R., (2012): 'Final results: Impacts on traffic safety, EuroFOT 2012'.
- [4] Definition of necessary vehicle and infrastructure systems for Automated Driving, EU Study report, 2010.
- [5] GBD 2010, the Institute for Health Metrics and Evaluation, 2010.
- [6] International Energy Agency (2010), 'CO<sub>2</sub> Emissions from Fuel Combustion 2010', OECD/IEA, Paris.
- [7] U.S Energy Information Administration (2009), 'Emissions of Greenhouse Gases Report 2008'.

[8] European commission (2011), 'Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system', White Paper 2011.

[9] The Lancet: 'The Global Burden of Disease Study 2010', Volume 380, Issue 9859, Pages 2253 - 2260, 15 December 2012

[10] Faber, F., Jonkers, E., Van Noort, M., Benmimoun, M., Pütz, A., Metz, B., Saint Pierre, G., Gustafson, D., Malta, L., (2012): 'Final results: impacts on traffic efficiency and environment, EuroFOT 2012'.

[11] Malta, L., Ljung, M., Faber, F., Metz, B., Saint Pierre, G., Benmimoun, M., Schäfer, R. (2012): 'Final results: impacts on traffic safety'.

[13] Schrank, D., Lomax, T. (2007): 'The 2007 urban mobility report', Texas Transportation Institute.

[14] Brännström, M., (2013): 'Commercial Viability', SARTRE, Volvo Car Corporation.

[15] Tientrakool, P. (2011): 'Highway Capacity Benefits from Using Vehicle-to-Vehicle Communication and Sensors for Collision Avoidance', Vehicular Technology Conference (VTC Fall), IEEE, 5-8 Sept., 2011

[16] McKinsey & Co., Focus: 'Rethinking Infrastructure', [Online]. Available at: <<http://www.mckinsey.com/features/infrastructure>>> [Accessed 28 February 2013]

[17] Self-Driving Cars: The next revolution, KPMG, 2012

[18] Smith, B., 2013. Focus: 'Planning for autonomous driving'. *The Center for Internet and Society*, [Online] 28 May 2012. Available at: <<http://cyberlaw.stanford.edu/blog/2012/05/planning-autonomous-driving>> [Accessed 3 March 2013].

[19] AAA, 'Crashes vs. Congestion. What's the cost to society?', 2011

[20] Avery, M., et. al. (2009), 'Autonomous Braking Systems and Their Potential Effect on Whiplash Injury Reduction', ESV 2009. Paper Number 09-0328

[21] Jos G.J. Olivier, Greet Janssens-Maenhout, Jeroen A.H.W. Peters (2012), 'Trends in global CO<sub>2</sub> emissions 2012 report', Netherlands environmental assessment agency (2012).

# Development of Reliable V2V system based on WAVE

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## ABSTRACT

This paper proposes a dynamic congestion control algorithm for a reliable message transmission in V2V communication environment based on IEEE 802.11p WAVE technology. Each vehicle periodically exchanges its status information like a position, speed and break control with other vehicles within a communication range. Without any control, each vehicle always uses the maximum transmitting power and data rate. From our experiments, at heavy traffic flow, the higher transmitting power and the higher data rate makes the wireless channel contentions and packet collisions more serious. In this paper, we propose the mean-based dynamic data rate control algorithm and the phase control using epoch to mitigate the congestion. The performance evaluations in Qualnet confirm that the proposed algorithm achieves better communication performance than the existing solutions and is more robust to the hidden terminal problems.

## INTRODUCTION

The WAVE (Wireless Access in Vehicle Environment), also known as the IEEE 802.11p is the technology to support Intelligent Transportation Systems (ITS) regarding Vehicle to Infrastructure, and Vehicle to Vehicle communication.

The U.S. Department of Transportation (US DOT) funded government projects to develop the V2X system using the WAVE are underway in North America and the 2013 NHTSA regulatory decision will be made based on the result of those projects. To support the regulatory, each OEM is required to develop the core technologies like a congestion control, relative positioning, V2V security for the system production. Among these core technologies, the congestion control is very important to guarantee the reliable V2X communication performance and that is not defined as technical standard yet. For cooperative vehicular safety applications, each Vehicle must periodically broadcast its current status to its neighboring vehicles. The current status includes speed, longitude, latitude, heading, car type

and so on. Each vehicle can monitor its neighboring vehicles' status to help the driver to avoid the traffic accidents possibility like a forward collision, rear-end collision, intersection collision, etc.

Because the existing WAVE technical specification does not consider the congestion control, each vehicle always use the maximum transmitting power and the fixed data rate and message sending period. From our experiments, at heavy traffic flow, the higher transmitting power and the smaller data rate and the frequent data transmission can cause the safety packet collisions. It causes a serious problem for the V2V system to operate successfully. In this paper, we identify these problems and we propose the dynamic data rate control algorithm and phase control algorithm using the epoch to solve the congestion condition. We confirm the performance of our algorithm using the Qualnet simulator.

## RELATED WORKS

The congestion algorithm in V2X communication environment to exchange the vehicle to vehicle safety message has been studied in the several papers.

[2] proposes a distributed and localized algorithm, distributed fair power adjustment, for adaptive transmit power level which is formally proven to achieve max-min fair allocation, based on the location of the other vehicles within the sender's range. [5] proposes a method to increase channel coverage and reduce latency for safety messages in multi-channel vehicular environments. It includes the congestion control protocol for vehicular communication networks that use CSMA/CA channel access mechanism. [6] uses the GPS error measured by host vehicle and relative vehicle and controls the transmission rate control and power control independently. The power control depends on the channel state estimated periodically. Because each vehicle determines the control value independently, anomaly can occur.

In [7], each vehicle determines the congestion state by measuring CBP and the vehicle controls the message rate according to the CBP value.

## THE PROPOSED ALGORITHM

In order to design and analyze the congestion control algorithm, we define the two performance metrics : Channel Busy Percentage (CBP), PDR (Packet Delivery Rate). CBP is the percentage of the time during which the wireless channel is busy to the period of time over which CBP is being measured. The busy is determined by that energy level is higher than the carrier sensing threshold. The PDR is percentage of the number of received packets at a receiver from particular transmitter and total number of packets sent by that transmitter.

Figure 1 shows the CBP comparison result estimated during the simulation. The simulation is performed under vehicle number 150, 600 (one lane), 600 (2 lanes), 900 (3 lanes), 1200 (4 lanes). The more vehicles cause the higher CBP and this results an decrease of the PDR value. So, we need to maintain the certain level of CBP to gurantee the V2V communication performance regardless of the number of vehicle within the communication coverage.

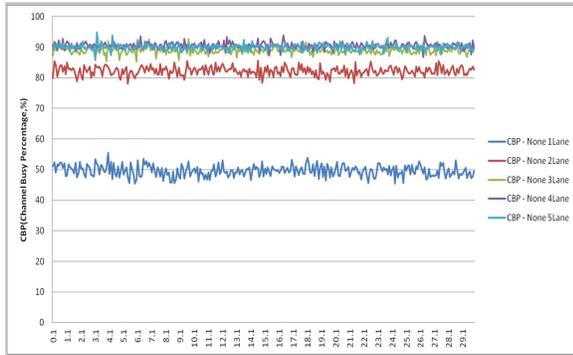


Figure1. CBP comparison under vehicle number

The figure 2 shows the total procedure of the proposed algorithm. The proposed algorithm is composed of two main procedure. The first one is Mean-based data rate adaptation. The second one is Phase control algorithm using Epoch.

### (1) Mean-based Data Rate Adaptation procedure

The 802.11p defines 8 data rates: 3 ~ 27Mbps. But according to the result of field test using the WAVE module, we don't consider the 24, 27Mbps in our algorithm because the PER value is estimated as very high remarkably like figure 2. In high SNR condition, the higher data rate causes the high throughput. But in low SNR condition, the lower data rate can gurantee the reliable transmission.

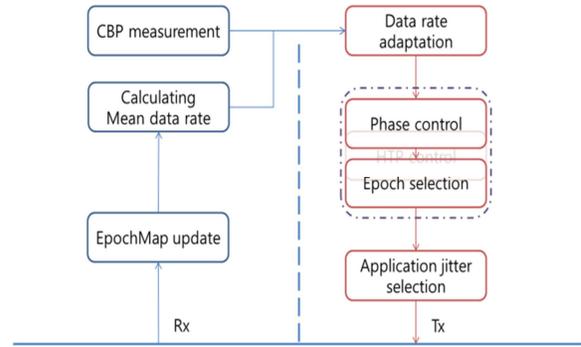


Figure2. The proposed algorithm

We calculated the coherence time and the expected time to finish a successful transmission, which are calculated as we vary the mobility of the vehicle and the number of contending vehicles. We consider the transmission rate 3 and 18Mbps. The required time duration is approximatey 760 $\mu$ s (3Mbps), 520 $\mu$ s (4.5Mbps), 400 $\mu$ s (6Mbps), 280  $\mu$ s (9Mbps), 224 $\mu$ s (12Mbps), 160 $\mu$ s (18Mbps). For this calculation, we assume that the packet size is 266 byte considering the standard message size, BSM(basic safety message) defined in IEEE SAE J2735.

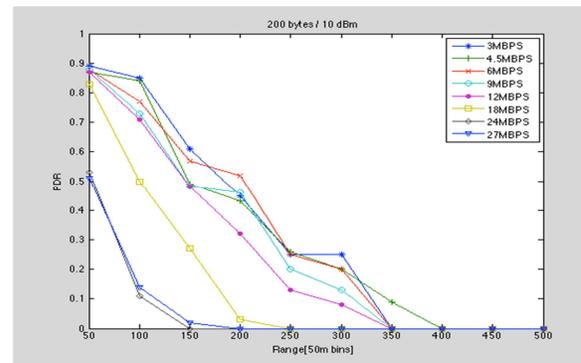
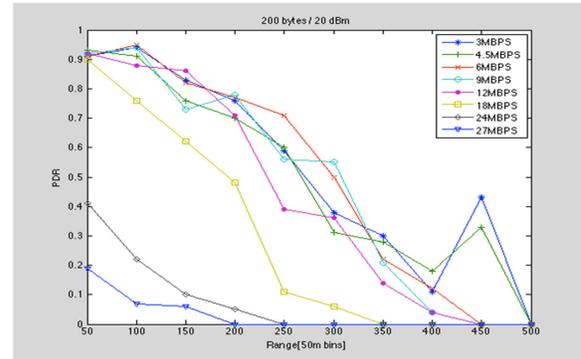


Figure3. Packet Delivery Rate vs Data rate

When the transmission duration is reduced, the packet collision possibility from the MAC collision

and hidden terminal can be reduced. By selecting the higher data rate in the heavy traffic condition, the transmission duration can be reduced. Also, Because the increase of the data rate bring the scale-down of the communication coverage, that can reduce the number of vehicle which attend the transmission competition and reduce the packet collision case. But, in the case of the light traffic condition, the lower data rate is good for the communication coverage and throuput aspect. So, our proposed algorithm determines the realtime channel status and controls the data rate based on that to reduce the packet collision possiblity. To determine the channel status, our algorithm uses the CBP value measured every 100msec. If the CBP is over the pre-defined value, 40%, our algorithm regards the current channel condition as the congestion.

The our algorithm for the mean-based data rate adaptation is like table 1.  $R_{init}$  is 6Mbps as the initial data rate.  $\bar{R}(N)$  is the mean data rate and  $\bar{R}(N)$  is calculated using the data rate value in the WSMP header in the received BSM message from the neighboring vehicles. If the CBP is over  $\theta$ , 40% and its data rate value is smaller than minimum data rate value, the vehicle changes the data rate value to the minimum value between the next level data rate and maximum data rate value. If the CBP is recovered to under  $\theta$  and the current data rate is higher than mean data rate, the vehicle changes the data rate to the maximum value between the previous lower value and minimum data rate.

**Table1. Mean-based data rate adaptation**

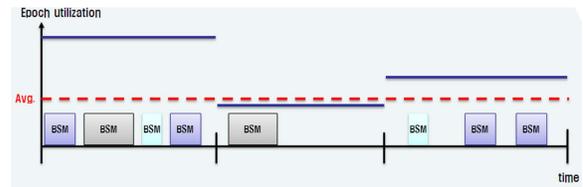
1: $R = R_{init}$
2: for each period T do
3: if $CBP \geq \theta$ then
4: if $R \leq \bar{R}(N)$ then
5: $R = \min(R + 1, R_{max})$
6: end if
7: else if $CBP < \theta$ then
8: if $R > \bar{R}(N)$ then
9: $R = \max(R - 1, R_{min})$
10: end if
11: end if
12: Transmit with data rate R
13: end for

**(2) Phase control algorithm using Epoch**

Even though we can reduce the packet collision possibility by controlling a data rate, if two more vehicles try to transmit the safety message at the

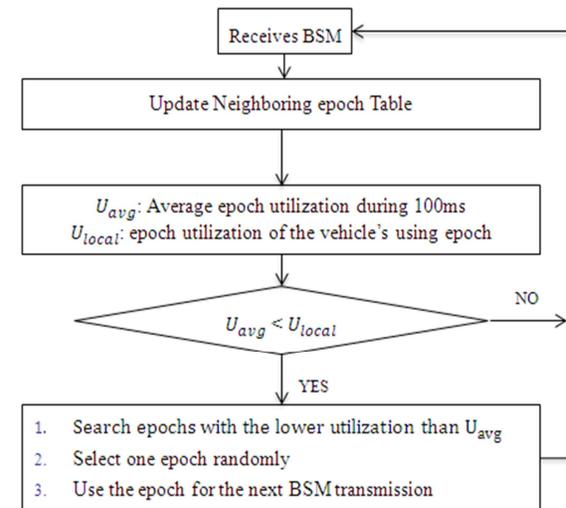
same time, the packet collision is inevitable. So, as the second step, we proposed the phase control algorithm using the pre-defined time interval, Epoch to solve that packet collision condition. Under the heavy traffic condition, that situation can occur very frequently.

In the proposed algorithm, we define the epoch. The epoch size is defined as 2ms and the number of BSM which one epoch can accept depends on the data rate of each BSM. In case that all vehicles which try to transmit using the specific epoch use 3 Mbps, the epoch can accept 4 vehicles. If there are vehicles using the higher data rate, the epoch accepts more vehicles.



*Figure4.* Epoch utilization example

To distribute the vehicles to the epoch evenly, we use the proposed phase control algorithm. Whenevner each vehicle receives the BSM message, it creates and updates its neighboring epoch table. The epoch table has the data rate and vehicle's MAC ID as an element. Each vehicle calculates the utilization for the epoch it use and average unitilization value in the neighboring epoch table every 100msec. The calculation considers the number of BSM as well as the data rate of each BSM. The BSM with higher data rate has the high weight factor.



*Figure5.* Phase control algorithm

If the calculated utilization value is lower than the average value, the vehicle uses the current epoch for the next BSM transmission. But, if the calculated utilization value is higher than the average value, the vehicle determines its jump rank. The jump rank can be calculated by considering a data rate, vehicle's MAC ID and the number of using time of the current epoch. The vehicle can calculate the required number of vehicle to satisfy the average utilization value with the neighboring epoch table. If the number is higher than the calculated jump rank, the vehicle re-selects other epoch with the lower utilization and uses the epoch for the next BSM transmission.

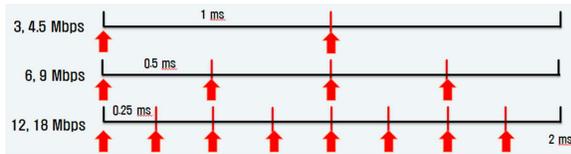


Figure6. Intra epoch definition within epoch

The proposed phase algorithm defined on the intra epoch to avoid the packet collision within the one epoch (2msec). To distribute the vehicles without overlapping interval, we define the different transmittable time depending on the BSM's data rate within the epoch like figure 6. Also, we apply the application random jitter to prevent the same transmission in the intra epoch.

## PERFORMANCE EVALUATIONS

We implement WAVE and our proposed algorithm with the Qualnet simulator. For our simulations, we define the following parameters.

Table2. Simulation parameters

Parameter	Value
Path-loss	Two-ray ground model
Shadowing	Constant/Mean 4.0
Fading	Rician, K-factor 3
MAC-model	802.11p with 1609.4 (continuous mode), CW-min: 3
Road	3000m, 2 lane
Mobility	Average 30Km/h, variance 0.3
Vehicle spacing	5m, 10m equal-distance
BSM size	200 bytes
Number of Vehicle	1200, 600

For the performance evaluation, we compared the our algorithm's performance with the existing algorithm defined in [6]. We call that algorithm as the AlgX

and our algorithm as the AlgH. The AlgX uses the GPS error measured by host vehicle and relative vehicle and controls the transmission rate control and power control independently. We estimate the PDR and CBP under the same simulation environment and compare with AlgX and AlgH.

Figure 7 shows the PDR comparison between AlgX and AlgH, PDR versus range. We choose one reference node and measure the distance from the reference node. We make a congestion condition with 1200 vehicles. The distance between two vehicles is fixed to 5m. We get the lower PDR values at longer ranges due to fading in addition to the other factors like a fading. The higher PDR values are experienced at shorter ranges because of the packet collision. Our algorithm's PDR is about 51% and the AlgX's one is about 39%. In the total range, our algorithm showed the better PDR results.

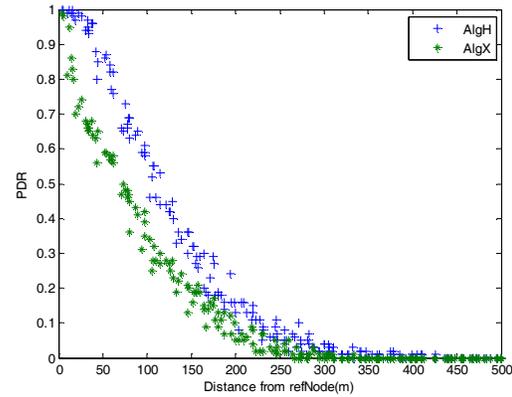


Figure7. PDR comparison (PDR vs Distance)

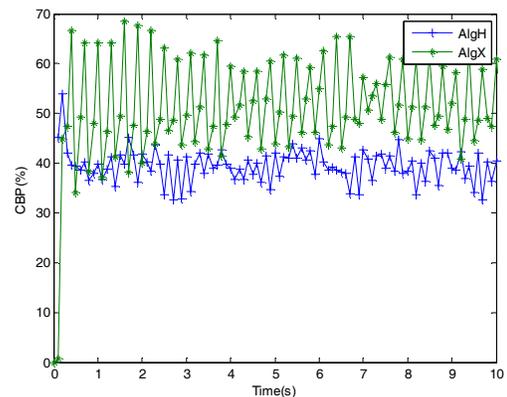


Figure8. CBP comparison (5m equal-distance)

Figure 8 shows the CBP comparison between AlgX and AlgH measured every 100msec. While the AlgX controls the message interval and transmission power in the traffic congestion condition, our algorithm

reduces the CBP by controlling a data rate and prevent the packet collision with the phase control. For the traffic congestion modeling, we put 1200 vehicles for the simulation. Our algorithm's average CBP is about 39% and the AlgX's one is about 51%. We can validate that our algorithm can control the traffic congestion condition and maintain the stable channel condition than AlgX.

We evaluate the impact of hidden terminal to the AlgX and AlgH. Because our algorithm is based on the data rate control according to the real-time channel condition, we expect our algorithm is robust to the hidden terminal problem. For the validation, we simulated with 600 vehicles. The distance between two vehicles is fixed to 10m.

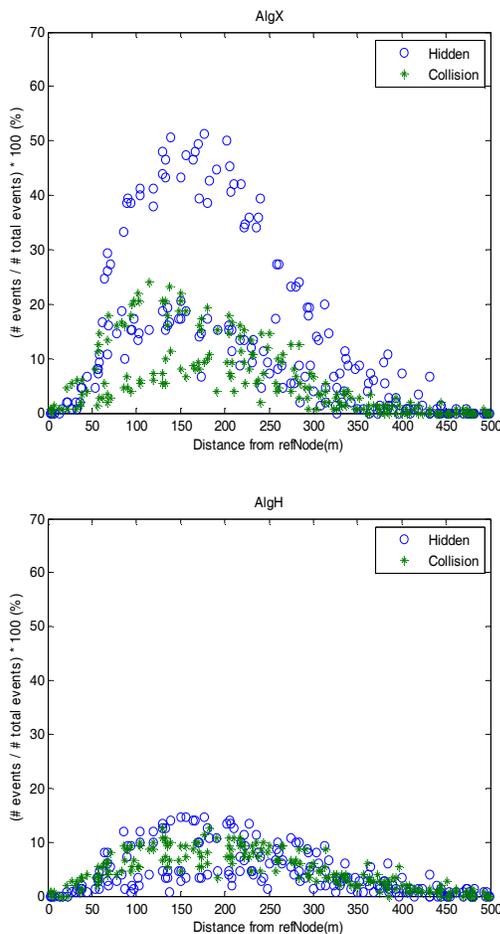


Figure 9. Hidden terminal impact (AlgX vs AlgH)

From the simulation result, AlgX has a packet collision caused by the hidden terminal. Because the design of AlgX does not consider the hidden terminal problem, it does not manage the problem efficiently. But, our algorithm is validated that it can drop the possibility of the hidden terminal efficiently.

## CONCLUSIONS

In this paper, we have analyzed WAVE performance under traffic congestion condition. Based on the analysis, we proposed the dynamic congestion control algorithm using the mean-based data rate control and the phase control using epoch.

The performance evaluations in Qualnet confirm that the proposed algorithm achieves better communication performance like a channel busy percentage and packet delivery rate than the existing solutions and is more robust to hidden terminal problems.

The proposed algorithm does not consider the coverage reduction from the data rate control. As our future work, if a variable transmission power is used by each vehicle with the data rate control, there could be further performance improvement.

## REFERENCES

- [1] A. Weinfield, "Methods to Reduce DSRC Channel Congestion and Improve V2V Communication Reliability", ITS World Congress, October 2010
- [2] M. Torrent-Moreno, J. Mittag, P. Santi, H. Hartenstein, Vehicle-to-Vehicle Communication: Fair Transmit Power Control for Safety-Critical Information, IEEE Transactions on Vehicular Technology, Vol. 58, No. 7, September 2009
- [3] F. Bai, H. Krishnan, Reliability Analysis of DSRC Wireless Communication for Vehicle Safety Applications, Intelligent Transportation Systems Conference, September 2006
- [4] C-L. Huang, Y. P. Fallah, R. Sengupta, and H. Krishnan, Intervehicle Transmission Rate Control for Cooperative Active Safety System, to appear in IEEE Transactions on Intelligent Transportation Systems
- [5] Guo J.-L. and Zhang J.-Y., "Safety Message Transmission in Vehicular Communication Networks", 17th ITS World Congress 2010. Busan 2010.
- [6] Ching-Ling Huang, Hariharan Krishnan, Raja Sengupta, Yaser P. Fallah, "Implementation and Evaluation of Scalable Vehicle-to-Vehicle

Transmission Control Protocol", VNC 2010

[7] John B. Kenney, Gaurav Bansal, Charles E. Rohrs, "LIMERIC: A Linear Message Rate Control algorithm for Vehicular DSRC Systems". The Eighth ACM International Workshop on Vehicular Inter-NEtworking (VANET 2011)

[8] Hakyung Jung, Ted Kwon, Kideok Cho, Yanghee Choi, "REACT: Rate Adaptation using Coherence Time in 802.11 WLANs", Computer Communication Journal, February 2011