STAND-ALONE COLLISION WARNING SYSTEMS BASED ON INFORMATION FROM ON-BOARD SENSORS
– Evaluating Performance Relative to System Penetration Rate –

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This paper looks at stand-alone collision warning systems that are based on information from on-board sensors and evaluates their safety performance relative to system penetration rate. The authors developed an autonomous microscopic traffic simulator for collision warning systems, including both forward vehicle collision warning systems and side collision warning systems, then evaluated such systems through simulation. Safety performance from the perspective of drivers was evaluated using the average distance driven without an accident for both system-equipped and unequipped vehicles. Safety performance from the perspective of road administrators was evaluated using the average interval between accidents. The average distance driven without an accident for system-equipped vehicles, compared to that for a system in which no system-equipped vehicles exist, increases greatly beginning from a low rate of penetration, suggesting that increased rates of penetration are attended by even greater effectiveness. With regard to the average distance driven without an accident for unequipped vehicles, too, increased rates of penetration are attended by increased safety performance due to the collision avoidance effect of warnings produced by system-equipped vehicles. In terms of safety performance from the perspective of road administrators, that is, the average interval between accidents, evaluations indicated that safety performance increases dramatically when the penetration rate exceeds 60%. The above findings illustrate the effect of system penetration rate on the safety performance of stand-alone collision warning systems that are based on information from on-board sensors.

Key Words: ITS, Driving assistance systems, Collision warning, Traffic simulators, Safety assessment

1. INTRODUCTION

Driving assistance systems that reduce accidents caused by vehicles are one kind of ITS application whose early practical application is much anticipated. Driving assistance systems that are designed to prevent accidents with other vehicles enhance safety by first ascertaining both subject vehicle traveling information (such as position and speed) and information on the surroundings (such as position relative to other vehicles and external information), then either providing this information to the driver to avoid an accident, using it to assess danger and alert the driver, or assisting in vehicle operation when the driver’s response is too late.

Such driving assistance systems can be classified as autonomous systems that obtain information on the surroundings solely from the subject vehicle or cooperative systems that obtain information through communication with others. In addition, communicative systems can be further divided by whether their source of information on the surroundings is other vehicles or infrastructure. Here we define Type I systems as those that obtain information on the surroundings solely from the subject vehicle, Type II systems as those that receive such information from other vehicles, and Type III systems as those that receive such information from infrastructure (see Figure 1).

Type I systems obtain information on subject vehicle surroundings using only subject vehicle on-board sensors. Because such systems can be constructed using only subject vehicle sensing devices, they are easy to implement. For this reason, various systems have been researched, developed and commercialized from early on. However, occlusion and shadowing make it difficult to obtain information beyond the line-of-sight of the sensors. Type I systems using radar\(^1\) and camera images\(^3\) have undergone research and development and in some cases have already been brought to market.

Type II systems obtain information on subject vehicle surroundings using only subject vehicle on-board sensors. Because such systems can be constructed using only subject vehicle sensing devices, they are easy to implement. For this reason, various systems have been researched, developed and commercialized from early on. However, occlusion and shadowing make it difficult to obtain information beyond the line-of-sight of the sensors. Type I systems using radar\(^1,2\) and camera images\(^3\) have undergone research and development and in some cases have already been brought to market.

Type II systems obtain information and information on the surroundings from other vehicles through communication. Communication methods include vehicle-vehicle communication, vehicle-road-vehicle communication (relayed through roadside communication...
equipment), and vehicle-vehicle-vehicle communication (relayed among multiple vehicles). Such systems have the drawback of being ineffective unless other vehicles are equipped with the same devices. Nevertheless, they offer the potential for utilizing, through roadside infrastructure and other vehicles, vehicle and hazard information otherwise invisible to subject vehicle on-board sensors. Examples of research on such systems include that on the transmission of moving image information through vehicle-vehicle communication.

In Type III systems, roadside infrastructure provides information on the surroundings. Communication methods include road-vehicle communication as well as communication that is relayed among multiple vehicles, such as road-vehicle-vehicle communication. Installation of numerous infrastructure devices under this type of system enables the provision of detailed and wide-ranging services that hold the promise of improved safety, but installation cost is a problem. Type III systems have received a great deal of attention in recent years and real-world verification tests have been conducted as part of research into providing information on traffic congestion through road-vehicle communication.

Given the current state of system research and development and rate of penetration, one can envision a scenario for the future adoption of driving assistance systems in which Type I, II and III systems coexist in the traffic environment. Therefore, when developing and popularizing new systems, it will be important to conduct advance evaluations of their safety performance in a traffic environment where driving assistance systems of each type coexist. Doing so requires clarifying information concerning system models and basic functionality for each kind of system. The situation where system-equipped vehicles and unequipped vehicles coexist is the very essence of this kind of driving assistance system so it is particularly important to conduct an evaluation of safety under such conditions relative to the penetration rate for on-board devices.

Previously, the authors have evaluated safety performance relative to penetration rate for Type II driving assistance systems that obtain information on surrounding vehicles through a communication network made up of area vehicles and roadside communications devices. They found that the safety of system-equipped vehicles increased dramatically when the system penetration rate exceeded 60%. They did not, however, evaluate safety performance relative to penetration rate for Type I driving assistance systems that obtain information on the surroundings solely through the use of subject vehicle on-board sensors.

Therefore, in this paper the authors evaluate safety performance relative to penetration rate by using a microscopic traffic simulator to model driving assistance systems based on on-board sensors. Section 2 describes driving assistance systems and how they were evaluated using the microscopic traffic simulator. Section 3 describes the models for on-board sensor-based driving assistance systems that were loaded into the microscopic traffic simulator. Section 4 presents a simulation-based evaluation of safety performance relative to penetration rate from the perspective of both drivers and road administrators.

### 2. Driving Assistance Systems and Their Evaluation Using a Microscopic Traffic Simulator

#### 2.1 Driving assistance systems designed to prevent collisions

Driving assistance systems are classified by which of three types of support they provide: information, warnings, or operational assistance. Systems that provide information simply supply the driver with information collected by the system, which the driver then uses to assess risk and take risk-avoiding behavior. In systems that provide warnings, the system-equipped vehicle uses information collected on the surroundings to assess whether or not the vehicle is in danger, and alerts the driver when it is. Systems that provide operational assistance determine the risk of imminent accident, such as when operation by the driver would be too late, and aids the driver by intervening in driving operation. This paper
STAND-ALONE COLLISION WARNING SYSTEMS BASED ON INFORMATION FROM ON-BOARD SENSORS

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1) Forward Vehicle Collision Warning Systems (FVCWS)
In 2002, ISO/TC204 WG14 established standards for FVCWS as systems addressing collisions with vehicles and obstacles forward of subject vehicles. An FVCWS uses sensor devices to obtain speed and distance between the subject vehicle and a forward vehicle in the same lane, checks this data against warning criteria and provides the driver with a warning when it determines there is danger. Such a determination is made when the following basic formula for assessing risk (Formula 1) is satisfied:

\[ D \leq V \times T + \left( \frac{V_f^2}{2a} - \frac{V^2}{2a_f} \right) \] ..............................(1)

Here, \( D \) is the following distance obtained by the sensors, \( V \) is the velocity of the subject vehicle, and \( V_f \) is the velocity of the forward vehicle. Free-running time \( T \), subject vehicle deceleration \( a \) and forward vehicle deceleration \( a_f \) are system parameters.

2) Side Collision Warning Systems (SCWS)
An SCWS uses sensor devices to detect vehicles on either side of the subject vehicle and provides the driver with a warning if there is danger of collision. SCWS are designed to address collisions that could occur when the vehicle moves in a lateral direction, such as when merging or changing lanes. Methods used to assess whether to issue a warning include determining whether or not a collision will occur based on speed and the lateral and longitudinal distances to adjacent vehicles and determining the danger of collision based on a calculation of obstacle trajectories.

2.2 Sensor devices used in driving assistance systems
The sensor devices need to model collision warning systems are discussed below.

1) Long-Range Millimeter Wave Radar Sensor
Long-range millimeter wave radar sensors are used as devices for detecting forward vehicles primarily in adaptive cruise control (ACC) and pre-crash safety systems. Many commercially available models are capable of recognizing forward obstacles at ranges up to 100 to 150m. Also, because range accuracy is high but angular resolution is low, obstacle detection systems have been developed that merge information from such sensors with that from short-range radar sensors and camera images, discussed below, to achieve greater accuracy, higher resolution and broader range.

(2) Short-Range Radar Sensor
Over short distances, 24GHz short-range radar sensors have a higher resolution than long-range millimeter wave radar sensors. With a range of about 20m, they are used to detect nearby forward vehicles as well as side vehicles and obstacles, which are relatively difficult for long-distance radar to detect.

(3) Cameras
Processing images from CCD or CMOS cameras can enable recognition of vehicles, obstacles and lane markers. The range at which a camera can independently detect obstacles varies with camera capability and image processing method but generally extends to about 50m.

2.3 Microscopic traffic simulator for evaluating driving assistance systems
The authors have previously represented the occurrence of accidents between vehicles and developed a microscopic traffic simulator to evaluate vehicle safety. Elements like vehicle following were added to the basic simulator. Basic facts about the improved microscopic traffic simulator are discussed below.

The simulator is an autonomous cruising traffic simulator that assumes there is a driver controlling each vehicle. Each individual driver is provided with attributes such as desired speed and total delay, and vehicles travel autonomously. Each driver’s total delay is the sum of driver delay and mechanical delay. Total delay leads to dangerous delays in action and to the occurrence of accidents. Figure 2 indicates one example of a simulation for evaluating driving assistance systems. Figure 2 shows partial results for a straight-line, three-lane expressway simulation, indicating vehicle behavior over the first 300m segment of the road. (The vertical black lines drawn across the road demark 100m segments). Vehicles are displayed in different colors according to their individually assigned attributes (in this case, desired...
This microscopic traffic simulator is composed of a driver model, a vehicle model and a road model. Also, a periodic scanning approach is used for the simulation’s time marching method, with each vehicle’s status updated periodically (at each scanning interval).

(1) Driver Model

The driver model defines factors such as driver field of vision (the range over which the driver is aware of position and speed information for other vehicles), desired speed (the maximum speed the driver wishes to attain), total delay, vehicle speed control method, and lane-changing behavior.

Each driver obtains ever-changing information about the leading vehicle (the nearest vehicle positioned to the front, and within half a road’s width to either side of center, of the subject vehicle) from his field of vision. Depending on the headway to the leading vehicle, the driver decides to use one of two speed control modes: following mode or free-running mode. Figure 3 indicates the acceleration decision flowchart.

![Driver acceleration decision flowchart](image)

Fig. 3 Driver acceleration decision flowchart

The determined acceleration is reflected in vehicle speed after an adjustment for the total delay time assigned to the driver. In this simulator, following mode acceleration is determined using Formula 2 below, which accounts for distance and speed relative to the leading vehicle, as well as vehicle speed after adjustment for total delay, and is based on previous work.

\[
\ddot{x}(t + \Delta) = \frac{a\dot{x}_m(t + \Delta)(\dot{x}_{lead}(t) - \dot{x}(t))}{(x_{lead}(t) - x(t))^3} \quad (2)
\]

\(l, m, a: \text{Const} (l = 0.8, m = 0.05, a = 0.3)\)

\(\Delta: \text{Total delay}\)

\(x: \text{Position of the subject vehicle}\)

\(x_{lead}: \text{Position of the leading vehicle}\)

\(\dot{x}: \text{Velocity of the subject vehicle}\)

\(\dot{x}_{lead}: \text{Velocity of the leading vehicle}\)

\(\dot{x}: \text{Accelerate of the subject vehicle}\)

Acceleration in free-running mode, on the other hand, is determined using Table 1. In addition, when a following state has continued for a set length of time, the driver changes lanes if conditions in his field of view lead him to decide that a lane change can be performed safely. Lane change decision criteria are outlined in Table 2.

(2) Vehicle Model

| Table 1 Determining acceleration in free-running mode |
|---------------------------------|-----------------|
| \(\dot{x}(t)\)                                | \(\dot{x}(t+\Delta)\) |
| \(\dot{x}(t) < 0.8\dot{x}_{\text{MAX}}\)  | +0.25G       |
| \(0.8\dot{x}_{\text{MAX}} < \dot{x}(t) \leq 0.95\dot{x}_{\text{MAX}}\) | +0.125G     |
| \(0.95\dot{x}_{\text{MAX}} < \dot{x}(t) \leq 1.05\dot{x}_{\text{MAX}}\) | 0G          |
| \(1.05\dot{x}_{\text{MAX}} < \dot{x}(t)\)     | -0.2G        |

\(\dot{x}_{\text{MAX}}: \text{Desired Speed}\)

![Sample display of simulation results](image)

Fig. 2 Sample display of simulation results

Table 2 Lane change criteria

If all of the conditions below are met, it is determined that a lane change can be performed safely:

- No vehicle is in the target lane within 50m to the front or rear;
- No vehicle is entering the target lane from another lane within 50m to the front or rear;
- No vehicle is traveling in another lane, forward of the subject vehicle and at lower speed, while signaling its intention to enter the target lane; and
- No vehicle is traveling in another lane, to the rear of the subject vehicle and at higher speed, while signaling its intention to enter the target lane.

The vehicle model defines factors such as vehicle type (ordinary passenger car or full-sized car) and size (width, length and height). Also, vehicles are assumed to appear at the starting point of the road in...
each lane by Poisson occurrence, traveling at a speed of 70 km/h.

(3) Road Model
The road model describes an expressway and defines road shape, lane width, number of lanes, and road length.

Implementing the driving assistance system model using the microscopic traffic simulator makes it possible to conduct safety evaluations. In addition to driving assistance systems, implementation of a communications system model can also enable safety evaluations of communications systems.16,17

2.4 Indices for evaluating driving assistance systems
Indices for evaluating driving assistance systems include safety performance from the perspective of road administrators and safety performance from the perspective of drivers.

One index for evaluating safety performance from the perspective of road administrators is average accident interval (AAI). The average accident interval is a guide for evaluating the effect of the system on accident occurrence within the target road section, and is defined as the average interval between accidents within the target road section.

When looking at safety performance from the perspective of drivers, because system-equipped and unequipped vehicles will coexist in the actual operating environment for driving assistance systems, one must consider safety performance for both types of vehicles. Safety performance for system-equipped vehicles is defined as the average distance traveled without an accident among drivers of system-equipped vehicles (No-Accident Traveling Distance for Equipped Vehicles = NATD for EV). Similarly, safety performance for unequipped vehicles is defined as the average distance traveled without an accident by drivers of unequipped vehicles (No-Accident Traveling Distance for UnEquipped Vehicles = NATD for UEV).

3. BUILDING A SIMULATOR THAT INCLUDES STAND-ALONE COLLISION WARNING SYSTEMS BASED ON ON-BOARD SENSOR INFORMATION
This section describes the models loaded into the simulator for the collision warning system based on sen-
distance to and speed of the vehicle detected nearest the subject vehicle. On-board sensors also provide the speed of the subject vehicle. The data refresh cycle is $T_s [s]$. Based on the accumulated data, the system conducts a warning assessment for each warning assessment cycle $T_w [s]$. The system decides to issue a warning when formula 1, the ISO standard warning criteria, is satisfied. System parameters are free-running time $T$, subject vehicle deceleration $a$ and forward vehicle deceleration $a_f$.

(2) Side Collision Warning System (SCWS)
Sensor devices frequently used in side collision warning systems include short-range radar and cameras that can cope with a wide range over short distances. This paper assumes the use of short-range radar to obtain information from the sides of subject vehicle. Sensors are positioned on either end of the rear bumper, each pointing perpendicular to the side of the vehicle. Sensors are capable of detecting both distance to and speed of (both laterally and longitudinally for each) all vehicles with radius $R [m]$ and viewing angle $\pm \phi [\degree]$ (see Figure 5). The data refresh cycle is $T_s [s]$. Based on the accumulated data, the system conducts a warning assessment for each warning assessment cycle $T_w [s]$. The system decides to issue a warning when warning assessment criteria (Formula 3) concerning time to collision (TTC) are satisfied both laterally and longitudinally.

$$D \geq (V_2 - V_1) \times T ...................................................(3)$$

Here, $D$ is the distance to the other vehicle, $V_1$ is the velocity of the subject vehicle, $V_2$ is the velocity of the other vehicle, and $T$ is the system parameter of free-running time.

Tables 3 and 4 indicate the elements of FVCWS and SCWS. Elements for each sub-system were determined by consulting reference 18. Collision warning parameters are derived from reference 7, although free-running time has been set slightly higher and the presumed vehicle deceleration set slightly lower. This reflects the paper’s interest in gentle warnings concerning the danger of collision rather than emergency collision evasion.

(3) Driver Action in Response to Warnings
Drivers are assumed to respond to warnings from the FVCWS by engaging their brakes (0.15G). However, when a driver decides that braking in excess of 0.15G is required, the driver brakes to decelerate as much as he deems necessary. Drivers in the midst of changing lanes are assumed to abort the lane change in response to a SCWS warning. Warnings from each direction are independent and drivers are assumed to react unerringly in taking evasive action.

4. SIMULATION

4.1 Simulation elements
We evaluated safety performance of a driving assistance system on a straight expressway. Simulation elements are listed in Table 5.

For the simulation, vehicles were randomly assigned as system-equipped or unequipped based on penetration rate and put through 40,000 hours worth of simulations, resulting in measurements for average accident interval and for no-accident traveling distance for both system-equipped and unequipped vehicles. Each vehicle’s no-accident traveling distance was calculated by dividing total distance traveled by number of accidents. This made it impossible to calculate no-accident traveling distance for vehicles that were not involved in any accidents during the course for the simulation (no-accident vehicles). In such cases, the no-accident traveling distance for no-accident vehicles was assumed to be double the total distance traveled. In addition, average accident interval was calculated for the straight 10km, 3-lane simulation roadway.

<table>
<thead>
<tr>
<th>Table 3 FVCWS elements and parameters</th>
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<tbody>
<tr>
<td>Detection Distance $D$</td>
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<tr>
<td>Detection Width $W_L$</td>
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<tr>
<td>Data Refresh Cycle $T_s$</td>
</tr>
<tr>
<td>Collision Warning</td>
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<tr>
<td>Warning Assessment Cycle $T_w$</td>
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<tr>
<td>Free-Running Time $T$</td>
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<tr>
<td>Subject Vehicle Deceleration $a$</td>
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<tr>
<td>Forward Vehicle Deceleration $a_f$</td>
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<table>
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<tr>
<th>Table 4 SCWS elements</th>
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<tr>
<td>Detection Radius $R$</td>
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<tr>
<td>Viewing Angle $\phi$</td>
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<tr>
<td>Data Refresh Cycle $T_s$</td>
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<tr>
<td>Collision Warning</td>
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<tr>
<td>Warning Assessment Cycle $T_w$</td>
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<tr>
<td>Free-Running Time $T$</td>
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4.2 Penetration rate characteristics

Penetration rate means the proportion of system-equipped vehicles among all vehicles. Penetration rate characteristics were evaluated for average accident interval and for the no-accident traveling distance of both system-equipped and unequipped vehicles. Evaluation results for average no-accident traveling distance are presented in Figures 6-8. The no-accident traveling distance for system-equipped vehicles increases, compared to an environment with no system-equipped vehicles (that is, compared with the average no-accident traveling distance for unequipped vehicles when penetration rate is 0%), by about 2 to 3 times when vehicle density is 5veh/km/lane, about 4 to 14 times when vehicle density is 15veh/km/lane, and about 7 to 23 times when vehicle density is 20veh/km/lane. In an environment where system-equipped vehicles and unequipped vehicles coexist, there are three possible two-vehicle approach patterns with risk of collision: two system-equipped vehicles, one system-equipped and one unequipped vehicle, and two unequipped vehicles. Of the two approach patterns involving system-equipped vehicles (two system-equipped vehicles or one system-equipped and one unequipped vehicle), the former case shows higher safety performance because both vehicles take evasive action while in the latter case where only one vehicle takes evasive action. Accordingly, an increase in penetration rate increases the likelihood that two system-equipped vehicles will approach each other, thereby in-
incident traveling distance for system-equipped vehicles is higher than that in an environment where there are no system-equipped vehicles. This means that system-equipped vehicles benefit from the system even when penetration rates are low.

On the other hand, unequipped vehicles also show an increase in safety performance, to as much as double, with increased penetration rates. This is because they benefit from efforts by system-equipped vehicle to avoid accidents with unequipped vehicles. This demonstrates the characteristic of stand-alone systems that the presence of system-equipped vehicles improves safety performance for both system-equipped and unequipped vehicles.

Next, evaluation results for safety from the perspective of road administrators are presented in Figures 9-11. Average accident interval increased, compared to that in an environment with no system-equipped vehicles (that is, compared to when penetration rate is 0%), by about 4 times at a penetration rate of 60% and 8 times at a penetration rate of 80% when vehicle density is 5veh/km/lane, by about 4 times at a penetration rate of 60% and 10 times at a penetration rate of 80% when vehicle density is 15veh/km/lane, and by about 5 times at a penetration rate of 60% and 20 times at a penetration rate of 80% when vehicle density is 20veh/km/lane. This demonstrates that the average accident interval increases dramatically when the penetration rate exceeds 60%. This is because, for the same reasons mentioned above, accidents are less likely to occur. It also illustrates how the system increases in effectiveness in higher density traffic. This is because higher density traffic flows generate more opportunities for vehicles to approach each other with the risk of collision.

5. CONCLUSION

The authors built a microscopic traffic simulator to evaluate stand-alone collision warning systems that are based on information from on-board sensors, and performed an evaluation of safety performance relative to penetration rate. Evaluation of safety performance from the perspective of drivers was based on average no-accident traveling distance for both system-equipped and unequipped vehicles, while evaluation of safety performance from the perspective of road administrators was based on average accident interval. In the evaluation of safety performance from the perspective of drivers, no-accident traveling distance increased with higher rates of penetration for both system-equipped and unequipped vehicles.

At a vehicle density of 15veh/km/lane and a penetration rate of 80%, the average no-accident traveling distance for system-equipped vehicles was about 14 times higher, and for unequipped vehicles was about 2 times higher, than in an environment with no system-equipped vehi-
cles. Average no-accident traveling distance for system-equipped vehicles indicated greatly improved safety performance even from a low penetration rate; at a vehicle density of 15veh/km/lane and a penetration rate of 20%, safety performance was about 4 times better than in an environment with no system-equipped vehicles. In the evaluation of safety performance from the perspective of road administrators, average accident interval increased greatly when the penetration rate exceeded 60%. At a vehicle density of 15veh/km/lane, the average accident interval was about 4 times higher at a penetration rate of 60%, and 10 times higher at a penetration rate of 80%, than in an environment with no system-equipped vehicles.

This paper conducted a simulation using an expressway but it is also important to evaluate the situation for ordinary roads. Possible topics for further research include performance evaluations, in a variety of road environments, of situations where stand-alone driving assistance systems using on-board sensors coexist with driving assistance systems using communication.

REFERENCES