Traffic Safety at Road-Rail Level Crossings Using a Driving Simulator and Traffic Simulation

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A number of Intelligent Transportation Systems (ITS) were used with an advanced driving simulator to assess its influence on driving behavior. Three types of ITS interventions namely, Video in-vehicle (ITS1), Audio in-vehicle (ITS2), and On-road flashing marker (ITS3) were tested. Then, the results from the driving simulator were used as inputs for a developed model using a traffic micro-simulation (Vissim 5.4) in order to assess the safety interventions. Using a driving simulator, 58 participants were required to drive through a number of active and passive crossings with and without an ITS device and in the presence or absence of an approaching train. The effect of driver behavior changing in terms of speed and compliance rate was greater at passive crossings than at active crossings. The difference in speed of drivers approaching ITS devices was very small which indicates that ITS helps drivers encounter the crossings in a safer way.

Since the current traffic simulation was not able to replicate a dynamic speed change or a probability of stopping that varies based on different ITS safety devices, some modifications of the current traffic simulation were conducted. The results showed that exposure to ITS devices at active crossings did not influence the drivers’ behavior significantly according to the traffic performance indicators used, such as delay time, number of stops, speed, and stopped delay. On the other hand, the results of traffic simulation for passive crossings, where low traffic volumes and low train headway normally occur, showed that ITS devices improved overall traffic performance.

**Keywords:** Intelligent Transportation System (ITS), transportation simulation, safety, traffic performance, railway crossings, traffic simulator
INTRODUCTION & LITERATURE REVIEW

Accident analysis at Railway Crossings

In the United States, empirical formulas based on historical accident data at a level crossing have been used to predict the expected crash rate. These formulas such as the Peabody-Dimmick Formula, New Hampshire Index, The National Cooperative Highway Research Crash Prediction Formula, The USDOT crash prediction formula, and The Mississipi and the Ohio methods consider the crash history, as well as some of the causal factors in determining the crash rate at a particular crossing. While a hazard index is a relative ranking, the crash prediction models calculate the actual frequency of crashes at crossings (1). Statistical collision prediction models are used to assess how specific countermeasures act to reduce collisions at specific grade crossings. In Australia, the Australian Level Crossing Assessment Model (ALCAM) is used to identify contributing risk factors at level crossings. This tool helps prioritize the level crossings that are to be upgraded.

Despite the fact that the procedure for archiving crash data seems to have become more systematic, it often contains significant discrepancies. Many crash related organizations such as police, insurance companies, and bureaus of statistics collect crash data in different ways. Police reports are prone to have an under-reported bias. Elvik and Mysen (2) analyzed crash recording rates in 13 countries. In their study, only 95% of the fatal crashes, 70% of the serious injury crashes (in hospital), 25% of the slight injury crashes (outpatients), 10% of the very slight injuries (sent home), and 25% of property-damage-only crashes were reported compared to the real accident frequency. Mills, Andrey and Hambly (3) investigated vehicle collisions and injury risk using not only police records but also insurance data in Canada. They concluded that the number of collisions and injuries from the insurance data was far higher than the police record. This implicates that an inconsistency of the accident record from police should be taken into account when other sources of accident data are not available.

Although emerging technologies and innovative roadside interventions have been introduced in order to change driver behavior (4), there is a lack of research on the integration of different Intelligent Transportation System (ITS) technologies and transportation simulation with driving simulator to assess its influence on driving behavior. Ideally, constructing overhead bridges or underpasses is the best way to secure safety at railway crossings. However, local governments and councils cannot afford the cost as they have other high profile priorities on which to spend their annual budgets. Upgrading crossings from stop signs or rumble strips to flashing lights and boom barriers is financially burdensome for some governments, especially if there are several in their region. Evaluating the danger level of railway crossings is very important for decisions related to the wise spending of taxpayers’ money. Rather than involving high levels of infrastructure spending, ITS can warn drivers of approaching trains and assist them to comply with the road rules when approaching and using a rail crossing.

To date, there have been no studies that use transportation simulation to identify the safety of a specific system. Most crash models regarding railway crossings are based on historical records, which are input into statistical models. In addition, driving simulator-based studies have not been used to identify the causes of crossing collisions whereas a significant amount of research has been conducted on road safety (5-7).

In this study, different scenarios have been designed for the driving simulator in such a way that an approaching train; vehicular traffic in the proximity of railway crossings and the infrastructure (e.g. road type) surrounding railway crossings; and in-vehicle devices have been as realistic as possible. In order to determine the performance of the ITS devices at railway crossings, the driving simulator was used to collect the stopping distances, approaching speeds of vehicles, and compliance rates with a sufficient degree of accuracy. Traffic micro-simulation was also used to assess traffic safety that might be affected by the ITS device installation. This framework will examine whether driver compliance with stopping requirements at railway crossings equipped with ITS devices will perform better than only the usual controls at rail crossings. As part of the project funded by Cooperative Research Centres (CRC) for Innovation, Australia, this study specifically focused on how
the different types of drivers respond to different types of ITS interventions (visual, sound, maker) and what traffic conditions would be expected under these research settings.

The Use of Driving Simulator and Traffic Simulation for Railway Crossings

It is obvious that collecting real field data is the best way to analyze different driving behaviors when testing different safety devices. However, the number of events in which a train and a vehicle overlap in the same time and space is fortunately very low. Using a driving simulator is a good alternative for creating as many events as possible in order to obtain reliable data (8; 9) although some shortcomings such as a limited fidelity and validity of simulator and sickness were reported (10).

Recently, there have been many studies in Australia on driving behavior at railway crossings which have used a driving simulator. For example, Tey, Ferreira and Wallace (11) compared driving behaviors between field data and a driving simulator in terms of compliance rate, speed profile, and final breaking position at railway crossings equipped with a stop sign, flashing lights, and half boom barrier. In another study by Tey et al. (12), four different warning devices – flashing lights, in-vehicle warning, rumble strips, and stop sign – were tested according to the age and gender of the participants. They used a fixed driving simulator in order to identify compliance rate, driver accelerator release position, and initial/final breaking position. Lenné et al. (8) conducted an experiment to compare railway crossings equipped with a stop sign, flashing lights, and traffic lights in a driving simulator and concluded that traffic signals alone provided adequate warning to drivers. Rudin-Brown et al. (13) extended their previous study by identifying the effectiveness between traffic lights and flashing lights with boom barriers at railway crossings using the same simulator. Their results revealed that traffic lights were not superior to flashing lights with boom barriers in terms of safety benefit.

Traffic simulation also has gained increasing popularity in traffic safety assessments. Traditional methods, such as statistical models and before-and-after comparisons have been difficult to assess accurately, mainly due to the short length of an observation period, sample size problems and reporting errors or missing data (14). The use of microscopic simulation with surrogate traffic conflict measurements enables new techniques to provide an enhanced way of conducting safety evaluation without interrupting existing traffic conditions (15). Simulation-based surrogate safety measurements identify not only the probability of collisions, but also the severity of these potential collisions.

Using a driving simulator with traffic simulation, this study attempts to discover how drivers react to different ITS safety devices and how these in turn determine different driving behaviors, which may then impact traffic conditions. This paper is structured as follows: the section ‘Driving simulator’ provides a brief description of the procedure and scenarios tested in the driving simulator. Next, the section ‘Modified traffic simulation’ sets out the model development steps to demonstrate what has been modified in traffic simulation. The ‘Results’ section first details the results of the driving simulator (as input for the modified traffic simulation), and then provides the results from the developed model in order to evaluate crossings with various traffic conditions along with ITS interventions. The section ‘Discussion’ explains what is found beyond the results. The final section concludes the main findings and suggests areas for future study.

DRIVING SIMULATOR

Participants

Leaflets were designed to advertise for participants in a campus notice board on line. They were also posted to the Facebook page to have more recruitment outside of campuses. Maximum 3 participants per day were experimented. Fifty-eight participants, 39 males and 19 females, aged between 19 and 59 years (Mean = 28.2, SD = 7.63) agreed to take part in the study. Participants were divided into three groups, each group testing one particular ITS intervention. The first group comprising 20 participants tested the visual in-vehicle ITS. The second group comprising 19 participants tested the
audio in-vehicle ITS. The last group comprising 19 participants tested the on-road flashing marker system.

**Driving Simulator Setup**

Participants were asked to drive three different itineraries consisting of a number of active and passive crossings (shown in FIGURE 1) with and without an ITS device, and in the presence or absence of an approaching train. Drivers rely on warning flashing lights at the active crossing while they need to make a decision whether or not to stop at the passive crossing. Drivers followed the speed limit of 40 km/h in the city area, 80 km/h in some portions of the road, and 60 km/h in most sections of the road. Crossing geometries and signage were designed based on the Australian Standards (16). Three trials were implemented namely; Video in-vehicle (ITS1), Audio in-vehicle (ITS2) and On-road flashing marker (ITS3) as shown in FIGURE 2. The audio in-vehicle ITS used the speakers of the simulator positioned inside the car (under the seat) to provide warning messages, such as, “Train approaching the crossing ahead”, and “Stop at the crossing”.

![FIGURE 1 Active(left) and passive(right) crossing source from: Transport and Main Roads (16)](image1)

![FIGURE 2 Video in-vehicle (left) and On-road flashing markers (right)](image2)
A road map of the Brisbane CBD area in Queensland, Australia, as well as one of the surrounding road network were used, which included a number of railway crossings. Each driver encountered eight crossings (passive or active crossings were chosen randomly) per itinerary. As participants drove three different itineraries, a total of 24 profiles per driver were collected.

MODIFIED TRAFFIC SIMULATION

Pre-Processing for Gender and Age

The distribution of gender and age in Queensland, Australia was obtained from the number of driving licenses currently held by the Department of Transport and Main Roads (17), which comprised 1,612,887 males and 1,519,454 females. As TABLE 1 shows males were allocated to profiles 1, 2 and 3 while females were allocated to 4, 5, and 6. Profiles 1 and 4 included those aged under 20, profiles 2 and 5 included those aged 30 to 40, and profiles 3 and 6 included those aged over 50 years. Whenever VISSIM detected a vehicle that held more than 5 seconds headway, the vehicle was regarded as a leading vehicle. The leading vehicle then followed the speed profile derived from the driving simulator. The specific speed profile number was chosen based on gender and age group as shown in TABLE 1.

<table>
<thead>
<tr>
<th>Profile No.</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Under 20s</td>
<td>12%</td>
<td>19%</td>
</tr>
<tr>
<td>30s to 40s</td>
<td>19%</td>
<td>20%</td>
</tr>
<tr>
<td>Over 50s</td>
<td>20%</td>
<td>12%</td>
</tr>
<tr>
<td>Under 20s</td>
<td>19%</td>
<td>18%</td>
</tr>
<tr>
<td>30s to 40s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 50s</td>
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Evaluation Tool Using VISSIM COM Interface

The VISSIM COM interface enables the developed model to be enhanced by adjusting the objects, methods, and properties in the default VISSIM. This application provides traffic engineers with a lot of freedom in the analysis of a variety of different projects (18; 19). Like many other traffic simulation software, VISSIM also allows access from an external interface.

The VISSIM COM interface also enables the automation of certain tasks. For example, in order to ensure a good quality of model calibration, multi runs of scenarios need to be performed by changing the random seed number. An external program like Excel and VBA can automatically increment the seed number sequentially so that the VISSIM results can be balanced.

Due to a limitation (e.g. control of speed at certain locations, a probability of stopping categorized by demographic) of using the current traffic simulation, some external controls need to be implemented. In our case, for example, only the behavior of the leading vehicle needed to be changed based on what was observed from the driving simulator. The follow-on vehicles then needed to be moved by the car-following theory that mainly controlled all the vehicles in the simulation.

VISSIM Setup

The developed simulation model contained train tracks, roads, various types of vehicles, detectors, and signals. Train tracks were stretched between north and south while roads intersected these train tracks in a horizontal direction. In this study, the simulation model was designed for two situations; an area where trains ran frequently (an urban area) and an area where trains ran relatively less frequently (a sub-urban area).

The simulation ran for 1 hour (3,600 seconds) with intervals of 1 second for the urban area and 10 hours for the sub-urban area. For the urban area, the active crossing characteristics were applied whereas for the sub-urban area, passive crossing characteristics were considered.

For the urban area (active crossing), trains passed every 3 minutes for the peak hour and vehicles were input to the network at 800, 1,000, and 1,500 veh/h. For the sub-urban area (passive
crossing), 17 trains passed the crossings per day (10 hours) and vehicles were introduced to the network at 200, 250, and 300 veh/h. Three detectors played a role in triggering a virtual signal control so that warning devices were activated accordingly.

With these data used as input for a traffic micro-simulation model, an sample network was developed to identify how vehicles would react to the railway crossing equipped with base (control), ITS1 (smart phone), ITS2 (audio) and ITS3 (flashing markers on the road). A signal head function in VISSIM was adopted as the stop line at the railway crossings. Vehicles moved from the left to the right and were recorded every second.

Before running the modified model, speed profiles were pre-processed based on the driving simulator’s results. There were two sets of speed profiles; in the case of an approaching train (speed profile 1) and no approaching train (speed profile 2). Each speed profile consisted of 20 average speed values measured every 5 meters for 100 meters from the crossing. Also, standard deviation values for each speed were taken into consideration.

As shown in FIGURE 3, the loop between start and finish continued running every second. A detector located 120 m away from the stop line checked the traffic headway. In the studied case, 5 seconds was used. If the headway of traffic was more than 5 seconds, it was considered as a leading vehicle approaching the railway crossing. The vehicle travelling 5 seconds after the last vehicle became the leading vehicle when it reached the detector, to represent how the subject in the driving simulator responded to various situations.

At the same time, the model detected if a train was approaching the crossing. When there was no train in the network, the subject vehicle held speed profile 2. If the train passed detector 1 (train approaching), the subject vehicle changed its speed to that of speed profile 1. Then, the model checked if the subject vehicle complied with the traffic rules. A binary response that is randomly generated based on the compliance rate of the driving simulator results was produced. If the binary response was 1, the subject vehicle complied. During the simulation run, the value (1 or 0) kept changing dynamically according to the compliance rate calculated from the driving simulator. A value of 1 indicated that the leading vehicle complied with the warnings at the crossing while a value of 2 showed non-compliance. When the train passed detector 2 (train has passed), vehicles passed through the crossing and the subject vehicle regained speed profile 2. In a case of the subject vehicle not obeying the traffic rule, it passed through the crossing and touched detector 3. Then it was assumed that the following vehicle was forced to stop at the stop line.
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![Flowchart of the process in the modified model](image)

- Speed profile1: Speed when a train approaches
- Speed profile2: Speed when there is no train
- D: Detector

**FIGURE 3** A flow chart of the process in the modified model

**RESULTS**

**Results from Driving Simulator**

**FIGURE 4** shows the speed profiles of the different types of devices on a straight road. Four-speed profiles out of eight straight crossings were taken to feed the traffic simulator.

As the four sets of graphs show, drivers maintained speed until they were approximately 100 meters from the stop line at passive crossings. The speed curves appeared similar between passive and active crossings on a straight road (high visibility) but approaching speeds at passive crossings were lower than at active crossings until about 75 meters from the stop line when a train was approaching. This suggests that drivers approach passive crossings cautiously compared to active crossings. When the four-speed profiles from passive and active crossings were compared for the distances between 70 meters and 25 meters, large speed differences between devices were found at passive crossings while they were steady at active crossings. This indicates that drivers are more influenced by the different warnings at passive crossings than at active crossings.

This trend also can be seen when no train is approaching. When drivers approach a crossing, they react to the warnings differently. Drivers begin to brake about 50 meters away from the stop line at passive crossings, whereas they gradually slow down at active crossings.

<table>
<thead>
<tr>
<th></th>
<th>Train presence</th>
<th>Train absence</th>
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8

8
FIGURE 4 Speed profiles for crossings on a straight road

FIGURE 5 shows a speed profile at passive crossings for each device with standard deviation. Compared to the ITS devices, the speed profile of drivers at base control crossings has a larger deviation. This suggests that crossings controlled by ITS devices lead drivers to more consistent driving behavior. These data sets were used in the modified traffic simulation as important inputs (refer to VISSIM setup section above).
FIGURE 5 Speed Distributions (Base:top, ITS:bottom)

TABLE 2 shows the compliance rates for the four safety devices, the two types of crossings, and with and without an approaching train. Non-compliance categories for passive crossings consisted of ‘Stopped almost completely’, ‘Left before the end of warning’, ‘Went before the train’ and ‘Did not stop’ and for active crossings, ‘Left before the end of warning’ and ‘Did not stop’.

The compliance rates for passive crossings were divided into train approaching or not approaching, as drivers needed to stop at the stop line regardless of the ITS device’s activation. Drivers obeyed the traffic rules at the active crossings more than at passive crossings. When a train was approaching a passive crossing, the ITS devices appeared to assist drivers to stop to allow the train to pass, showing 90%, 100%, 88%, 86% for ITS1, ITS2, ITS3, and Base, respectively. However, when there was no train approaching, drivers relied on the devices and showed less compliance rates of 57%, 61%, 59%, and 73% for ITS1, ITS2, ITS3, and Base, respectively. On the other hand, drivers approaching the active crossing positively responded to the warning by showing more than 90% compliance in all cases. Drivers approaching a crossing with ITS1 ‘Left before the end of warning’, rather than ‘Did not stop’ in the non-compliance category.

TABLE 2 Compliance rate average (%) for active and passive crossings

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<th>Active</th>
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<td></td>
<td>Base</td>
<td>ITS1</td>
</tr>
<tr>
<td>Train presence</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Compliance (%)</td>
<td>86</td>
<td>73</td>
</tr>
<tr>
<td>Non-compliance (%)</td>
<td>14</td>
<td>27</td>
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Results from Traffic Simulation

Delay is an appropriate measure not only for traffic efficiency but also for traffic safety. Here, the definition of delay is the time that speed is under a certain speed (e.g., 2 km/h) and not above a certain speed (e.g., 5 km/h). In particular, when some drivers experienced delays near railway crossings, they tended to change their driving behavior in three possible negative ways: they crossed the railway crossing illegally, made a U-turn to find an alternative route, or lost attention to warnings. Under such conditions unsafe practices may result.
Active crossings

Train headway of 180 seconds only is explained as an example of a peak time. Other cases, for example, headway of 300 and 420 seconds were also simulated and showed a similar pattern to the headway of 180 seconds. Base, ITS1 and ITS3 showed similar results in all measures including delay, stopped delay, the number of stops, and average speed for the tested route. ITS2 had less traffic efficiency by showing a little more delay and a number of stops. This resulted in a lower average course speed.

As shown in the FIGURE 6(a), average delays for different devices were similar although there was a marginal difference for ITS2. When traffic volume increased from 800 veh/h to 1,500 veh/hr, average delays for all devices linearly increased by approximately 35% at a headway of 180 seconds. However, when the train headway decreased (to 300 seconds) the increase in delay was less. This graph shows that when trains run every 300 seconds, there is an approximate 20% delay increase between traffic volume of 800 veh/h and 1,500 veh/h.

The FIGURE 6(b) shows the distributions of average delay time for all cases at headway of 180 seconds and traffic volume of 1,000 veh/hr. In this particular case, the base and ITS3 crossings have a similar distribution whereas ITS2 is located more to the left and ITS3 is located more to the right. All crossings are scattered in a range of about 4 to 8 seconds.

The FIGURE 6(c) shows the number of stops that vehicle traffic has encountered when it has crossed the railway crossing. Unlike delay, the number of stops increases exponentially with traffic volume. Once the leading vehicle stops in order to obey traffic regulations the following vehicles also have to stop. As vehicle volume increased, the number of ‘stop and go’ situations increased.
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![Graph showing average delay per vehicle and distribution of average delay for each device at 1,000 veh/hr, and number of stops (bottom).]

**FIGURE 6** (A) Average delay per vehicle (sec), (B) Distribution of average delay for each device at 1,000 veh/hr, (C) Number of stops (bottom).

**Passive crossings**

The conditions for passive crossings were different from active crossings. In real situations, passive crossings are operated in areas of low traffic volume and low train headway. This study has replicated as close as possible to what happens in real life. In this study, simulation runs were performed for 17 trains passing per day (10 hours of operation) at different times against traffic flows of 200, 250, and 300 veh/hr. Unlike active crossings, average delays for ITS devices were less than without ITS devices as shown in **FIGURE 7**. As traffic volume was very low, delay was also low compared with active crossings.
As traffic volume and train headway is very low, the average number of stops per vehicle and average stopped delay per vehicle are close to 0. However, average speed at the passive crossings ranged from 52 to 56 km/h across different traffic volumes for each ITS intervention. On the other hand, average speed at the active crossings ranged from 44 to 48 km/h. It was noticed that ITS devices had a positive impact on passive crossings more than on active crossings in terms of traffic performance.

**DISCUSSION**

Three different ITS interventions were tested in a driving simulator: a visual in-vehicle ITS, an audio in-vehicle ITS, and an on-road marker system. The results indicated that driver behavior was more influenced by passive crossings with ITS intervention than active crossings. In general, when a train was approaching, the drivers slowed down more at passive crossings than at active crossings. Large speed differences between devices were obvious at passive crossings while they were steady at active crossings. This indicates that drivers were more influenced by the different warnings at passive crossings than at active crossings. When a comparison was conducted among ITS devices, the speed profile of drivers toward ITS devices showed less deviation than base case. This suggests that the crossings controlled by ITS devices led drivers to a more consistent driving behavior.

Both the visual in-vehicle ITS and the on-road markers ITS produced similar compliance rates at passive crossings. All ITS devices increased compliance rates when a train was approaching these crossings. However, as compliance rates at active crossings without ITS devices were already 100%, nothing further could be shown.

The results obtained from the traffic simulation for the urban region indicated that railway crossings equipped with ITS devices did not lead to significant changes for most traffic performance indicators at active crossings. Railway crossings using ITS2 (audio) had slightly increased delay and number of stops; and decreased average speeds when compared to other cases. These results clearly show that implementing ITS devices does not have a great impact on traffic performance as all indicators were similar to the crossings without ITS devices.

The results of traffic simulation for the sub-urban region with low traffic volumes, low train headway, and where passive crossings are normally implemented showed that the ITS devices improved the traffic performance with less delay time, lower number of stops as well as a higher compliance rate.
CONCLUSIONS AND RECOMMENDATIONS

The research reported different aims to investigate the effects of three ITSs at level crossings. They included both in-vehicle (smart phone) and road-side warning, and protection systems. Driving simulator data have been integrated with traffic simulation in order to assess whether ITS can improve safety and efficiency at railway crossings.

Statistical models using historical data generally consider the occurrence of accidents between vehicles and a train. However, traffic simulation is able to quantify the impacts at a network level and allows mimicking not only of how a lead vehicle responds to warnings, but also what happens to the vehicles following it.

The safety outcomes for ITS systems have been compared with those for current safety systems (passive and active) at railway crossings. The outputs of the driving simulator experiments have been a critical input for traffic simulation. The latter has been used to simulate realistic driving scenarios.

In conclusion, the transportation simulation results showed positive impacts of introducing ITS as a complementary system at railway crossings to ensure a better safety outcome for users at both active and passive crossings.

This research can be further improved by doing more driving simulator experiments in order to verify the results of speed profiles and compliance rates. As the number of participants was low compared to the entire population, not all age groups or genders were equally represented. Therefore, a few demographic categories were assumed by using data from a neighboring group. If more data for these under-represented groups are collected in the future, the results can be applied more confidently to the population. Furthermore, alternatively, a binary logistic model based on demographic information and the type of crossings can be used to decide whether drivers tend to go through or stop when they are required to stop.

This research provided a promising methodology of using a driving simulator and traffic simulation to evaluate railway crossing safety and efficiency. The ITS solutions tested in this research were similar to the types considered by the Australian rail industry to complement current safeguards. Also, a network performance influenced by those driving behaviors was calculated by the modified traffic simulation. With the usefulness of traffic simulation, various scenarios including by not limited to different traffic volumes, train headway, geography, and a proportion of transportation modes could be tested in the future.

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REFERENCE


