Evaluating Safety at Railway Level Crossings with Microsimulation Modeling

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Safety at railway level crossings (RLXs) is a worldwide issue that increasingly attracts the attention of relevant transport authorities, the rail industry, and the general public. The differences in the operation characteristics of varying types of warning devices, together with differences in crossing geometry, traffic, or train characteristics, leads to different driver behaviors at crossings. The aim of this study was to use traffic microsimulation modeling based on field video recording data to compare the safety performance of varying conventional RLX warning systems. The widely used microsimulation model VISSIM was modified to produce safety-related performance measures, namely, collision likelihood, delay, and queue length. The results showed that RLXs with an active warning system were safer than those with a passive sign by at least 17%. Integration of surrogate measures in conjunction with traffic simulation models determined which safety approach was more efficient for specified traffic and train volumes.

Railway level crossings (RLXs) present serious potential conflicts between road vehicles and trains that can produce severe traffic outcomes. Safety at RLXs is a worldwide issue that increasingly attracts the attention of transport authorities, the rail industry, and the general public. More than 2,000 accidents occurred at active and passive railway crossings in the United States each year from 2006 through 2010 (*1*). Each year, hundreds of people across Europe die in accidents at level crossings; these deaths account for one-third of all rail fatalities and 1% to 2% of all road deaths (*2*). In Australia (excluding New South Wales), 366 fatalities and 909 serious personal injuries resulted from 654 road vehicle collisions at RLXs between 2001 and 2009 (*3*).

Like many countries, Australia has seen an improvement in terms of safety at RLXs as active or automated systems have replaced passive warning systems (*4, 5*). Studies show that driver behavior responses are different at RLXs with different control devices (*6, 7*). Active or automated systems promote safer driver behavior. However, upgrading conventional active warning systems at RLXs is costly, especially in regional areas where train frequency and roadway traffic volumes are low. Furthermore, vehicle collisions at crossings are reported to be mainly attributed to driver behavior (i.e., noncompliance) in response to the warning device (*8*). Therefore, evaluating the safety of different types of warning systems at RLXs is of importance.

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This paper evaluates and compares the safety performance of the various existing RLX warning systems. Traffic microsimulation modeling was used to collect field data from the selected sites. The use of microsimulation with surrogate measures provides an enhanced way to conduct safety evaluation without risk. The use of traffic simulation for safety assessment usually confronts some difficulties, because traffic simulation assumes, based on car-following theory, that each vehicle has a gap in terms of distance. Some adjustments have been implemented to overcome this issue. This study includes three indicators to evaluate safety: the potential number of conflicts, delay, and queue length. The paper is structured as follows. The section on past work critically reviews traffic conflict techniques in traffic microsimulation modeling; the section on the development of the simulation model provides a brief description of the procedure and results of the field data collection (as input for model development in the next section); and the section on simulation results sets out the model development steps to present and compare the results. The final section concludes with the main findings.

PAST WORK

Safety-Related Issues

Accident data are traditionally gathered through police records. Safety assessments of traffic systems are usually analyzed on the basis of particular police-reported historical accident data. Therefore, safety assessments are usually reactive. However, it is unreasonable to wait for a large enough sample size (accidents) to occur before traffic systems can be evaluated, especially at RLXs, where police-reported historical records may not be sufficient for analysis either quantitatively or qualitatively (collisions at RLXs are rare but catastrophic). To address these constraints, traffic conflict techniques provide the possibility of modeling driver variation and proactive measurements.

The concept of traffic conflicts was first proposed by Perkins and Harris as an alternative to accident data, in relation to evasive maneuvers taken by drivers (*9*). In the early studies, an assumption that the conflicts must exist before crashes occurred was widely accepted to define the conflicts. However, in many cases, the accuracy of this assumption was doubtful (*10, 11*). At the First Workshop on Traffic Conflicts, an enhanced definition was suggested and agreed upon. Thereafter, the internationally accepted definition of a traffic conflict became (and remains) "an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged" (*12*). This alternative definition has been adopted in a number of safety studies (*13–17*). Sayed and Zein developed predictive models that use linear regression analysis to relate the number of traffic conflicts to traffic volume and accidents (*18*). Sayed et al. related the traffic conflict technique to traffic microsimulation for safety assessment at unsignalized intersections (*19*). Archer regarded the traffic conflict technique as the most developed indirect measure of traffic safety (*20*).

Speed, as one of the fundamental characteristics of traffic flow, is commonly used to measure traffic performance on highway systems. It is also used as an indication of level of service in accident analysis, and in economic studies (*21*). Anderson and Krammes, in their research analyzing the statistical relationship between mean accident rate and mean speed reduction, suggested that estimated speed reduction is a useful measure that helps explain how an accident experience at horizontal curves on rural two-lane highways varies with the degree of curvature (*22*). Noncompliance refers to nonadherence to the traffic rules or traffic control devices (i.e., running a red light, not stopping at a stop sign, etc.). A study by Abraham et al. tested the relationship between driver violations and RLX collisions (*23*). It revealed the potential of using violation data to determine the relative hazardousness of highway–rail crossings in combination with crash histories. The violation data may also be used to develop countermeasures that would help alleviate violations and eventually traffic collision problems at RLXs. Lee emphasized that delay was one of the prime indications for evaluating RLXs because the crossings might create excessive delays for road traffic and therefore possible violations (*24*). He concluded that a more detailed analysis had to be performed if the average delay exceeded a certain level.

Application of Traffic Microsimulation in Evaluation of Safety Measures

Traffic microsimulation models play a pivotal role in assessing current traffic conditions and then analyzing, assessing, and evaluating traffic problems. They allow alternative traffic operation systems to be tested in a simulated environment without physical interruption of existing traffic networks. This approach provides a platform for a performance comparison of varying solutions for decision making. It is a cost-effective approach for accessing implications of alternative traffic systems.

The use of traffic microsimulation for safety assessment usually encounters some difficulties because the microsimulation assumes that all road users drive their vehicles in a safe manner. Most of the commercially available microsimulation models are designed to evaluate traffic efficiency rather than traffic safety. Safety-related behavior assumptions in most of the traffic microsimulation models are tailored to represent rule-adherent drivers, which may not replicate real-world situations (e.g., speeding or red light running).

Therefore, traffic microsimulation models have a number of restrictions for traffic safety analyses. This limitation is mainly attributed to the high degree of variance in driver perception, reaction, and driving behavior and errors. These variations in human factors create potential conflicts such as incidents, near misses, and collisions. In addition, traffic microsimulation models are designed to avoid an occurrence of traffic collisions. In other words, all the driver–vehicle units in the traffic microsimulation will comply with traffic regulations (preset traffic microsimulation rules). However, this simulated situation does not exist in reality. For instance, not all motorists adhere to traffic control devices at RLXs (*6*).

As pointed out by Archer and Kosonen, the relatively strict deterministic rule base that governs this type of simplified driver behavior must be loosened to allow for a realistic amount of behavioral variance and a possibility for errors to occur (*25*). These limitations have been addressed by some researchers (*14, 20, 26, 27*). Gettman and Head evaluated important parameters in characteristics against commercially available traffic microsimulation models (*28*). All of the reviewed models required some level of modification, upgrade, or enhancement to support the derivation of surrogate safety measures. It does not appear possible to obtain surrogate measures from any of the reviewed traffic microsimulation models without some internal modifications to either the application programming interfaces or the source code modules themselves.

Despite the limitations, the traffic microsimulation approach is recommended for safety assessment because it has several advantages:

- It allows a hazardous circumstance to be explored safely. It is difficult to conduct field research on the likelihood of a crash, because such research may endanger lives or interrupt traffic operations.
- The output obtained should be reliable if calibration of the simulation is done logically.
- It enables users to evaluate a result with a relatively small amount of time and money.
- It enables users to evaluate a benefit before a safety system is implemented.
- Many different scenarios can be tested.

Several approaches to traffic safety issues in traffic microsimulation have appeared in recent years. Although a significant number of studies have focused on road safety, none have involved RLXs (intersection collisions). Through the use of railway crossings as case studies, this paper attempts to apply a traffic conflict technique to traffic microsimulation. Three surrogate safety measures are adopted: compliance, delay, and queue length.

DEVELOPMENT OF SIMULATION MODEL

General Approach

VISSIM was selected as a traffic microsimulation tool for this study. It is a widely used software package for microscopic multimodal traffic flow simulation that was developed in Germany. The general form of the car-following model is based on the psychophysical driver behavior model developed by Wiedemann and Reiter (*29*). The basic concept of this model is that a faster-driving vehicle reduces its speed to that of a slower-driving vehicle as a driver's perception threshold is reached. The faster-driving vehicle decreases speed below the slower-driving vehicle until it can reaccelerate after the event. This iterative procedure remains until the simulation is finished (*30*).

In this study, a component object model interface developed in Visual Basic was integrated with VISSIM 5.3. VISSIM has been modified to produce safety measurements at RLXs with varying warning devices. Field data collected from three RLXs near Brisbane, Australia, were input to the model. The procedures of field data collection and the results are discussed in the next subsection. The outline of the model development is shown in Figure 1.

Model development involved two components: compliance (probability of stopping) and speed profile. The probability of stopping in this study was defined as the rate of driver compliance with the warning devices at RLXs. This component indicates whether or not drivers proceed across crossings when warnings are activated.

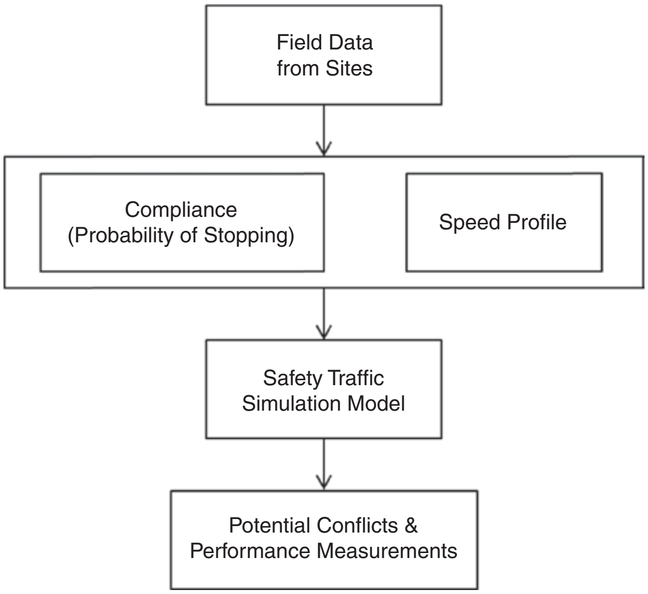

FIGURE 1 Outline of model development procedure.

In VISSIM, this is a part of the signal control function under the driving-behavior parameter sets. Speed profiles that were collected from the field data were used. These two analyzed components were the main factors that contributed to the development of the simulation model. A detailed explanation about these components is given in the following paragraphs.

Field Data Collection

Data were collected with a portable traffic surveillance camera. The selected study sites were carefully investigated so that the installed camera would be hidden from the view of the drivers, because their knowledge of the device could affect their driving behavior. The camera was erected near the crossing area to capture the operation of the warning devices as well as a roadway section of more than 200 m from the stop line. Once the recording process started, distance was measured. Steel plates painted in white were placed at 20-m intervals from the stop line (referred to as 0 m) to 200 m on both sides of the road.

Video footage was captured under normal daylight conditions from 6:00 a.m. to 5:30 p.m. at 25 video frames per second. Data were collected for all vehicle types, including passenger vehicles, trucks, and buses. From field observation during site selection trips, an approaching distance of 200 m was determined to be sufficient for drivers of all vehicle types to react appropriately to the warning devices. Because the major traffic composition at all three study sites was mainly passenger vehicles, data were not grouped into vehicle types.

The primary data retrieved were stopping compliance (violation) and approaching speed profile (*7*). The results summarized in Table 1 were input to the modified VISSIM model; Site 1 has a stop sign, Site 2 has flashing lights only, and Site 3 has a boom barrier with flashing lights. The data input included the stopping-compliance rate, the average speed recorded at the last two intervals (0 to 20 m and 20 to 40 m) of road section approaching an RLX, and the standard deviation of the averaged speed.

Driver stopping compliance is defined as total adherence to traffic rules. For instance, crossings with stop signs require a motorist to stop completely to look for the presence of a train in both directions. Similarly, motorists should stop when an active control system is activated by an approaching train. For Site 1, vehicles that did stop in front of the stop line were regarded as compliant; other movements such as slowing down and driving through were categorized as noncompliant. For Sites 2 and 3, stopping compliance was measured as soon as the warning devices were activated. The two reactions were categorized as stopped (compliance) or drove through (noncompliance). The observations show that the compliance rate at the passive crossing with stop sign (Site 1) was 41%, which is considerably lower than that at the two active crossings (70% at Site 2; 77% at Site 3). The compliance rate at Site 3 was slightly higher than that at Site 2. Similar results have been reported by various studies (*31–33*), although Abraham et al. found that drivers tended to commit more violations at the gated level crossings than they did at those that had only flashing lights (*23*). These differences exist as a result of different localized site conditions, driver behavior, and environmental conditions.

TABLE 1 Field Results for VISSIM Model Development

Input Datum	Site 3	Site 2	Site 1
Compliance rate (%)	77	70	41
Average speed (km/h)			
0–20 m	24.7	27.2	16.3
20–40 m	34.5	33.8	38.4
Standard deviation (km/h)			
0–20 m	18.9	19.9	6.4
20–40 m	16.2	11.3	9.6

Probability of Stopping (Driver Compliance)

At a crossing equipped with flashing lights only or with boom barrier with flashing lights, drivers tended to drive as if they were driving through a road intersection with an amber (yellow) signal. Although some drivers were willing to comply with flashing lights or boom gates, others were not patient enough to wait until a train passed the RLX. Because drivers make a decision either to go or stop, a probability model in VISSIM was used to replicate the stopping-compliance rate, as shown in Table 1. The probability model, p, is given by Equations 1 and 2:

$$p = \frac{1}{1 + \exp^{-ui}} \quad (1)$$

$$ui = \alpha + \beta_1 v + \beta_2 \mathrm{dx} \quad (2)$$

where

v = speed,
dx = distance, and
α, β_1, and β_2 = constants.

In VISSIM, speed and distance are variables used as a function of the probability of stopping at road intersections. In the study reported here, speed and distance were ignored (β_1, $\beta_2 = 0$) and α was replaced with the actual compliance rate from the field results because a major factor in this study is how warning systems themselves affect driving behavior. As the compliance rate of the RLX with flashing lights, boom barrier with flashing lights, and stop signs is 70%, 77%, and 41%, α becomes 0.8, 1.1, and –0.4, respectively.

Safety Simulation Model

The signal control function in VISSIM has been modified to simulate a violation, which allows output of numbers of likelihood of collision. The developed simulation model contains train tracks, roads, types of vehicles, detectors, and signal controls as shown in Figure 2. Train tracks run east and west in both directions; roads intersect these train tracks in a vertical direction. In this study, the simulation model was designed for an area where trains run relatively less frequently (a suburban area at off-peak times). Trains arrived every 30 min and vehicles were introduced to the network at 450 and 900 vehicles per hour (vph), respectively. The simulation ran for 5 h (18,000 s) with intervals of 0.1 s. Three detectors played a role in triggering a virtual signal control so that warning devices were activated accordingly.

With these data as input for a traffic microsimulation model, an example network was developed to identify how many collisions were likely to take place at the RLX equipped with a stop sign, flashing lights, or boom barrier with flashing lights. The developed model assumed the following:

- A signal head function in VISSIM was adopted as stop line at the RLX.
- Vehicles moved in each direction and were simulated every second.
- Trains ran in each direction based on headway.
- The proportion of heavy goods vehicles was 10%.
- To reduce the theoretical deviations, the Monte Carlo method was applied.

Fifteen different random seeds were repeated to decrease uncertainty.

The following procedure is shown in Figure 2:

- When a train touched Detector 1, the signal head turned amber. In reality, RLX warnings are activated to approaching vehicles. Detector 1 was placed at the location where the warning was activated approximately 30 s before the train arrived at the crossing area; this procedure is in accordance with the Association of American Railroads manual, which is followed by the Australian Rail Track Corporation (*34*).
- Vehicles then followed the rule of the probability of stopping, which is derived from the compliance rate.
- If the vehicles proceeded to touch the area called likelihood of collision, then the simulation stored the vehicle identifier, speed, and vehicle type.
- When the train touched Detector 2, the vehicles completely stopped in front of the signal head. Detector 2 was placed at the location where, for the situations with the stop sign and the flashing lights, drivers could clearly see the train approaching but the boom barrier with flashing lights prohibited vehicles once they were fully closed.
- When the train touched Detector 3, the signal head turned green, allowing vehicles access to the RLX. Detector 3 was placed at the location where warning was deactivated.

SIMULATION RESULTS

When the RLX warning was activated by the train at Detector 1, detailed outputs from the VISSIM simulation, such as vehicle coding and the vehicle's speed, updating position, and acceleration, were extracted from the likelihood of collision on second-by-second and a vehicle-by-vehicle basis. Because there is a high possibility of a conflict at that point, vehicles involved in the likelihood-of-collision instances were recorded as potential conflicts.

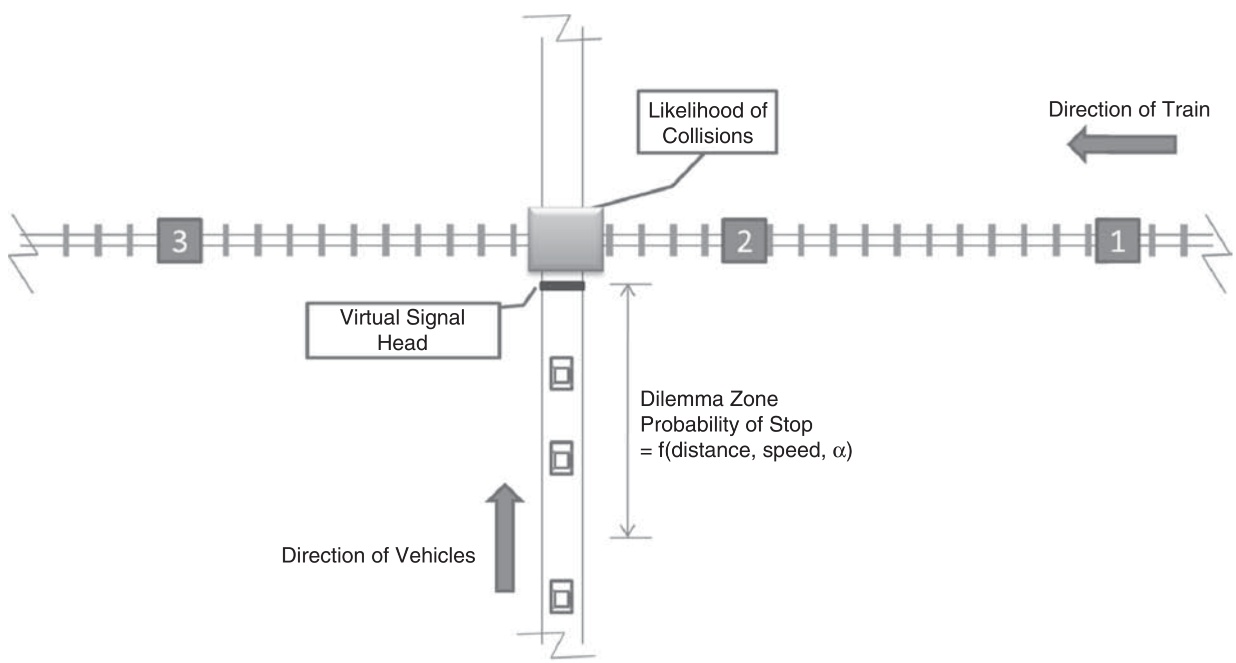

FIGURE 2 Layout of model in VISSIM.

TABLE 2 Number of Potential Conflicts

Seed	Traffic Flow of 450 vph (each direction)			Traffic Flow of 900 vph (each direction)		
	Site 3	Site 2	Site 1	Site 3	Site 2	Site 1
Run 1	10	13	37	7	13	74
Run 2	16	12	36	13	20	58
Run 3	19	21	33	11	14	38
Run 4	16	24	40	10	15	46
Run 5	15	20	41	12	17	55
Run 6	10	12	45	17	21	63
Run 7	12	15	59	13	17	55
Run 8	15	16	47	10	12	50
Run 9	9	9	39	17	18	48
Run 10	13	17	44	15	23	54
Run 11	11	18	55	9	13	43
Run 12	6	11	43	8	12	37
Run 13	6	7	30	9	10	32
Run 14	9	12	39	13	13	35
Run 15	6	10	42	14	15	34
Number of potential conflicts	12	14	42	12	16	48

Likelihood of Collision

The number of likely conflicts was compared at Sites 1 (stop sign), 2 (flashing lights), and 3 (boom barrier with flashing lights). Table 2 summarizes the results based on the number of trains and vehicles at the three RLXs. When the traffic flow was 450 vph in each direction and the train ran every 30 min, 14 potential conflicts were recorded at Site 2; in contrast, 12 potential conflicts were found at Site 3. In relative terms, there were 17% fewer potential conflicts at the crossing with a boom barrier with flashing lights than at the crossing with flashing lights only. When the traffic flow was increased to 900 vph in each direction, the potential conflicts recorded at Site 2 increased to 16, but the potential conflicts remained at 12 at Site 3. The results also show that Site 3 and Site 2 were safer than Site 1 by 300% and 350% to 400%, respectively.

As expected, the crossing equipped with the boom barrier with flashing lights (Site 3) had the least number of potential conflicts. When compared with the crossing with flashing lights only (Site 2), the difference was very small, but the crossing with the flashing lights had a high potential for conflicts. A comparison between different traffic volumes did not show significant relationships between warning systems. This is mainly because potential conflicts would occur for the first car approaching. If the first car stopped, then the cars following it had to stop behind it.

Delay and Queue Length

Delay and queue length are appropriate measures not only of traffic efficiency but also of traffic safety. Here, the definition of delay is the time a vehicle is stopped or its speed is reduced below a certain speed (e.g., 2 km/h) and does not exceed a certain speed (e.g., 5 km/h). When some drivers experience delays to some extent near railway crossings, they tend to change their driving behavior. They may cross the crossing illegally, make a U-turn to find an alternative route, or lose attention to proximity. Under such conditions, unsafe practices may result. As shown in Table 3, Sites 2 (flashing lights only) and 3 (boom barrier with flashing lights) show similar results on all measures. A comparison between Site 3 and Site 1 at 450 vph in each direction shows that Site 3 has 9% less total delay,

TABLE 3 Output for Delay and Queue Length

Variable	Traffic Flow of 450 vph (each direction)			Traffic Flow of 900 vph (each direction)		
	Site 3	Site 2	Site 1	Site 3	Site 2	Site 1
Total delay (h)	8.2	8.1	8.9	47.2	47.0	57.0
Total stopped delay (h)	1.2	1.2	0.8	4.0	3.9	3.1
Average queue length (m)	7.9	7.7	5.6	40.8	40.3	31.6
Number of stops	222	218	168	707	701	595
Total vehicles for 5 h	4,525	4,525	4,529	9,005	9,005	9,010

33% more total stopped delay, 29% more queue length, and 24% more vehicle stops than does Site 1. This result means that although stop signs lead to more delay, the flashing lights and the boom barrier with flashing lights caused more stopped delay, longer queue length, and more stops.

One of the advantages of using traffic microsimulation is that the results can be used to identify traffic phenomena for each specific time interval. This helps researchers focus on critical indicators. In this study, a time interval was set for every 30 min over 5 h. Figure 3*a* shows that the average queue length for Sites 2 and 3 was identical for every time interval of 450 vph in each direction. Figure 3*b* shows the average total delay that each vehicle experienced every 30 min. Each vehicle that neared the boom barrier with flashing lights and the flashing lights only experienced a delay from 33 to 40 s, but the delay was from 36 to 45 s at the stop sign. Figure 3*c* shows the way in which the number of stops changed over the 30-min period. Comparable results were obtained when the traffic flow was increased to 900 vph.

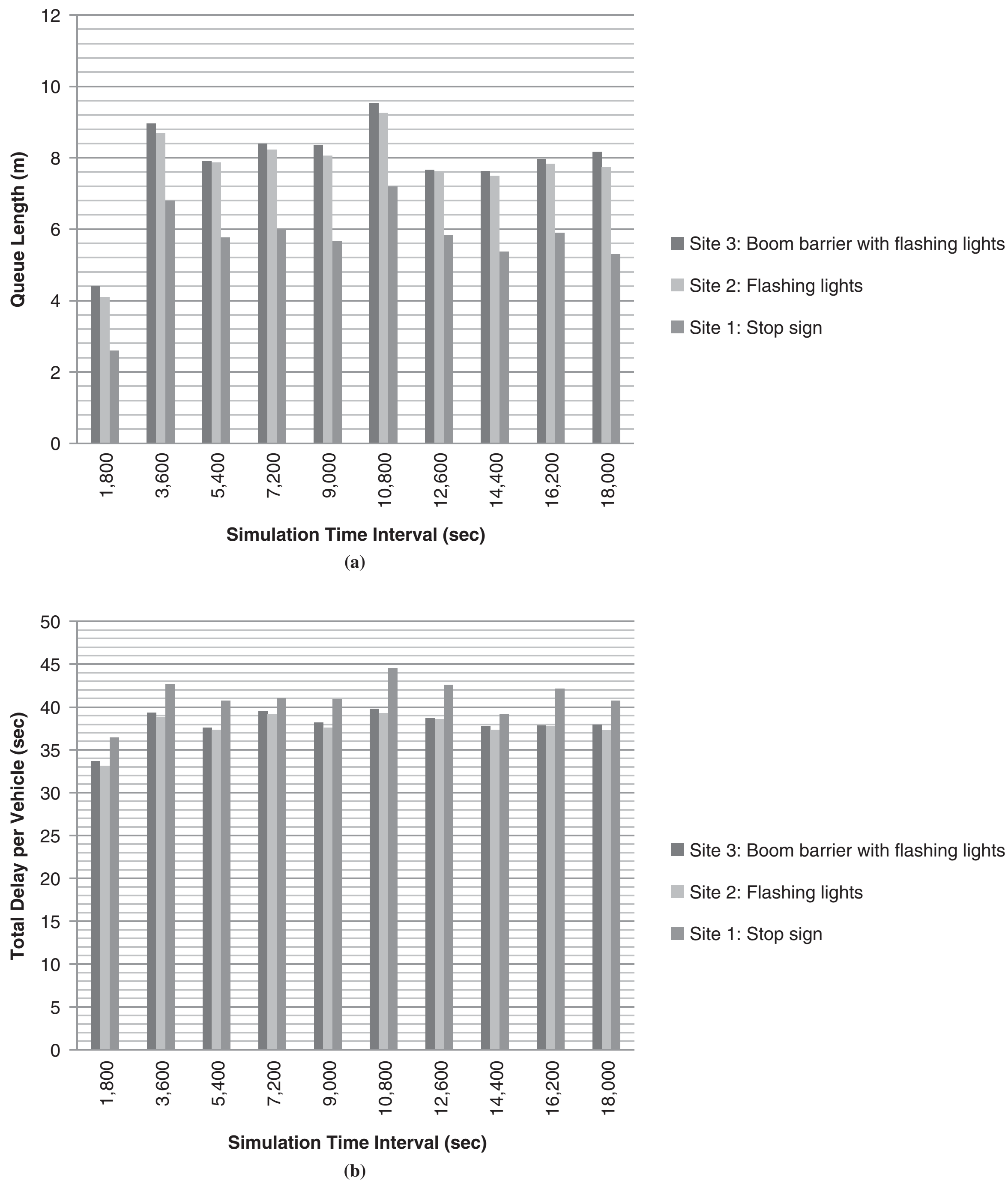

FIGURE 3 Results of 450-vph testing in each direction: (*a*) average queue length and (*b*) average total delay per vehicle.

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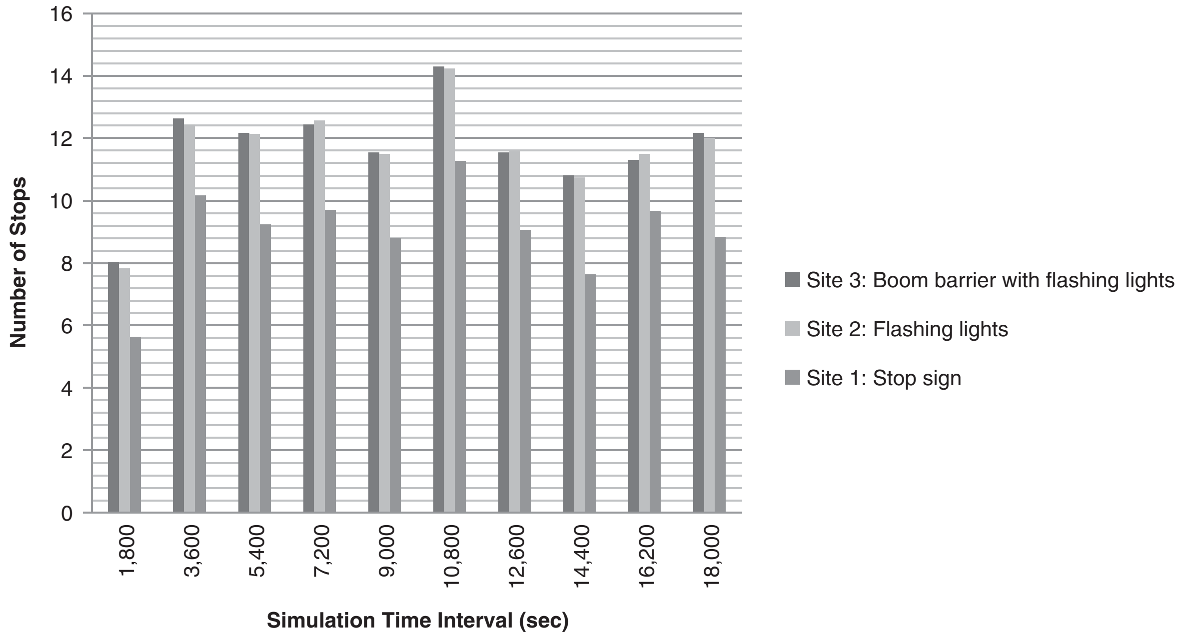

(c)

FIGURE 3 *(continued)* **Results of 450-vph testing in each direction: (*c*) number of stops.**

CONCLUSIONS

Much research has been conducted on safety at road intersections. This paper shows that with the integration of surrogate safety measures and commercially available traffic simulation software, microsimulation can be used to evaluate RLXs with different types of warning devices. By incorporating actual field violation data in the model, the number of likely collisions for different warning devices was estimated. This microsimulation tool will assist in determining which safety approach is most efficient for specified traffic and train volumes. This application can be extended to assess issues of traffic queue backup over crossing from an adjacent intersection located downstream, and varying countermeasures can be evaluated. By integration with a driving simulator, this approach can be applied to evaluate and compare the safety performance of alternative warning devices such as rumble strips and in-vehicle audio warnings.

Some limitations have to be overcome in further research for a better understanding of railway safety. Occurrences of vehicle and train conflicts at RLXs are low compared with road intersection conflicts, so there is not enough data from which to draw definite conclusions. The characteristics of RLX and road intersections are different in terms of traffic volume, posted speed, and environmental setting. Another shortcoming of the study reported here is that the speed profiles were obtained from only three sites, and therefore cannot be generalized across other environments. Although other vehicle types such as trucks may possibly exhibit different vehicle and driver characteristics, traffic compositions other than passenger cars in the field were not considered in view of the nonsignificant volume. In general, it is thought that further refinements of the method are worthwhile. For improved calibration purposes, other VISSIM input parameters such as perception–reaction time, car-following characteristics, and deceleration distribution should be investigated in the field. Nevertheless, the following conclusions can be drawn from this study:

- Traffic microsimulation can be used with some modifications to evaluate RLX safety.
- The difference found in terms of a number of potential conflicts at RLXs with boom barriers with flashing lights and those with flashing lights only is relatively small, because main inputs such as speed and compliance rates measured in the field are similar for these two warning devices.
- The number of potential conflicts at stop signs is significantly higher than it is for other warning systems.
- Although delay at stop signs is higher than it is for other treatments, the total stopped delay is lower. This phenomenon implies that drivers tend to slow down but not completely stop near RLXs equipped with stop signs.
- As the stopped delay is low, the queue length is also shorter at stop signs.

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