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Research Article

Active Warning System for Highway-Rail Grade Crossings Using Connected Vehicle Technologies

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Highway-rail grade crossing (HRGC) collisions are a significant safety concern around the world. HRGC collisions have a high risk of injuries and fatalities. To mitigate that risk, safety countermeasures for both active and passive HRGCs have been implemented. Leveraging the latest developments in connected vehicle (CV) technologies, CV-based warning systems perform well in safety applications for roadway networks. However, few have been developed to focus on safety improvements specifically for HRGCs. To bridge this gap, this paper proposes a novel active warning system that was created with readily available CV technologies and devices. A crossing risk assessment model was developed and evaluated in simulation and field applications. The proposed model predicts the crossing risk probabilities in the near future. When road users are in great risk of a collision, the warning system sends out auditory and visual alerts and displays the estimated waiting time. The test results reveal that the proposed warning system is promising for field implementation to improve safety at grade crossings.

1. Introduction

Highway-rail grade crossing (HRGC) collisions are a primary concern for railway authorities and the public at large. The Canadian Transportation Safety Board [1] reported that more than 240 fatalities and 260 serious injuries took place in Canada as a result of grade-crossing collisions over the past decade. Grade crossings can be classified as active HRGCs or passive HRGCs. Usually, more incidents, injuries, and fatalities occur at active HRGCs than in passive HRGCs. Active HRGC incidents are mainly caused by drivers violating or ignoring the control devices meant to keep them safe as trains arrive at the crossing [2]. Thus, safety measures at active HRGCs, such as signals and automatic gates, have been meticulously investigated [3–12] from which safety risk countermeasures have been implemented to provide dynamic train information to drivers and pedestrians.

In recent years, the emergence of connected vehicle (CV) technologies has enabled vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), and vehicle-to-pedestrian (V2P) communication applications. In mitigating the risk of grade-crossing collisions, CV-based active warning systems have shown great promise because they incorporate the latest advances in CV technologies. CV-based active warning systems apply CV technologies to remind crossing road users of the right-of-way on railroads. It warns road users to stop for crossing or approaching trains regardless of whether the safety devices installed at the crossing are passive or active.

Previous research has validated the use of CV technologies in various safety applications [2, 9, 10, 12–16]; however, few studies have focused on CV-based applications in rail safety management. There is a significant need to design and evaluate CV-based warning systems at grade crossings in a multimodal user environment. Therefore, the primary focus of this study was to develop and evaluate an active warning system for grade crossings. The proposed active warning system is promising in real-world applications to reduce grade crossing incidents.

The remainder of this paper is organized into sections: the next section reviews the existing conventional and advanced warning applications to improve grade crossing safety; the Methodology section describes the system framework, probabilistic kinematic model, and crossing risk assessment method; the Case Study section presents the simulation and

field test results of the proposed active warning system; and the last section discusses the concluding remarks and suggests future work.

2. Literature Review

Signs are the first line of defense but also the most marginal measure in terms of warning devices that prevent HRGC violations and collisions. Regulated by Transport Canada [17], the installation of grade crossing signs is mandatory in Canada. A STOP AHEAD sign or a YIELD sign must be installed along with a warning sign to enhance safety. However, these signs provide no information on the actual presence of a train to vehicle drivers and pedestrians.

Additional devices, such as obstacle detectors, signals, law enforcement cameras, and horn systems, have been implemented to provide real-time warning of the presence of trains. Existing studies [3–8] have confirmed that these devices improve safety performance at HRGCs. Unfortunately, a communication failure between control devices and road users often causes collisions at passive grade crossings. Thus, many studies have been devoted to enhancing communication by updating control devices. Noyce and Fambro [3] installed a vehicle-activated strobe light and a supplemental sign. The sign tells drivers the desired action at grade crossings. The before-and-after tests showed that the enhanced sign system increased drivers' caution at grade crossings. Similarly, Gent et al. [4] implemented an automated-horn system to alert road users at crossings. Two horns were mounted at a crossing and activated using the track-signal circuitry for the gate arms and bells. The system proved to be less annoying for nearby residents and slightly safer from the locomotive drivers' perspective than the previously installed measures. Moreover, Gilleran [5] discussed the use of presignals at grade crossings. The author found that proper implementation of presignals effectively prevents vehicles from crossing the track area when trains are approaching. To compare the effectiveness of different warning control devices, Hu and Lin [6] conducted a before-and-after study using 15-year data. They found that both the LED approaching train indicator and the law enforcement camera are more effective than obstacle detectors in reducing collisions and improving safety. In addition, other studies attempted to enhance the operational policy of control devices. For example, Moon and Coleman [7] presented an operating policy for a four-quadrant gate, which determines a dynamic dilemma zone and gate operation parameters to reduce grade crossing collisions. Likewise, Siques [8] defined the four phases of pedestrian behaviours at crossings: Pedestrians must (1) be aware of the crossing; (2) take the appropriate path; (3) be aware of an approaching train; and (4) understand potential hazards. Siques then proposed amelioration measures, including passive signs, pedestrian channelization and gates, audio warnings, and public education.

Advanced driver or pedestrian assistance systems improve traffic safety from the road users' perspective. Alerting drivers through in-vehicle systems was proposed as early as 1975 [18]. Since then, several tests have been conducted for in-vehicle warning systems, in which trains send signals to alert vehicles within the radio range [19, 20]. However, these systems lacked vehicle-to-train communication, and they were not in control of drivers' dangerous crossing behaviours. Thus, Hartong et al. [9] integrated positive train control systems with vehicular ad-hoc networks to fulfill their communication. To avoid HRGC incidents, they provided integration architectures and identified protocols. Following this, several studies focused on different aspects of grade crossing warning based on wireless communication. To evaluate the feasibility of wireless communication, Ku [10] established a detecting and warning system. The system shows grade crossings in real-time video to the train drivers through an onboard unit and alerts road users about the train's distance through a roadside unit. These components are linked by wireless communication. Ku's subsequent field tests prove that the system is feasible, and live videos help train drivers react fast. As for auditory alerts, Landry et al. [11] conducted driving simulator experiments to investigate the effectiveness of in-vehicle auditory alert systems at grade crossings. Their experiment results show that human voices, especially female voices, are more effective than text-to-speech voices. In-vehicle auditory alerts improve driver compliance. In terms of stopping distance, Hsu and Jones [2] conducted a sensitivity analysis on stopping distance at grade crossings. Field data from two sites was used for the non-CV case while data from a driving simulator was used for the CV case. The sensitivity analysis shows that the initial speed and perception-reaction time are the most sensitive safety factors at grade crossings. Earlier onboard warning in CVs reduces the initial speed and thus improves safety at grade crossings. In addition, for signal propagation, Tedesso et al. [12] investigated the dedicated short range communications (DSRC) signal propagation conditions encountered in a railroad environment. The train-to-infrastructure communication in both clear and cluttered environments was set up. They proved that DSRC signals can handle relatively long-distance communication.

Existing studies have examined the feasibility of CV-based warning at grade crossings. When the warning system is properly designed, it addresses the non-line-of-sight problem and improves safety at grade crossings. However, throughout the related literature, few studies have been devoted to developing a risk assessment method for grade crossings and evaluating its safety performance in simulation or in the field. To bridge this research gap, this study included the development of a novel probabilistic kinematic model that replicates the motion of road users and rail trains and applies a crossing risk assessment model to evaluate crossing risk in real time. There were three objectives of this study: (1) developing an active warning system for road users at grade crossings; (2) validating the developed warning system in simulation and field tests; and (3) assessing the sensitivity of the model parameters. This paper presents the proposed system's design. The system was evaluated through simulation and field tests conducted in Edmonton, Alberta, Canada. The developed warning system is promising for field implementation to reduce collisions and improve safety at grade crossings.

3. Methodology

3.1. System Framework. Enhancing communication between railway warning systems and road users can reduce collision probability and improve overall safety at HRGCs. The main function of the proposed active warning system is to alert road users of crash-imminent situations at a grade crossing through CV technologies. The system includes a wireless connection via DSRC between roadside equipment (RSE) and onboard equipment (OBE) to activate crucial warning messages about an approaching train. The warning messages can be either visual or auditory. While the system may not prevent all crashes, it is expected that, with an effective warning system, the number of violations will decrease, which will in turn reduce the number and severity of crashes at railroad crossings.

Figure 1 illustrates the basic components, conceptual communication framework, and system framework of the proposed active warning system. On one end of the communication pathway, RSE is installed at the grade crossing and OBE is placed on trains. The basic parameters of the grade crossing and the train need to be written into the RSE and OBE in advance, respectively. On the other end of the communication pathway, road users (i.e., vehicles and pedestrians) equipped with OBE can receive grade crossing and train information in real time when they are in proximity to the grade crossing. The system evaluates the collision risk and sends out warning messages by smart devices when required.

Specifically, the RSE archives basic static information of the grade crossing and receives real-time information from any control devices. The static information includes geometric characteristics and positioning accuracy parameters for collision risk assessment. Additional information, such as real-time control device status and communication latency, can be customized in the RSE. In the meantime, the OBE obtains location information from its Global Position System (GPS) module and thus derives the approach speed and travel direction. Together with the information archived in the RSE, the system first estimates actual locations considering communication latency and user reaction behaviours. Then, the actual locations are formulated as probabilistic kinematic models to account for positioning inaccuracy. The system then assesses the collision probability through a crossing risk assessment model. Once the collision probability between a road user and a train is larger than a predetermined threshold, the warning is activated and sent to road users immediately. At the same time, the road user can also receive the estimated waiting time for the train to pass.

3.2. Probabilistic Kinematic Model of Highway-Rail Crossing System. This study included the development of a probabilistic kinematic model to assess the actual locations of trains and road users with positioning accuracy. The model was extended and modified from the one proposed by He et al. [21] and adapted to reduce grade crossing collisions. The model proposed by He et al. [21] is for vehicle-to-pedestrian system so the following extensions and modifications have been made to adapt the characteristics of highway-rail crossing system. First, the vehicle-to-pedestrian system involves the locations of pedestrians in order to prevent vehicle-pedestrian collisions. However, the highway-rail crossing warning system needs to prevent not only collisions between vehicles and rail trains but also those between vehicles and gates at grade crossings. Thus, the extended probabilistic kinematic model also involves gate operation when gates are present. Second, the walking behaviours of pedestrians are highly dynamic and hard to predict, leading to the uncertainty of pedestrian location estimation, whereas rail trains travel along rail tracks so that the location estimation of trains is more certain compared with that of pedestrians. The modified model excludes the uncertainty of behaviors, which was done in the model of the vehicle-to-pedestrian system. Third, as the motions of trains are more certain than pedestrians, the time when trains leave grade crossings is predictable. The highway-rail crossing system provides remaining waiting time for road users.

The extended model quantifies collision risk in real time in consideration of the road user's reaction behaviours, communication latency, uncertainty of positioning accuracy, and grade crossing control system. Figure 2 demonstrates the relative motion between trains and other road users. It is important to note that road users include vehicles and pedestrians. Figure 2 uses a vehicle to represent all road users. In addition, the arrows in Figure 2 only indicate the travel directions of trains and road users but their real trajectories do not have to be always straight.

A probabilistic model describes the motions shown in Figure 2. As shown in Figure 2, the train is approaching the origin $O(0,0)$. First, at time instant t_0, the initial locations of the rail train and road users are measured as $p_{r,0}(x_{r,0}, y_{r,0})$ and $p_{u,0}(x_{u,0}, y_{u,0})$. However, the delay caused by the road user's behaviours influences the positioning measurements. Additionally, data is transmitted by vehicle-to-everything (V2X) communication, which may experience communication latency thereby affecting position measurements. Hence, the actual locations of the train and road users $\overline{p}_{r,0}$ and $\overline{p}_{u,0}$ in consideration of user behaviours and communication latency are given in the equations below:

$$\overline{x}_{r,0} = x_{r,0} - v_{r,x,0}\left(t_{prt} + t_{cl}\right) \tag{1}$$

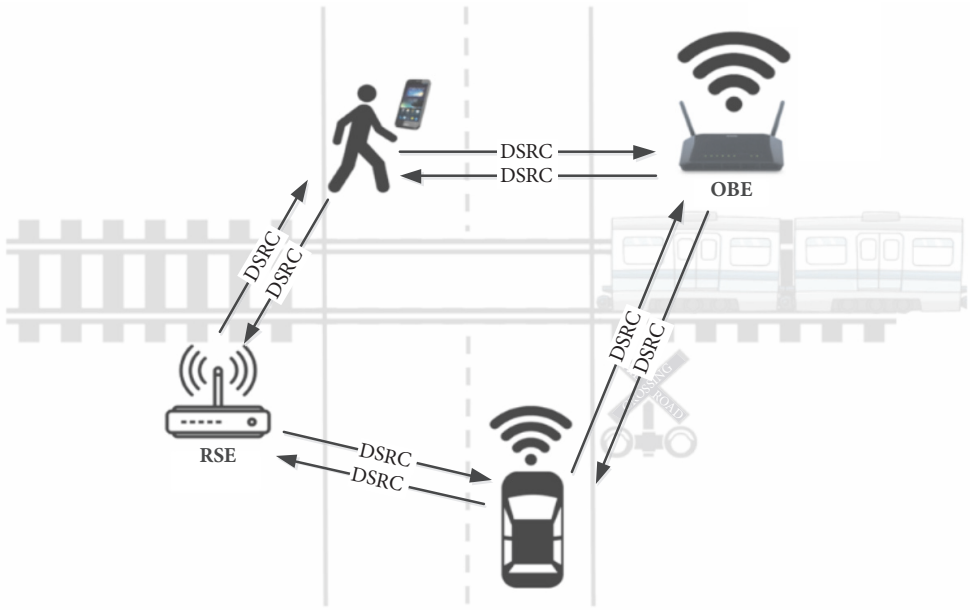
$$\overline{y}_{r,0} = y_{r,0} - v_{r,y,0}\left(t_{prt} + t_{cl}\right) \tag{2}$$

$$\overline{x}_{u,0} = x_{u,0} + v_{u,x,0}\left(t_{prt} + t_{cl}\right) \tag{3}$$

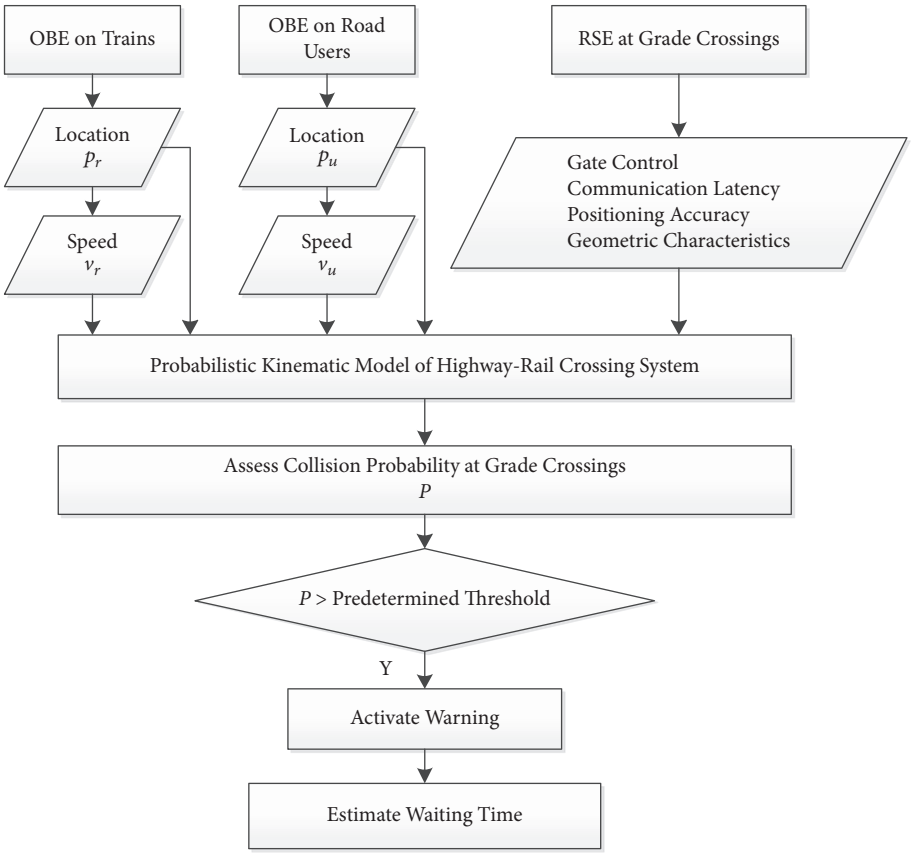
$$\overline{y}_{u,0} = y_{u,0} + v_{u,y,0}\left(t_{prt} + t_{cl}\right) \tag{4}$$

where $\overline{x}_{r,0}$, $\overline{y}_{r,0}$, $\overline{x}_{u,0}$, and $\overline{y}_{u,0}$ are the actual location coordinates of the train and road user in meters (m); $x_{r,0}$, $y_{r,0}$, $x_{u,0}$, and $y_{u,0}$ are the measured location coordinates of the train and road user in m; $v_{r,x,0}$, $v_{r,y,0}$, $v_{u,x,0}$, and $v_{u,y,0}$ are the measured velocity components on x and y axes in meters per second (m/s); and t_{prt} and t_{cl} are the road user's perception-reaction time and communication latency in seconds (s), respectively.

Then, the locations of the train and road users after time period t ($p_{r,t}$ and $p_{u,t}$) can be predicted. Assuming that



(a)



(b)

Figure 1: System framework. (a) Conceptual communication framework. (b) System flowchart.

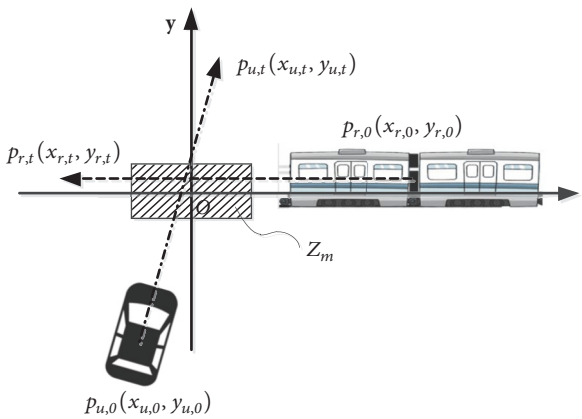


Figure 2: Kinematic model.

both the road segment and the rail track are straight, the corresponding coordinates of the train and road user at time instance t are as shown in the following equations:

$$\overline{x}_{r,t} = \overline{x}_{r,0} - v_{r,x,0}t \tag{5}$$

$$\overline{y}_{r,t} = \overline{y}_{r,0} - v_{r,y,0}t \tag{6}$$

$$\overline{x}_{u,t} = \overline{x}_{u,0} + v_{u,x,0}t \tag{7}$$

$$\overline{y}_{u,t} = \overline{y}_{u,0} + v_{u,y,0}t \tag{8}$$

However, the positioning accuracy is limited by the efficiency or inefficiency of the GPS service. Inaccuracy may result from device problems and environmental factors. Therefore, positioning uncertainty was considered in this research because the positioning accuracy plays a critical role in the active warning application. This study assumed that the actual locations of trains and road users were normally distributed: $p \sim N(\overline{p}, \delta^2)$. By this means, their probability density functions were formulated as follows:

$$f(p_{r,t}) = \frac{1}{2\pi\delta_{r,x}\delta_{r,y}} \exp\left\{-\frac{1}{2}\left[\frac{(x_r - \overline{x}_{r,t})^2}{\delta_{r,x}^2} + \frac{(y_r - \overline{y}_{r,t})^2}{\delta_{r,y}^2}\right]\right\} \tag{9}$$

$$f(p_{u,t}) = \frac{1}{2\pi\delta_{u,x}\delta_{u,y}} \exp\left\{-\frac{1}{2}\left[\frac{(x_u - \overline{x}_{u,t})^2}{\delta_{u,x}^2} + \frac{(y_u - \overline{y}_{u,t})^2}{\delta_{u,y}^2}\right]\right\} \tag{10}$$

where $f(p_{r,t})$ and $f(p_{u,t})$ are the probability density functions for the actual locations of the train and road user at time instant t, respectively; $p_r(x_r, y_r)$ and $p_u(x_u, y_u)$ are coordinates of any location along the railway track and the roadway; and $\delta_{r,x}$, $\delta_{r,y}$, $\delta_{u,x}$, and $\delta_{u,y}$ are the standard deviations of position measurements on x and y axes (in m).

3.3. Probabilistic Kinematic Model Considering Gate Operation. Transport Canada regulates that grade crossings that meet certain criteria must be equipped with a warning system with gates. The detailed criteria are listed in [17, 22]. For grade crossings with gates, the active warning system works to prevent the collision through gate operation. Thus, gate operation was also considered in the proposed model. First, road users who enter the grade crossing during the gate operation time t_g are regarded as collisions. As such, (1)–(4) were modified as follows. The locations after time period t ($p_{r,t}$ and $p_{u,t}$) are still predicted by (5)–(8):

$$\overline{x}_{r,0} = x_{r,0} - v_{r,x,0}\left(t_{prt} + t_{cl} + t_g\right) \tag{11}$$

$$\overline{y}_{r,0} = y_{r,0} - v_{r,y,0}\left(t_{prt} + t_{cl} + t_g\right) \tag{12}$$

$$\overline{x}_{u,0} = x_{u,0} + v_{u,x,0}\left(t_{prt} + t_{cl} + t_g\right) \tag{13}$$

$$\overline{y}_{u,0} = y_{u,0} + v_{u,y,0}\left(t_{prt} + t_{cl} + t_g\right) \tag{14}$$

where t_g is gate operation time ($t_g = t_d + t_i$, in s); t_d is gate delay time, which is the time between the initiation of flashing lights and entry gate descent (in s); and t_i is gate interval time, which is the time between entry and exit gate descent (in s) [7]. t_d is the necessary stopping time for vehicles to stop safely in front of the stop bar [23] and t_i is the necessary time for vehicles to completely pass the grade crossing. t_d and t_i can be determined by the following equations. For grade crossings without gate control, t_d and t_i are set zeros:

$$t_d = t_{prt} + \frac{v}{2(a + G \bullet g)} + \frac{D_{s2g}}{v} \tag{15}$$

$$t_i = \frac{D_{g2g}}{v_{cr}} \tag{16}$$

where a is the deceleration rate in meters per second^2 (m/s^2); g is the acceleration of gravity in m/s^2; G is the grade in percent/100; v is the road user's approach speed (in m/s); D_{s2g} is the distance between the stop bar and gate (in m); D_{g2g} is the distance between the entry and exit gates (in m); and v_{cr} is the critical minimum speed of a road user in the track zone (in m/s). These parameters are predetermined, while t_d and t_i can be measured from the field.

Likewise, the warning system calculates the relative distance of road users from the gates instead of the trains. Hence, in addition to the probabilities of the train and road user locations calculated in (9)-(10), the probability of the gate status is also taken into account. The gate status can be derived from the real-time train locations because the relationship between the gate operation and train arrival is fixed. As regulated by Transport Canada, gate arms must be horizontal at least five seconds before the train's arrival where trains travel faster than 25 kilometers per hour (km/h) [22]. Considering this relationship, the probability of the gate status $f(p_{g,t})$ is given as the following conditional probability:

$$f\left(p_{g,t}\right) = f\left(p_{g,t} \mid Y < 0\right) \bullet F\left(Y < 0\right) \tag{17}$$

where $Y = d_{r2g,t} - v_{r,t} \bullet T_{threshold}$; $d_{r2g,t}$ is the distance between the train and the centre of the gate zone; ($d_{r2g,t} = \|p_{r,t} - p_g\|_2$, p_g was assumed to be $O(0,0)$ in this study); $v_{r,t}$ is the approaching speed of the train at time instant t; and $T_{threshold}$ is the time gap from gate descent and train arrival, which is a fixed value from standards and guidelines.

Equation (17) can be degenerated to an equation for a no-gate grade crossing. In this case, the model assumes that a virtual gate exists. The virtual gate is equivalently open all the time and thus $f(p_{g,t}) = 1$. Consequently, the probability of the gate status in (17) in the no-gate scenario is degenerated as below:

$$f\left(p_{g,t}\right) = f\left(p_{g,t}\right) \bullet F\left(Y\right) = F\left(Y\right) \tag{18}$$

3.4. Crossing Risk Assessment. To assess the collision risk, the target roadway Z was divided into M subsegments. The width of the railroad track was W_r and road length was L, so M equaled L/W_r. Also, the width of the road user (e.g., vehicles and pedestrians) was W_u. Thus, the mth subsegment Z_m was defined as a region with $x_m^0 = -(1/2)W_u$ to $x_m^1 = (1/2)W_u$ for its x coordinates, and $y_m^0 = (m-1)W_r$ to $y_m^1 = mW_r$ for its y coordinates. The collision risk was defined as the collision probability $P_{Z_m}^{t_k}$ over Z_m at the time instant t_k ($t_k = t_0 + kt$ and k is the prediction time step) as follows:

$$P_{Z_m}^{t_k} = \int_{y_m^0}^{y_m^1} \int_{x_m^0}^{x_m^1} f\left(p_{g,t}\right) \bullet f\left(p_{v,t}\right)\Big|_{t=t_k} dx\, dy \tag{19}$$

where the double integral indicates the generic description of Z_m in the approaching rail track. The information of coordinates can be obtained from MAP data.

As mentioned in the System Framework subsection, when collision risk $P_{Z_m}^{t_k}$ at time instant t_k was larger than a predetermined threshold, a warning to road users was activated. In this study, the scenario that caused the most devastating collision was selected to calculate the collision probability P_{Z_m} in the collision moment. The threshold was determined as a certain percentage (e.g., 50%) of P_{Z_m}.

3.5. Waiting Time Estimation. When a crossing warning is activated, the active warning system also provides estimated waiting time at grade crossings. The gate arm starts to ascend after the train leaves by a safe distance, which was assumed to be $v_{r,0} \bullet T_{threshold}$. The safe point p_s is $(-v_{r,0} \bullet T_{threshold}, 0)$. After then, the time for the gate arm to ascend to vertical (T_{ascent}) must be 6 to 12 seconds, as regulated in [22]. Thus, the waiting time (T_w) was estimated as follows. Once the waiting time is estimated, the waiting time will be counted down:

$$T_w = \frac{\|p_{r,0} - p_s\|_2}{v_{r,0}} + T_{ascent} \tag{20}$$

4. Case Study

4.1. Study Site. The grade crossing at 82 Avenue and 114 Street in Edmonton, Alberta, Canada (as shown in Figure 3) was selected as the test site. This intersection is located at the south side of Health Sciences Jubilee Station. There are two light rail transit (LRT) lines running across. This location already had treatments to improve the grade crossing. Passive railway warning signs visually alert vehicle drivers and pedestrians of an imminent LRT crossing. Pedestrian paths across the tracks guide pedestrians to pass through the crossing in a safe manner. Horizontal entry gates and flashing lights prevent road users from entering the crossing when a train is in hazardous proximity. Moreover, LRT trains have the priority of the signal control to ensure safety. The tested grade crossing is close to the University of Alberta and experiences heavy traffic during AM and PM peaks. Although the treatments were well designed and well implemented, alerts for road users can still be improved in terms of the communication between the railway warning and road users to improve safety. Therefore, the proposed active warning system was applied to this grade crossing.

4.2. Simulation Results. Prior to the field tests, simulation tests were conducted by coding the collision risk assessment model in MATLAB to evaluate the model effectiveness and parameter sensitivity. It was assumed that there was no other road user in front of the target user. To simplify the computation of crossing risk, a random location, which obeyed the normal distribution of the location measurement, was assumed to be the actual location of a train or a road user. In this study, at each time instant t_0, 20 random locations were selected for each train and each vehicle, separately. The crossing risk was calculated as the average collision frequency based on the 20×20 random location combinations.

Two scenarios were tested: no-control and control. The signal and gate control were operated for the control scenario, while no controls were operated for the no-control scenario. The two scenarios were designed to show the safety performance difference resulting from traditional control treatments. Three specific cases were simulated for one-parameter sensitivity analysis: Case 1 varied the road user's initial speed and fixed the other parameters; Case 2 varied the vehicle's initial locations and fixed the other parameters; Case 3 changed the communication latency only but fixed the other parameters; and Case 4 changed the standard deviations of GPS position measurements while other parameters were fixed. Table 1 lists the model parameter values used in the

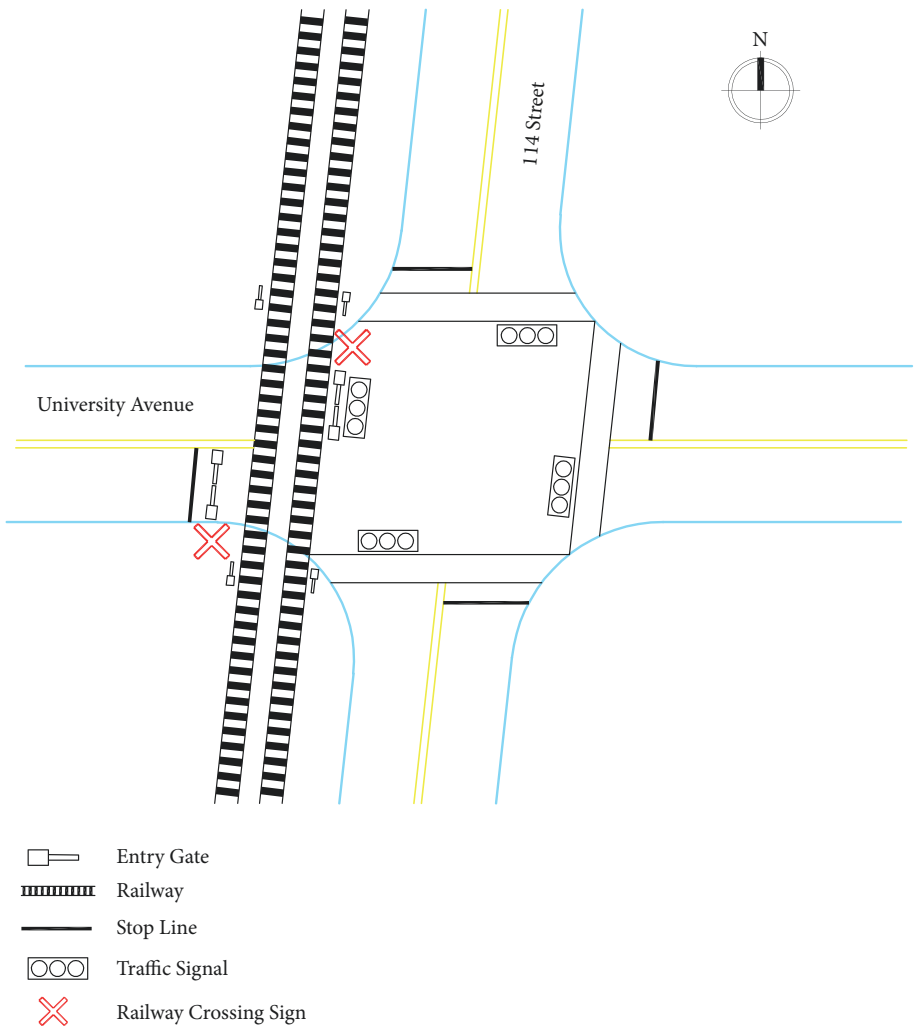


Figure 3: Study site.

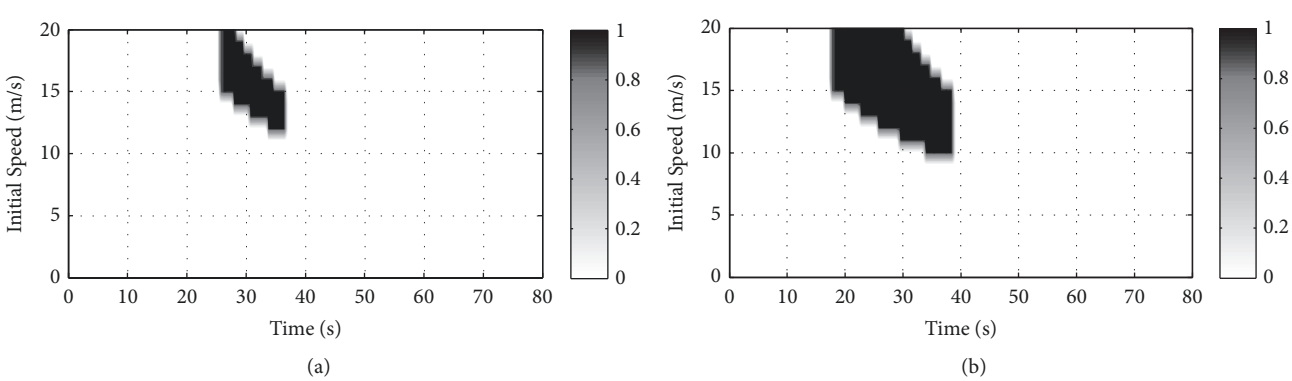


Figure 4: Crossing risk probability for different initial road user speeds. (a) No-control scenario. (b) Control scenario.

simulation. The three cases show how the crossing risk varies for road users in different conditions.

Figures 4–7 show the simulation results for the three cases, respectively. Throughout the contour maps, the high-risk areas in parts (a) in all figures are the collisions with the train, while those in parts (b) are the collisions with the gate. Obviously, the high-risk areas in parts (a) are all larger than those in parts (b). These results show that the traditional control equipment at the grade crossing can keep road users away from trains. In this way, the traditional control equipment effectively reduces collision frequency and severity.

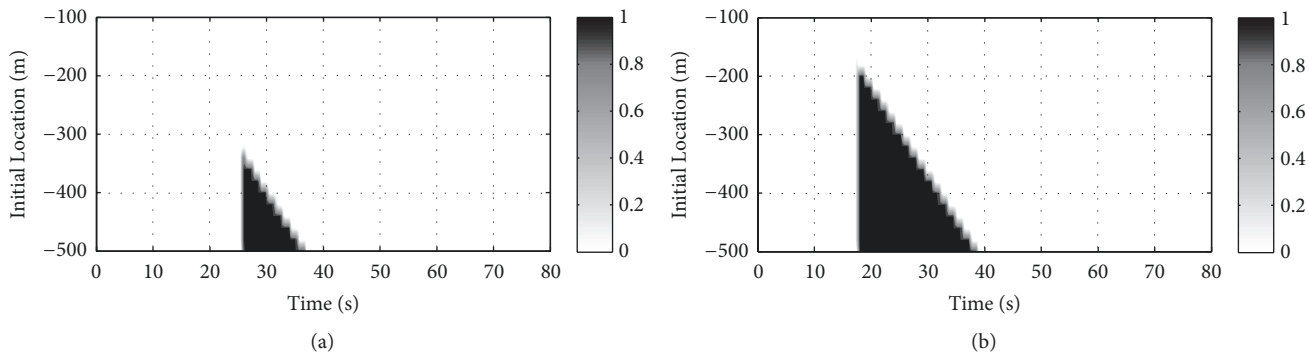


Figure 5: Crossing risk probability for different initial locations. (a) No-control scenario. (b) Control scenario.

Table 1: Model parameter values in simulation. (a) Location parameters. (b) Speed parameters. (c) Communication latency parameter. (d) Other parameters.

(a)

Parameter	$p_{r,0}(x_{r,0}, y_{r,0})$ [m]	$p_{u,0}(x_{u,0}, y_{u,0})$ [m]
Value	(500, 0)	Case 1: (0, -500) Case 2: (0, -500 ~ -100) Case 3: (0, -500) Case 4: (0, -500)

(b)

Parameter	$v_{r,x,0}$ [m/s]	$v_{r,y,0}$ [m/s]	$v_{u,x,0}$ [m/s]	$v_{u,y,0}$ [m/s]
Value	-15	0	0	Case 1: 0 ~ 20 Case 2: 15 Case 3: 15 Case 4: 15

(c)

Parameter	t_{cl} [s]
Value	Case 1: 0.1 Case 2: 0.1 Case 3: 0~1 Case 4: 0.1

(d)

Parameter	t_{prt} [s]	t_g [s]	$T_{threshold}$ [s]	$\delta_{r,x}, \delta_{r,y}, \delta_{u,x}, \delta_{u,y}$ [m]	t [s]
Value	2	3	10	Case 1: 3 Case 2: 3 Case 3: 3 Case 4: 0~10	0.2

In addition to the high-risk conditions, there are other conditions that will not cause a collision. For example, if a pedestrian walks at 1 m/s in the control scenario of Case 1 (see Figure 4(b)), the pedestrian has no collision risk as predicted by the model. As a result, the model can predict the collision risk at grade crossings. Road users and trains have collision risks only under certain conditions, which are combinations of real-time road user and train travel speeds, locations, and other environmental factors. Only the road users who are in risk of collision will be alerted to the impending collision. In contrast, road users who do not have a collision risk will not receive a warning. Additionally, the model estimates waiting time so that road users can plan their travel behaviours. By these means, the model improves the warning system reliability and user compliance.

Moreover, as shown in Figure 4, the collision risk decreased with a decrease in speed. This means that early speed reduction can remarkably reduce collision probability and severity. As for communication latency, as shown in Figure 6, considering communication latency in the model provides earlier warning. Thus, the consideration of communication latency in the model has a positive impact on the risk

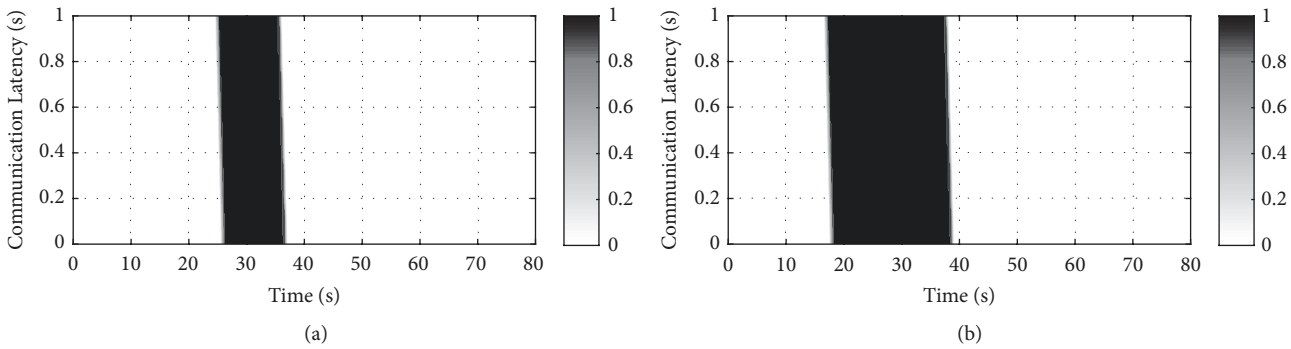


Figure 6: Crossing risk probability for different communication latencies. (a) No-control scenario. (b) Control scenario.

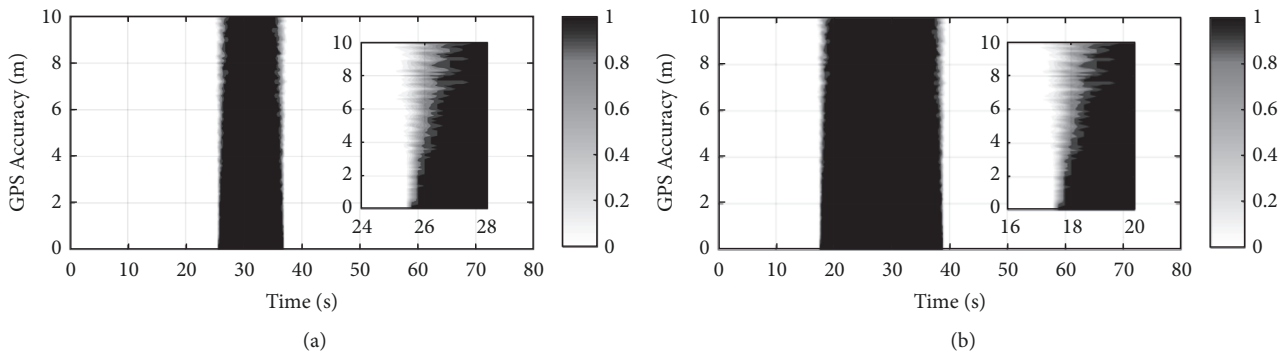


Figure 7: Crossing risk probability for different GPS accuracy. (a) No-control scenario. (b) Control scenario.

assessment and system effectiveness. For GPS accuracy, when crossing risk probability is about to increase, compared with a smaller standard deviation of GPS position measurements, a larger one generates a lower risk probability. As the system predetermines a warning threshold, the warning delay is minor even when the standard deviation is 10 m, which is the positioning accuracy obtained from nearly the least accurate GPS devices in practice.

4.3. Field Test Results. After the model performance was confirmed in simulation, the active warning system was tested in the field. During the field tests, the OBE devices, which are self-contained portable units, were placed on LRT trains and in the test vehicle. The OBE devices transmitted messages between one another via DSRC. The active warning system described in the last section was coded in C++ for the field test. The location-specific parameters of the grade crossing were input into the model beforehand. The field tests were conducted from 1 PM to 2 PM on July 13, 2018. During the tests, the test vehicle with OBE and smart devices travelled across the intersection. Using the real-time information from the test vehicle and trains collected every 1 s, the risk assessment model in the system predicted the collision risk 30 s in advance. The communication latency value in the model was 0.1 s and the standard deviation of GPS position measurements was 3 m. Once the model obtained a high-risk probability, the system sent out the warning to the vehicle driver. Along with auditory alerts, the smart devices displayed warning messages and waiting times when an LRT

Figure 8: User interface on smart devices.

approached or crossed (as displayed in the interface shown in Figure 8). Real-time location and speed data from both the LRT and the vehicle was collected to evaluate the CV technologies and improve the safety of grade crossings.

Figure 9 shows the results from the two field tests. In the first test (Figure 9(a)), the test vehicle travelled from the west to the east along University Avenue, while an LRT train travelled from the north to the south. At the time of 13:17:20, the warning system predicted that the vehicle and train would have a high collision risk at 13:17:31 under their current speed and location combination. The system alerted the vehicle driver by auditory and visual warnings. After the warning, the vehicle driver decelerated and stopped behind the stop

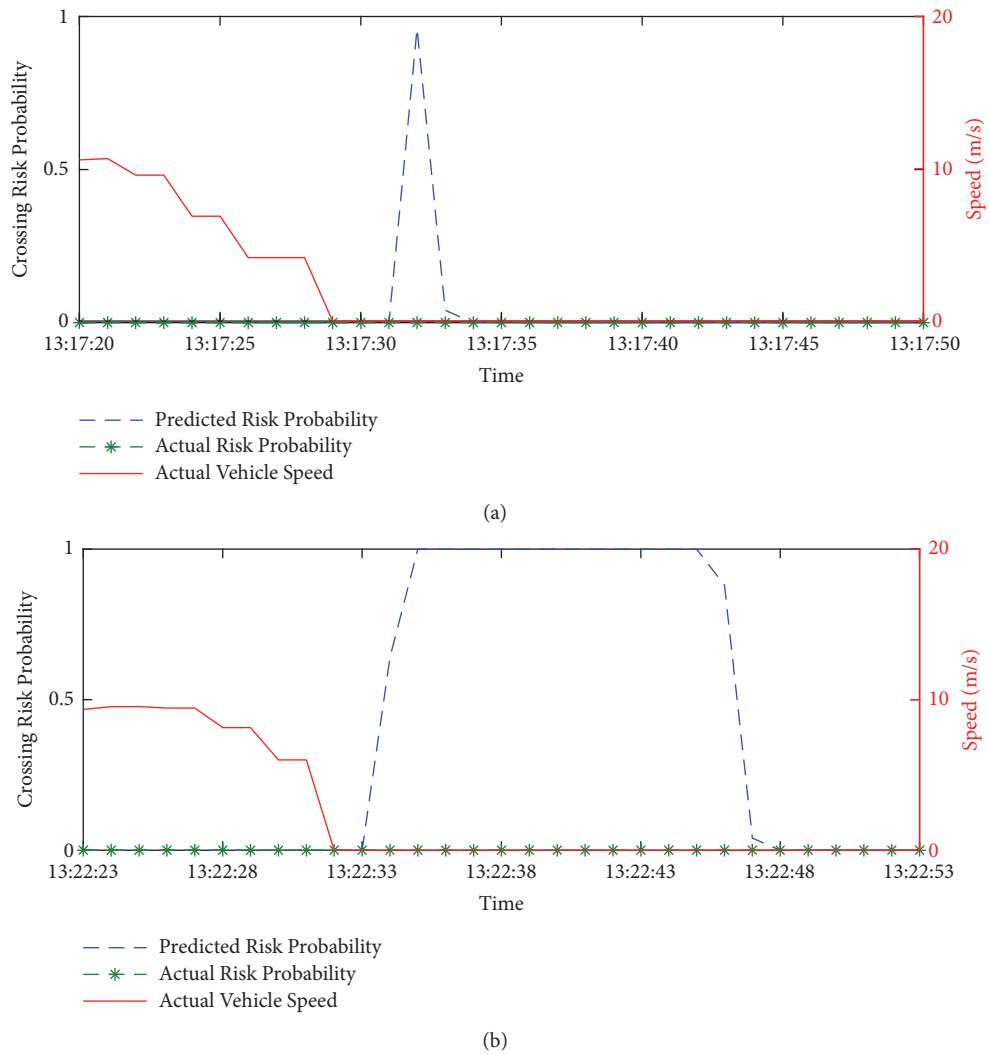


Figure 9: Field test results. (a) Test 1. (b) Test 2.

line. With the help of the warning system, the crossing risk remained at zero during the test. Likewise, in the second test (Figure 9(b)), another train travelled from the north to the south while the test vehicle travelled from the east to the west. At the time of 13:22:23, the warning system sent out a warning message to alert the driver of the potential collision risk. After the driver decelerated gradually, the predicted risk decreased. Based on the observations from the two tests, it can be concluded that the proposed grade crossing warning system forecasts collision risk, alerts road users to take proactive driving behaviours, and decreases collision risk.

5. Conclusions and Future Work

Traffic safety at highway-rail grade crossings is a major concern for transportation authorities and the public at large. CV technologies have performed well in active driver assistance systems. This paper presented an active warning system, which aims at eliminating collisions at grade crossings. The proposed model and system were evaluated in simulation and field tests. The simulation and field tests revealed several key findings.

(a) The proposed model predicts the crossing risk in near future based on real-time information from road users and trains. The developed system sends auditory and visual alerts to road users who are at risk of a collision. Results from the simulation and field tests show that the accurate estimation of risk probability enhances the system effectiveness and reliability.

(b) When road users have collision probabilities with trains, the collision risk decreases with a decreased speed. The early deceleration alert given by the proposed active warning system effectively mitigates collision risk.

(c) The proposed active warning system performed well in field tests. After the drivers responded to the warning messages, the collision risk decreased remarkably compared with the predicted risk probability.

Based on the findings, future work will make effort to evaluate the warning system in various grade crossing locations and traffic scenarios. In the present study, only communication latency was considered in the proposed

model, future work will also analyse the system performance based on other important communication parameters, for example, packet loss rate. In addition, more field tests are required to assess the model parameter relationships, system performance, and reliability.

Data Availability

The GPS data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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