DYNAMIC MODEL OF DRIVER APPROACHING BEHAVIORS AT HIGHWAY-RAIL GRADE CROSSINGS

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ABSTRCT

The objective of this paper is to evaluate individual driver behavior during the approach to a highway-rail grade crossing (HRGC). An HRGC locates in Lincoln, Nebraska that is equipped with a standard 2-quadrant gate system is used as a test site. A total of 106 speed profiles of drivers who have to make a decision to stop or proceed in response to a train event are identified using a radar sensor. Among them, 47 vehicles stop at stop-line while 59 vehicles proceed through the HRGC. Standard engineering theory postulates that after a perception-reaction time drivers make a choice to proceed or stop. However, it is observed that the drivers do not appear to treat the stop/proceed decision as a static binary choice because their speed profiles exhibit a wide range of acceleration and deceleration behaviors. It is hypothesized that the decision to stop or proceed through an HRGC is best modeled as a dynamic and stochastic process. It is decided to divide the approach into three zones: awareness zone, assessment zone, and action zone. A stochastic model of drivers' decision-making as they approach an HRGC is developed. The speed profiles of drivers who violate the traffic laws and those that do not are compared and it is found that the former experienced a longer decision-making time. It is hypothesized that if information is provided earlier to drivers about a potential train event then the decision-making time would be reduced and the violation rate would decline.

Keywords: Driving approaching process, Three-zone model, Violation, HRGC

INTRODUCTION

Fatal crashes at U.S. highway-rail grade crossings (HRGCs) have declined from 359 in 2005 to 231 in 2013 due, in part, to deployment of a wide range of active countermeasures such as signal warnings and automatic gate controls (*1*). Automatic gates are considered to be among the most effective and safest HRGC countermeasures (*2*). However, the crash rate at these locations is still relatively high at 9.1 per 1 million train events (*3*). HRGCs are still among the top locations for fatal crashes and continue to be of major concern despite an ever-increasing focus on improved design and engineering practices (*4*-*5*).

It is the automobile driver's responsibility to take appropriate actions to avoid hazards at HRGCs when trains are present. The "appropriate actions" at an active HRGC are defined in the Uniform Vehicle Code and Model Traffic Ordinance (*6*-7). For example, the driver should stop within 15.3 m, but no less than 4.6 m, from the nearest rail when the warning system indicates a train is coming. It also states that the driver should not drive through the crossing when "a clearly visible electric or mechanical signal device gives warning of the immediate approach of a railroad train." Similarly in Nebraska, the law states that a driver should "Never drive any vehicle through, around or under any crossing gate or barrier" at a railroad crossing while such gate or barrier is closed or is being closed (*8*). Typical violations at HRGCs include:

1. Driving through the flashing warning signals without stopping;
2. Driving under the gates as they are descending;
3. Driving around the gates after they are fully descended; and
4. Stopping past the stop-line before, during, or after the gate descent.

Though some of these violation types may be considered less hazardous than others, they are all considered illegal and thus inappropriate. The focus of this paper is on violation 2 (i.e., driving under the gates as they are descending, or a gate violation) and violation 4 (i.e., stopping past the stop-line before the gate descent, or a stop-line violation).

As HRGC crashes are highly infrequent events, many researchers have identified surrogate measures for quantifying safety. For example, violation frequency was found to be a significant surrogate safety measure (*9*). HRGC violations are associated with driver's decision-making behavior and it is hypothesized that a better understanding of the decision-making mechanism will help to uncover underlying causes of violations and hopefully lead to an improvement in HRGC safety.

This paper focuses on the driver's decision to either stop or proceed when they approach an HRGC equipped with active control devices where the flashing lights are activated and the gates are either: 1) about to begin their descent; or 2) are descending. A test bed in Lincoln, Nebraska was chosen, and driver behaviors over space and time were observed during these situations. The speed profiles of proceeding vehicles and stopping vehicle were defined and obtained. The profiles were then analyzed to identify patterns of behavior during the time the HRGC warning system was active. It is found that there are three distinct zones related to driver behavior and the lengths of these zones vary. Based on this three zone hypothesis, a behavioral model of driver choice is developed. Finally, differences between drivers who commit violations and drivers who do not are compared in the context of this model.

LITERATURE REVIEW

Despite numerous studies focusing on improving the safety at HRGCs, the performance of the rail level crossing and crashes due to driver behaviors, such as decision making, driver error and situation awareness, remain ambiguous. This is largely because many factors contribute to a driver's behavior and these are difficult to measure. Studies have identified that drivers' failure to detect the level crossing signals (*10*), driver poor comprehension of signage and signals (*11*), and driver's lack of situational awareness (*12*), are key causal factors of crashes at HRGCs.

Previous studies have found that a vehicle's approach speed will decrease at an HRGC regardless of the presence of a train (*13*), due partially to the "bumpiness" of the HRGC and that drivers slow down to minimize the vibration they will experience as they cross the HRGC. Moon and Coleman (*14*) regarded a driver's approaching speed as a behavioral choice, and the vehicle speed was found to decrease as a vehicle got closer to the HRGC (*15*-*16*).

Another dynamic factor that has not been studied in the literature is the final decision point, which is defined in this paper as the point in time when the driver makes a final decision to stop or to proceed. Tey et al. (*17*) studied drivers that chose to stop and concluded that the final braking position is related to the probability of a crash. They found that the closer the braking position to the crossing, the shorter the time-to-collision and thus the higher the possibility of a collision. In standard HRGC design it is assumed that the driver's decision to stop or proceed is made at a single point and time and that this decision remains unchanged after this point (*18*).

It is hypothesized in this paper that a driver's decision process is dynamic, and drivers have the ability to adjust their decision to stop or proceed as they obtain more information (e.g., road geometry, traffic situation, warning signals, etc.) during the entire approach process. It is hypothesized that measuring drivers' profiles as they approach an HRGC and developing dynamic and stochastic models based on these profiles will lead to a better understanding of why violations occur. This would in turn allow countermeasures, including changes in design, operations, or enforcement, to be implemented. It should be noted that this type of detailed empirical driver profile analysis has not been done before at HRGCs.

DATA

Study Site

The HRGC test bed is located near the intersection of 35th Street and Adams Street in Lincoln, NE, where the BNSF mainline railway intersects with Adams Street at an approximate 35-degree angle. A layout of the testbed is provided in Figure 1. Adams Street is a two-lane road, and the eastbound lane is "fed" from both eastbound Cornhusker Highway and southbound traffic from 35th Street. This HRGC experiences relatively high train volumes of 50-70 trains per day. As such, there are numerous train events per day, and the HRGC has been identified as one of the most dangerous in Nebraska. The speed limits are 72 km/h (45 mph) on Cornhusker Highway and 56 km/h (35 mph) on both Adams Street and 35th Street.

FIGURE 1 HRGC testbed layout.

The HRGC is equipped with two-quadrant automatic gates, and two red flashing lights that become active 4 seconds prior to the start of the lowering of the gate arms. In other words, once the warning lights flash for 4 seconds, the gates begin their descent. It takes approximately 6 seconds for the gates to go from completely vertical to completely horizontal. Given that the railway provides a minimum of 20 seconds of warning time, this would imply the train arrives, at a minimum, 10 seconds after the gate is fully horizontal.

Figure 2 illustrates the trailer data collection system which was located 0.6 meters from the pavement edge of the eastbound Adams Street. As shown in Figure 2(a), the trailer was equipped with four data collection devices. The first is a Wavetronix Smartsensor Advance detector, which is used for tracking vehicular trajectory as defined by its speed, time, and distance to the stop-line. The measurable range of the detector is 183 meters (600 ft), which is a sufficient distance for drivers of all vehicle types to react appropriately to the warning devices (*17*). The second is a Wavetronix Smartsensor HD detector, which is used to obtain vehicle length and the speed of vehicle at the stop-line. The third is an analog camera focused on the nearest flashing lights and gate, with an Autoscope kit in loop to detect the start time and the end time of gate movements. The fourth is an Axis IP camera oriented toward the approaching traffic, which is used to record the vehicle's approaching process in the case that a visual confirmation is required. In addition, Figure 2(b) shows a screen shot of the vehicle approaching the HRGC on Adams Street from the west. Figure 2(c) shows the view of the vehicle that is proceeding through the HRGC, where the green rectangle represents the virtual detector from Autoscope and overlaps onto the video.

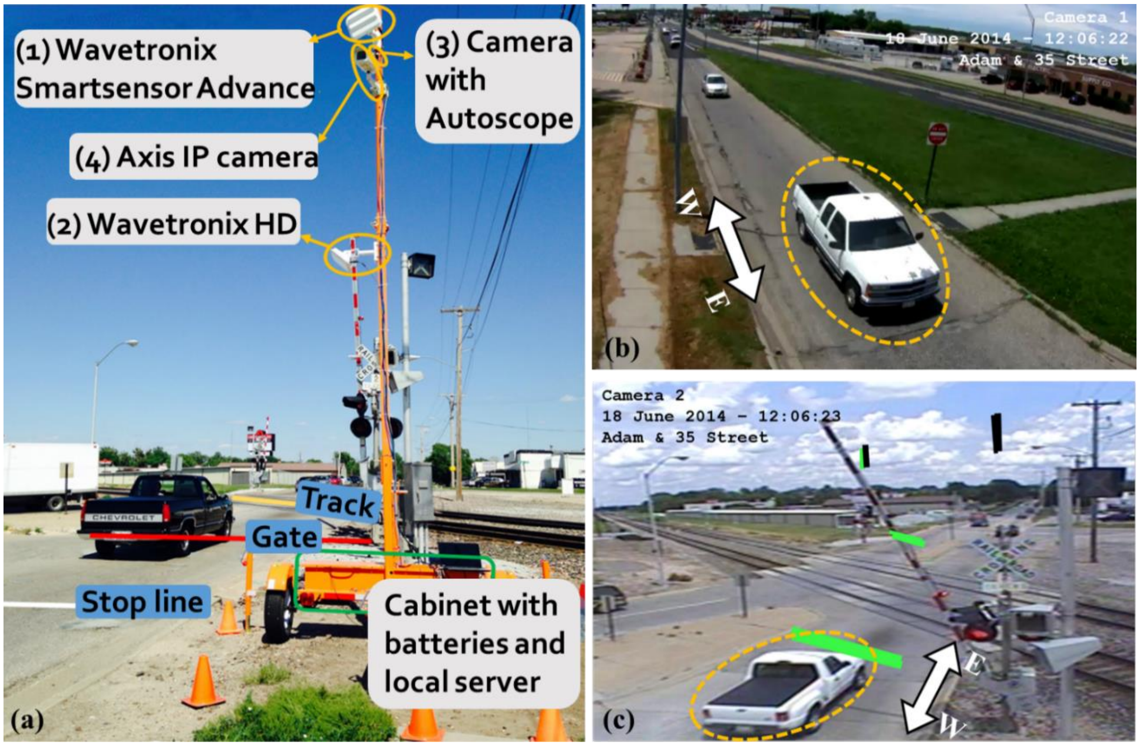

FIGURE 2 Mobile data collection trailer.

Data Collection

Data was collected from 9:00 am to 4:30 pm for 16 weekdays starting from May 24, 2014 and ending on June 20, 2014. Only data from days when there was no rain nor visibility were included in this study. Data on vehicle types including passenger cars, commercial trucks, and buses were collected. The majority (96 percent) of the traffic composition was passenger cars. Before the start of data collection, the trailer had been placed at the location for over a month in order to mitigate the impact of the trailer on driver behaviors. There were times when the data was not synchronized and/or not all equipment was functioning properly. In these situations, the data was discarded.

A series of automatic data reduction algorithms were used to identify vehicles with drivers who had to make a decision on whether to stop or proceed through the HRGC. The focus was on identifying: 1) vehicles that were the last to proceed through the HRGC prior to the arrival of the train, and 2) vehicles who were the first to stop for an approaching train. The former will be referred to as last-to-proceed vehicles and the latter as first-to-stop vehicles. After the data reduction, 106 vehicular trajectories were obtained, which consisted of 59 last-to-proceed vehicles and 47 first-to-stop vehicles.

Speed Profile and Final Decision Point

The empirical speed versus time profiles are shown in Figure 3, where the speed is on the y axis and the time is on the x axis. Figure 3(a) shows the profiles of the last-to-proceed vehicles and Figure 3(b) shows the profiles of the first-to-stop vehicles. Also shown on Figures 3(a) and 3(b) are the time the flashing lights become active (i.e., t = 0 second) and the time when the gates begin descending (i.e., t = 4 seconds). The profiles are color coded. Grey indicates a vehicle initially traveling above the speed limit, green indicates a vehicle initially traveling at or below the speed limit and ultimately proceeding through the HRGC, and red indicates a vehicle traveling at or below the speed limit and ultimately stopping prior to the HRGC. Note that while the profiles appear to be continuous, they are based on readings at 0.2 second intervals. It should be noted that the start time of the flashing lights on each speed profile is normalized to zero seconds for analysis purposes. Distance is not shown in Figure 3, therefore the vehicles are, in most cases, in different locations for a given time.

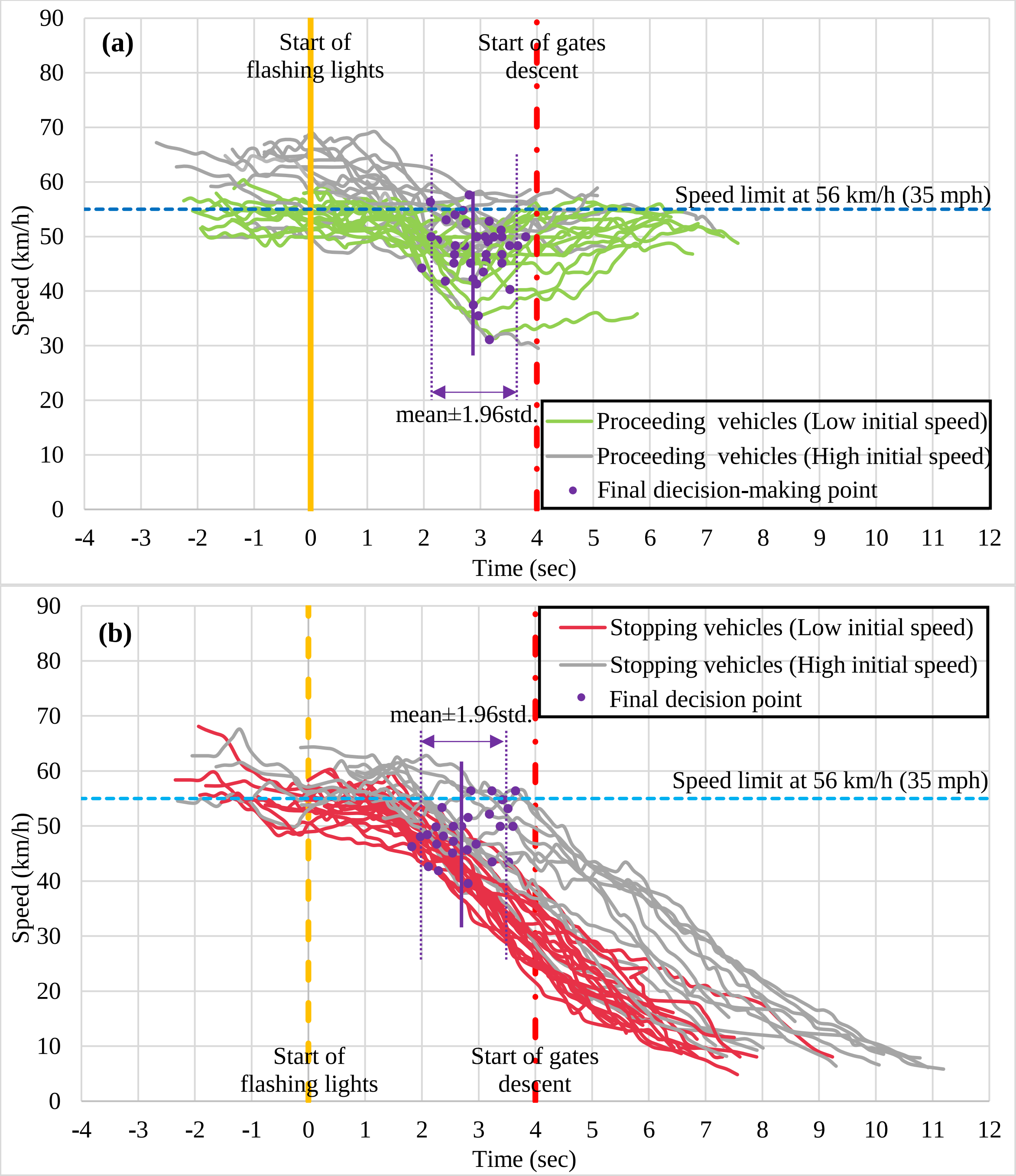

FIGURE 3 Speed profiles and final decision points for (a) proceeding vehicles, and (b) stopping vehicles.

The speed profiles prior to time 0 show driver behavior prior to the start of the flashing lights. As can be seen in Figure 3(a) for proceeding vehicles, the speeds prior to the start of the flashing lights are fairly stable and vary about the speed limit. However, for the stopping vehicles shown in Figure 3(b), drivers tend to reduce their speeds prior to the start of the flashing lights.

Table 1 shows the statistics of the differences between the instantaneous speed at the start of the flashing lights and the average instantaneous speed before that time (i.e., the time period that from the vehicle is first detected by the sensor to the start of the flashing lights). For the stopping vehicles, the reduced speed of 6.7 km/h is statistically significant at the 95 percent confidence level. Note that the change of speed limit from 45 mph to 35 mph, where vehicles exit from Cornhusker Highway to Adams Street, would account for some of the observed speed drop. Interestingly, the drivers that ultimately decided to stop are the ones that have, on average, the largest speed drop before the start of the flashing lights. It is hypothesized that these drivers are cautious and are therefore more likely to choose to stop when the warning lights begin flashing.

TABLE 1 Test of Speed Differences (unit: km/h)

	Obs.	Average instantaneous speed before the start of flashing light (*std.*[a])	Instantaneous speed at the start of flashing light (*std.*[a])	Speed difference	F statistic	Sig.
Last-to-proceed vehicles	59	57.5 (*5.54*)	56.3 (*5.32*)	1.2	2.14	.742
First-to-stop vehicles	47	58.8 (*4.18*)	53.1 (*3.75*)	6.7	10.37	**.024**[b]

[a] Standard deviation of the speed, in *italics*
[b] Statistically significant result (alpha = .05)

After the flashing lights are activated, drivers will have to make a decision to proceed or stop. Note that during this process the external information that the driver obtained is dynamic over time. This information includes warning signal flashing, automatic gates gradually descending, activation of train or wayside horn and, perhaps, visual confirmation of the train by the driver. This dynamic information may affect driving behavior and the driver's choice. For example, a possible scenario could be that the driver perceives the warning signal, decides to brake, subsequently changes his mind and begins to accelerate before changing his mind a second time and stops. These decisions, and their associated behavior, will be reflected in the speed profiles after the flashing lights are activated (i.e., 0 second) as shown in in Figure 3(a) and 3(b).

Once the final decision is made, the speed profiles show smooth trends. If the driver decides to proceed through the HRGC, the speed tends to increase to an upper limit speed before leveling out. If the driver decides to stop, the speed decreases at a fairly consistent rate. As shown in Figure 3, the purple dots represent the final decision points where it is assumed that the driver makes a final decision to stop or to proceed. In this study, the final decision point for proceeding vehicles is defined as the time when the vehicle begins to accelerate from its absolute minimum value of speed after the warning lights start flashing. Note that the driver might slow down later and that the average acceleration rate for these vehicles could be negative. For stopping vehicles, the final decision point is determined when the vehicle experiences a 15 percent drop in instantaneous speed compared to the instantaneous speed at the onset of the flashing lights.

With respect to Figure 3, for a given driver, the time from the start of the flashing lights to the final decision point is referred to as the decision-making time (DMT). Figure 4(a) and 4(b) show the histogram of the DMTs. Also shown are a fitted normal distribution curves for the proceeding vehicles and stopping vehicles, respectively. For proceeding vehicles, the average DMT is 2.02 seconds with a standard deviation of 0.703 seconds; for stopping vehicles, the average DMT is 2.47 seconds with a standard deviation of 0.826 seconds. The difference in average of DMT for stopping vehicles of 0.45 seconds, as compared to proceeding vehicles, was statistically significant at the 95 percent confidence level (p-value=0.003).

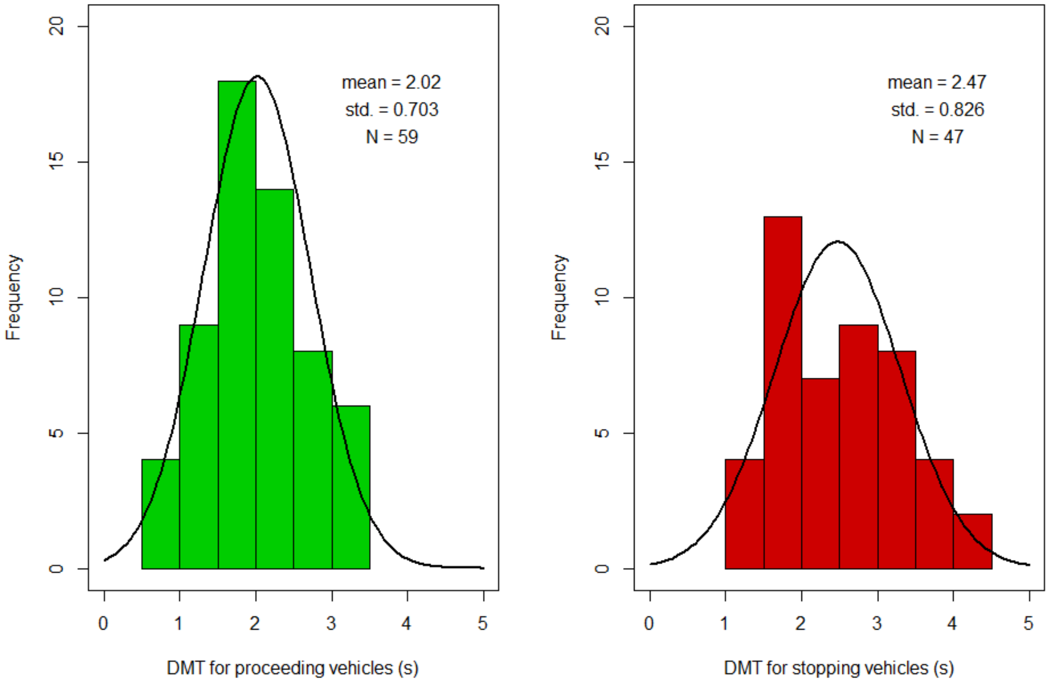

FIGURE 4 Histograms of DMT (in seconds).

As can be seen in Figure 4, the time at which a driver makes the final decision to stop or proceed varies considerably across drivers. It is expected as the DMT would be a function of driver's current speed, how long the active warning devices had been flashing, driver's distance to the HRGC, the presence of other vehicles, whether the train is visible to the driver, driver's familiarity of the HRGC, and individual driving risk profile, etc. It is also possible that the driver makes a series of choices several times before making a final decision. Note that the DMT is greater than the perception-reaction time used in the HRGC design. For example, ITE assumes 1.0 second and AASHTO assumes 1.5 seconds of perception-reaction time (*19-20*) for the driver's reaction and decision-making to the flashing lights. This implies that the drivers are using more time to decide fully on whether to stop for the train or proceed through the HRGC.

At the final decision point, the driver makes a final choice on whether to proceed through the HRGC or stop. After this point, the vehicle will accelerate or decelerate, depending on their choices, in an approximately continuous manner. Note that for the stopping vehicles the deceleration rate for an individual driver is relatively constant. In contrast, for the proceeding vehicles the acceleration rates for an individual driver varies over time. In addition, for those proceeding vehicles, the speed at the final decision point is noticeably reduced as compared with the speed at the start of the flashing lights (in Figure 3). As discussed previously it is assumed that the drivers slow down due to the "bumpiness" of the HRGC associated with proceeding through two sets of railway tracks.

MODEL OF THE THREE ZONE-BASED DRIVER DECISION-MAKING PROCESS

Based on the previous speed profile analysis, a conceptualization of the driver's decision-making process as they approach an HRGC was developed, as shown below.

Definition of the Model

As shown in Figure 5, the driver's approaching process is divided into three distinct zones as the driver approaches the HRGC: 1) the awareness zone, 2) the assessment zone, and 3) the action zone. Each zone is described in detail in the following paragraphs.

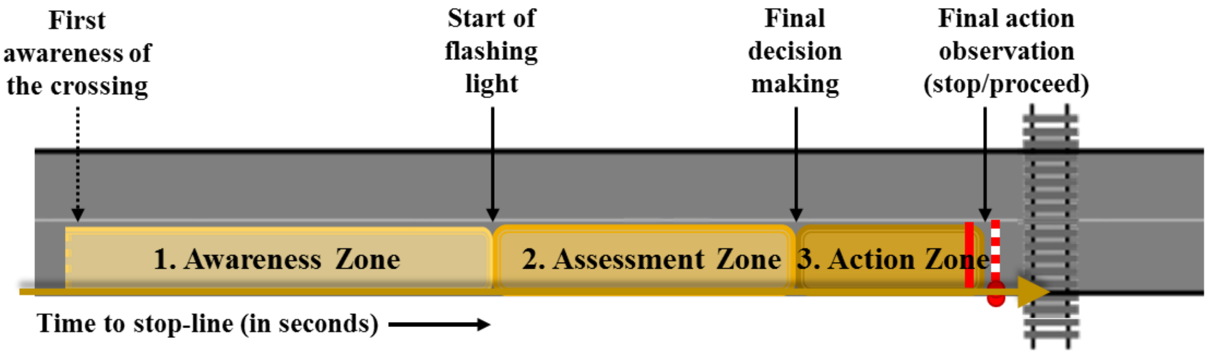

FIGURE 5 Conceptualization of driver's decision-making when approaching an actuated HRGC.

The awareness zone starts in the general vicinity of the first railway warning signs and/or pavement markings, where it is assumed that the driver first obtains information that there is an HRGC ahead. The first information usually takes the form such as advance warning signs or prior familiarity with the crossing. In chapter 2C of the MUTCD (*22*), the recommended distance for the placement of the advance warning sign is 122 meters (400 ft) away from the nearest track under a posted speed of 35 mph. In this zone, drivers are aware that there is an at-grade train crossing ahead, but they have been given no indication, other than possibly visual observation, that there is a train in the area. This zone is characterized by a decrease in travel speed as the driver approaches the HRGC. Note that if there are no trains in the area, the awareness zone will last from the time drivers identify the crossing to the time they safely proceed through the HRGC and neither of the other two zones, as described below, will exist.

The assessment zone begins when the flashing lights are on display. In this zone drivers become aware that the flashing lights are active and they know that they have to make a stop or proceed decision. Under traditional static modeling of HRGCs, the length of this period of time is equal to the perception-reaction time. That is, drivers make a binary decision immediately after they perceive the flashing lights are active. As hypothesized in this paper, the decision-making process at HRGCs are more complex than currently assumed, in that the driver may make a series of decisions, including to “wait and see”, before ultimately deciding on a course of action. The length of this zone is equal to the DMT, as defined previously. The high variability in speed that was observed at the test site tends to support this hypothesis.

The action zone starts immediately after the final decision point. For proceeding vehicles, it ends at the time when vehicles successfully traverse the gate; for stopping vehicles, it ends when vehicles complete a stop at the stop-line. In this zone, drivers implement their final decisions. This section is characterized by either near constant deceleration rate for stopping vehicles or near constant acceleration rate for proceeding vehicles.

Model Verification - Violation

The proposed three-zone model can be used to understand why violations occur. During the vehicle approaching process, it is hypothesized that drivers who commit violations behave differently from drivers who do not. By examining these drivers in the context of the proposed model, insights might be obtained that lead to a better understanding of the cause of violations.

First, the time lengths of the 106 vehicles in each zone are averaged. As shown in Table 2, the average time lengths of the awareness zone, assessment zone, and action zone for proceeding vehicles are 0.82 s, 2.02 s and 2.09 s, respectively. For stopping vehicles, the average time lengths of the three zones are 0.82 s, 2.47 s, and 4.85 s, respectively. There is no statistically significant difference at the 95 percent confidence level in the average time length of the awareness zone. The average time length of the assessment zone is approximately 20 percent longer for stopping vehicles as compared to proceeding vehicles, which is significant at the 95 percent confidence level. The difference in average time length of the action zone is also statistically different at the 95 percent confidence level. Due to the speed drop, drivers who choose to stop spend 2.7 seconds more than the proceeding vehicles in completing the action zone.

TABLE 2 Average of Time Length for Each Zone

	Observations	Violations	Length of Zone (seconds)		
			Awareness Zone	Assessment Zone	Action Zone
Last-to-proceed vehicles (1)	59	29	Mean=0.82 [0.64, 0.99]**	Mean=2.02 [1.84, 2.20]	Mean=2.09 [1.90, 2.28]
First-to-stop vehicles (2)	47	2	Mean=0.82 [0.60, 1.03]	Mean=2.47 [2.24, 2.71]	Mean=4.85 [4.41, 5.28]
Sig. of ((2)-(1)) *			0.983	0.003	0.000

*Results from t-test with significant level of 0.05

**Results in brackets are the confidence interval of the mean at 95 percent confidence level

Next, the total observations are divided into violation and non-violation groups. As shown in Figure 6, the stopping vehicles and proceeding vehicles are disaggregated based on whether there is a violation and their respective zone lengths are shown in the violin plots. Note that the width of the violin plot indicates the data distribution. The white diamond indicates the median and the red line with the label indicates the mean of the zone length.

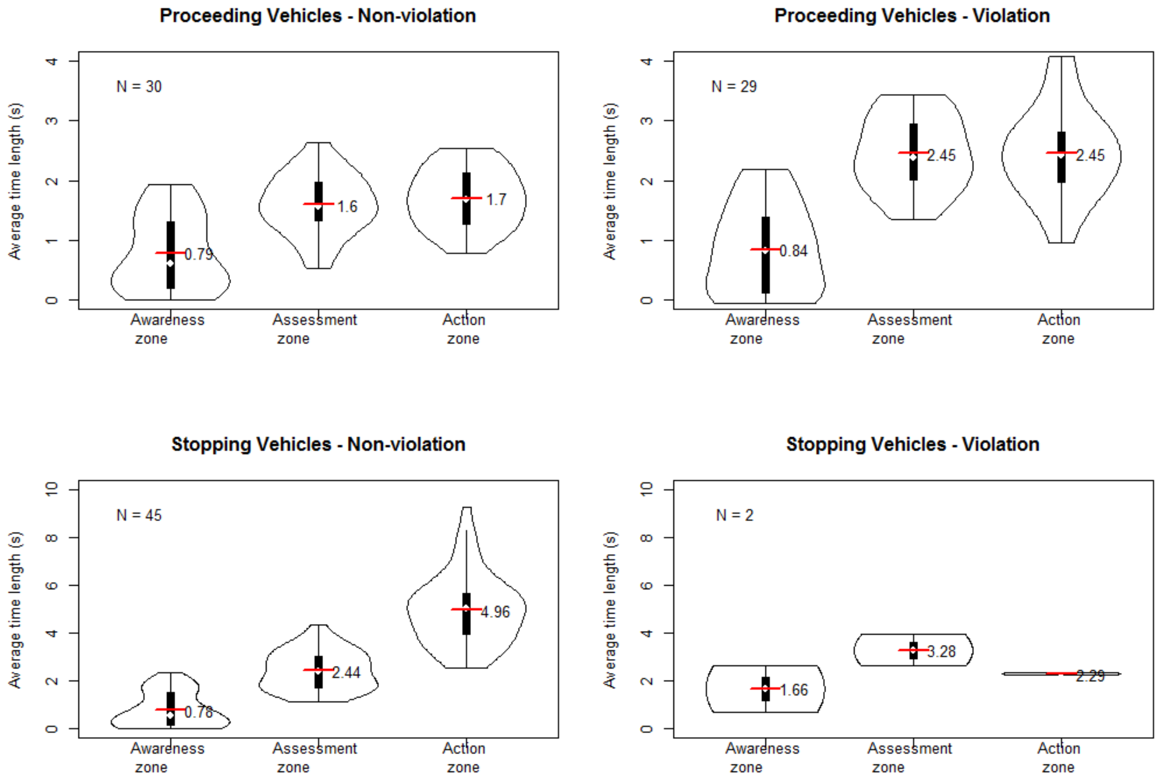

FIGURE 6 Comparison of non-violations with violations for the three zones.

It is found in Figure 6 that there is no difference in the average time length of the awareness zone for stopping and proceeding behaviors regardless of whether a violation occurs or not. This is expected because in this zone while drivers are aware that there is an HRGC ahead, they have not been notified by the active warning system that a train is approaching. The only exception is if they were able to visually identify the train which is extremely difficult at this test bed because of the geometry of the HRGC and the speed of the trains in the corridor. Specifically at this site, the advance warning sign is 79 meters (260 ft) upstream from the nearest track. This translates to a travel time of 5.1 seconds to the nearest track, assuming the driver is traveling at the average speed. As the warning flashing time is 4 seconds, there are only 1.1 seconds for drivers to aware of the HRGC ahead before the flashing lights are actuated.

It is found that the average time lengths of the assessment zone for drivers (both proceeding and stopping) who commit a violation are longer than those drivers who do not commit a violation. The DMTs are, 35 percent for proceeding vehicles and 26 percent for stopping vehicles, longer for drivers who end up committing a violation. There are two possible reasons for this issue. The first is that the awareness zone for drivers who commit a violation is shorter than for drivers who do not commit a violation. Thus these drivers have to increase their DMTs to react the flashing lights. The second possible reason is that these drivers make a decision and then subsequently change their minds as more information become available. In some instances a series of decision are made before the final decision, which is reflected in the variation of their travel speed profiles. This is different from the theoretical assumption in the past that drivers make stop-or-proceed decisions at a single point in time.

It is also found that the average time lengths of the action zone for proceeding vehicles that have a violation is longer, with a wider dispersion, compared to that of proceeding vehicles that do not have a violation. It is hypothesized that the reason is that these drivers originally decided to stop and when they change their minds (to proceed through), they do not have enough time to proceed through the HRGC without committing a violation. Although only two stop-line violations are observed, it is hypothesized that the average time length of the action zone for stopping violation vehicles is shorter, with a wider dispersion, compared to that of no stopping violation vehicles. This is because drivers who violate the stop-line usually are too close to the stop-line thus have to decelerate faster in a shorter amount of time.

CONCLUDING REMARKS

This paper studied drivers HRGC approaching behaviors in terms of the dynamic features at the HRGCs. The approaching process is divided into three continuous zones, which are the awareness zone, the assessment zone, and the action zone. Driver behaviors are characterized in each zone in order to quantitatively describe the process.

The awareness zone is characterized as the driver preparing a change in the possible driving environment from the highway road segment to a highway-railroad crossing area. This information comes from railroad warning signs, pavement markings, and/or prior knowledge. The distance should be long enough to allow drivers to detect a crossing and to adjust their speed to prepare a stop-or-proceed decision once the HRGC flashing lights are activated. For a 35 mph approach lane, the railroad-highway grade crossing handbook (*21*) recommends that the advance warning sign be placed 180 meters (590 ft) upstream from the HRGC while the MUTCD (*22*) recommends 122 meters (400 ft). For the test site used in this study the advance warning sign is placed 79 meters (260 ft) upstream from the nearest track. It is hypothesized that the short awareness zone is not beneficial because it does not provide sufficient time to aware the change of the road environment, which may aggravate the burden of the decision making to the next assessment zone.

The assessment zone is essentially a decision-making zone, where drivers are informed of an on-coming train by the start of the flashing lights. In this zone, drivers may make a series of decisions before the final decision is made. The current models in literature assume that a driver makes a single decision at the end of the perception-reaction time associated with the start of the flashing lights and that the driver does not change this decision at a later time. In other words, the perception-reaction time is all that drivers use to make a stop or proceed decision. However, as argued in this paper, the actual decision-making process requires a longer time as drivers may change their decisions during the approaching process.

To reduce violations, the transportation agency can either have earlier warning information of the HRGC (i.e., longer awareness zone) or shorten the decision-making process (i.e., shorter assessment zone). For example, advance warning flashers have been found to be effective in assisting the driver decision-making process at highway-highway intersections (*23*). Similarly, in-vehicle warning systems have the potential to provide an earlier warning regarding the presence of a train and to potentially provide advice on the safest course of action. These countermeasures would serve a similar purpose to the amber signal at highway-highway intersections and provide more advance warning about the activation of the warning signals.

It is hypothesized that reducing the vehicle speed, perhaps through a better enforcement of existing traffic laws, would reduce the number of violations. As can be seen from the speed profiles in Figure 3, a considerable number of drivers choose to drive faster than the speed limit and this is problematic when the flashing lights become active.

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