A Study on Impact of SPAD and Signal Failure Events on Railway Safety Based on Incorporating Train Drivers’ Behaviors into Train-Simulator

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Abstract

The human factor in the current railway system is a dominant cause of collision accidents. There exists a degree of uncertainty to the train driver on the timing of decision-making. Mitigating collision risks that are associated with the uncertainty of driving behavior is a challenging task. In this paper, we propose a train-simulator that incorporates the uncertainty of human driving behavior and its potential collision risk in the current train operation environment. The proposed simulator shows the impacts of driver behavioral errors on the safety performance and evaluates the collision risks associated with the various ranges of behavioral errors when a driver faces unsafe situations such as Signal Passed At Danger (SPAD) and signal failure events. The findings of this study reveal that there is a strong relationship between the number of taking evasive actions and the range of driving behavioral errors. This implies that the proposed train-simulator has a considerable effect in measuring the potential collision risks compared with the existing driving principles without the behavioral error consideration.

Keywords: Uncertainty of Driving Behavior, Train-Simulator, SPAD, Signal Failure, Potential Collision Risks

1. Introduction

One of the most common types of railway accidents is the collision. Although the collision accidents are relatively rare, the potential severity of collision events is greater than other types of accidents such as derailment, fire, and others. The Korea Transportation Safety Authority (TS) presented the statistics for each type of railway accident that took place in South Korea from 2010 to 2014 as in Table 1 [1]. As shown in Table 1, there are four collision events from February 1st, 2010 to December 31st, 2014. The collision accidents are rarer than other types of accidents, while it is the most severe event in terms of the average capital loss per accident type.

The Aviation and Railway Accident Investigation Board (ARAIB) revealed that the major cause of the collision events is the train driver’s misjudgment in high-speed situations such as an underestimation of required speed reduction and failure to comply with given signal [2]. Similar to the findings of the ARAIB, according to the Collision analysis Working Group (CAWG) of Federal Railroad Administration (FRA) in U.S., most of the collision events caused by the human factors contributed to the excess of train authority by failing to comply with the given speed signal or entering the territory without the granted authorization [3]. The FRA revealed that 19 out of 65 collisions failed to take appropriate evasive actions to avoid the collision events.

To mitigate the risk of collision events associated with the
human error, there have been enormous efforts to develop methodologies in railway transportation system to provide collision alerts to the train drivers, such as Automatic Train Protection (ATP), Train Protection Warning System (TPWS), Automatic Warning System (AWS) and Positive Train Control (PTC) [4-7]. The previous approaches primarily focused on the emerging technologies to provide a collision warning in a potential collision risk at the appropriate time. For example, when the train is likely to exceed the given line speeds, the ATP system is intended to support the train drivers to compute the braking distances and to apply the automatic brake applications based on the appropriate information at the right timing. However, the control is not automatically activated or overridden by the system, the train driver manipulates the system by means of traditional driving principles [8]. In addition, most of the existing driving principles are not based on the dynamic headway approaches. They are based on the fixed-block policies, which depend on the displaying signs at either sides of the track or the cab so that the existing driving principles cannot be applied in the current railway system. Moreover, since there is still a degree of uncertainty on the timing of decision-making and the detailed information regarding the timing. However, the control is not automatically activated or overridden by the system, the train driver manipulates the system by means of traditional driving principles [8]. In addition, most of the existing driving principles are not based on the dynamic headway approaches. They are based on the fixed-block policies, which depend on the displaying signs at either sides of the track or the cab so that the existing driving principles cannot be applied in the current railway system. Moreover, since there is still a degree of uncertainty on the timing of decision-making and the detailed information regarding the preceding train’s dynamics, an alternative plan in case of signal failure should be provisioned.

So far, even if the human factor is a significant source of collision event, only a few studies have explored the collision risk related to the human-train dynamics of situation awareness in the existing task environments [9, 10, 11]. Therefore, an advanced approach evaluating the potential safety risks associated with the uncertainty of situation awareness caused by the driving behaviors of train drivers shall be developed. With this background, we propose a train-simulator that incorporates the uncertainty of human driving behavior to consider the potential collision risks in the current operational environment. This research also aims to examine the impacts of driver behavioral errors on the safety performance using the proposed train-simulator. Furthermore, this study evaluates the collision risks associated with the various range of behavioral errors when faced with an undesirable event such as Signal Passed At Danger (SPAD) and signal failure events. A detailed framework on the proposed train-simulator is presented in Section 2. In Section 3, simulation results are demonstrated based on a given scenario. Findings and contributions of this study are presented in Section 4.

2. Framework for Development of Train-Simulator

The train-simulator involves several components to implement certain functional requirements. The following figure shows the components of the train-simulator.

Fig. 1 shows that the proposed simulator consists of four modules: (1) Train generator, (2) Signal controller, (3) Train operator, and (4) Station operator. The Train generator generates the train at the origin station. The train properties such as the train type, mechanical performance of train, human behavior type, human error range, and the start interval of the train are determined in this module. The signal controller controls the signal, which is installed in the railway based on the location of each train. The train operator makes the acceleration/deceleration action of each train based on the signal on the railway. The station operator regulates the access to the station of trains considering the delay and capacity of the station. The following subsections present a more detailed explanation on each module.

2.1. Train Generator

The train generator generates the train at the origin station and the properties such as the time intervals of train departure, train type, mechanical performance of train, human behavior type, and the human error range of each train are determined in this module. There are generally two types of trains in the current railway system, which are high-speed train and conventional train. These trains are generated at the origin station with a certain time interval (σ) with probability (p_{train}). These trains have different acceleration/deceleration capability and free speed. The properties of a high-speed train and a conventional train are set in reference to Korea Train eXpress (KTX) train and Intercity Train eXpress (ITX) train respectively since these two are the most widely used in the mixed operation of the current railway traffic in South Korea. The details are as follows.

The time interval (σ), which is related to the capacity in the railway traffic, indicates the time gap between two trains. Taking into account the long stopping distance of KTX, σ is set larger when the following train is a KTX [12].

Along with the train type, human behavior type and

<table>
<thead>
<tr>
<th>Table 2, Properties of trains for simulation</th>
<th>KTX</th>
<th>ITX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Speed (V_{free})</td>
<td>300 km/h</td>
<td>150 km/h</td>
</tr>
<tr>
<td>Maximum Acceleration Rate (α_{max})</td>
<td>1.6 m/s²</td>
<td>2.5 m/s²</td>
</tr>
<tr>
<td>Train Length (L_{train})</td>
<td>388 m</td>
<td>340 m</td>
</tr>
<tr>
<td>Normal Braking Rate (b_{norm})</td>
<td>-3.5 m/s²</td>
<td>-3 m/s²</td>
</tr>
<tr>
<td>Emergency Braking Rate (b_{emer})</td>
<td>-4.5 m/s²</td>
<td>-4 m/s²</td>
</tr>
</tbody>
</table>
human error range are determined in this module. The human behavior type represents how fast the train driver perceives the railway signals and takes the appropriate actions. The train drivers react differently to the signal depending on the characteristics of each driver, which are based on their experience and judgment as mentioned in the literature reviews [9, 12, 13]. To apply this behavior in the simulation, the human behavior type is presented with the probability ($p_{human}$). When the driver prefers to drive the train as the designed behavior of the signal system, the train is driven by using the Designed Train Operation Model (DTOM) (i.e. the train speed is controlled by the line speed). On the other hand, when the driver wants to drive the train based on his/her experience to increase the average speed near a station, the train is driven by using the Human Behavior-based Train Operation Model (HBTOM). The details on these two models are described in the following subsection 2.3. The human error range is a perception range of the driver when the driver makes a decision on the acceleration/deceleration actions in HBTOM. In HBTOM, the driver reduces the speed near his/her preferred location. In this situation, the preferred location of deceleration is fluctuated due to a limited perception capability of the human driver on the location and remaining distance to next signal or train. To apply finite perception thresholds, HBTOM randomly changes the location of deceleration with a standard deviation of human error range ($r_{human}$). Details on this behavior are also described in the following subsection 2.3.

2.2. Signal Controller

The signal system is originally designed to support two possible instructions of signal communication, either proceeding to the following signal or stopping at the current signal. The widely used colored light signaling system is employed in the current Korean railway system. This signal system enables the train driver not only to allow a shorter headway but also to provide an earlier warning of a hazardous event. The signal controller in the study adopts the colored light signaling system, in which the various combinations of colored lights represent five different states: 1) green (G): it is safe to proceed with the free speed 2) yellow and green (Y/G): prepare to slow down the speed 3) yellow (Y): the next signal is displaying double yellow 4) double yellow (YY): prepare to stop at the next signal and 5) red (R): the train should stop. Each colored light indicates pre-designated speed limits. Table 3 describes the speed limits corresponding to each colored signal light (i.e. line speeds).

The following figure shows the corresponding control strategies for signal lights when ITX and KTX are getting closer to the destination station.

Where $L_i$ is a general expression for a section length, $L_{total}$ is the sum of $L_i$ and it indicates the total distance between the origin and destination, where the distance between different signals of KTX is approximately twice

<table>
<thead>
<tr>
<th>Signal</th>
<th>KTX Speed Limit</th>
<th>ITX Speed Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>300 km/h</td>
<td>150 km/h</td>
</tr>
<tr>
<td>Y/G</td>
<td>270 km/h</td>
<td>105 km/h</td>
</tr>
<tr>
<td>Y</td>
<td>230 km/h</td>
<td>65 km/h</td>
</tr>
<tr>
<td>YY</td>
<td>170 km/h</td>
<td>25 km/h</td>
</tr>
<tr>
<td>R</td>
<td>Before Stop 0 km/h</td>
<td>0 km/h</td>
</tr>
<tr>
<td>R</td>
<td>After Stop 10 km/h</td>
<td>5 km/h</td>
</tr>
</tbody>
</table>

Fig. 1. Components in the train-simulator
as much as ITX [12]. Detailed descriptions of the parameter values are presented in the following subsection 3.1.

2.3. train Operator

As stated in section 2.1, this module determines two types of train operations using acceleration-based model, including Designed Train Operation Model (DTOM) and Human Behavior-based Train Operation Model (HBTOM). The basic concept of the acceleration-based model is to control the current acceleration/deceleration by comparing the current distance with the sight distance, which can be defined as the length of railroad ahead that is visible to the train driver. The detailed operation rules on the acceleration-based model are as follows.

\[
\begin{align*}
a_{\text{train}}(t+1) &= \\
&= \begin{cases} 
    b_{\text{emer}}, & \text{Dis}_{\text{vis}} + L_{\text{train}} \geq \text{Dis}_{\text{train}}(t) \\
    a_{\text{signal}}(t), & \text{Dis}_{\text{vis}} + L_{\text{train}} < \text{Dis}_{\text{train}}(t)
\end{cases}
\end{align*}
\]

Fig. 2. Principle of signal control for a) ITX and b) KTX

Where \( a_{\text{train}}(t+1) \) represents the acceleration/deceleration rate at time \( t+1 \), \( b_{\text{emer}} \) indicates the emergency braking rate, \( \text{Dis}_{\text{vis}} \) describes the sight distance in which the preceding train is detectable, \( L_{\text{train}} \) is the preceding train’s length, \( \text{Dis}_{\text{train}}(t) \) refers to the headway distance between the two trains at time \( t \), and \( a_{\text{signal}}(t) \) represents the acceleration rate designated by a given signal to follow the line speed.

The train driver applies the emergency braking when the summation of \( \text{Dis}_{\text{vis}} \) and \( L_{\text{train}} \) is greater than the space headway. Otherwise, the train is controlled by the designated line speeds at given signals. Detailed descriptions on the DTOM and HBTOM are presented in the following subsections.

2.3.1 Designed Train Operation Model (DTOM)

The Designed Train Operation Model (DTOM) controls the train movements by providing an adaptation strategy to apply acceleration actions for maintaining line speeds. The DTOM determines the acceleration rates designated by the given signals without any interruptions of human driving behaviors. The driving principles of the DTOM are as follows.

\[
\begin{align*}
a_{\text{signal}}(t+1) &= \\
&= \begin{cases} 
    \min\left(a_{\text{max}}, \frac{V_{\text{Limit}}(t) - V(t)}{R}\right), & 0 < V(t) < V_{\text{Limit}}(t) \\
    0(t) = V_{\text{Limit}}(t) \\
    \max\left(b_{\text{norm}}, \frac{V(t) - V_{\text{free}}}{R(t)}\right), & V(t) > V_{\text{Limit}}(t)
\end{cases}
\end{align*}
\]

Where \( a_{\text{signal}}(t+1) \) indicates the acceleration rate desig-
nated by the given signal to follow the line speed at time \( t+1 \), \( a_{\text{max}} \) represents the maximum acceleration rate in the current section, \( V_{\text{Limit}}(t) \) describes the line speeds depending on the current signals, \( b_{\text{norm}} \) is the normal braking rate, \( V_{\text{free}} \) indicates the maximum speed of the train, and \( R(t) \) represents the static range varied with the given signals to reduce the fluctuations in accelerations and decelerations for maintaining the line speeds. Detailed information about \( V_{\text{Limit}}(t) \) and \( R(t) \) are shown in (3) and (4).

\[
\begin{align*}
V_{\text{Limit}}(t) &= \begin{cases} 
V_{\text{free}}, & S(t) = G \\
V_{Y_G}, & S(t) = YG \\
V_{Y_Y}, & S(t) = YY \\
V_{\text{Limit}}, & S(t) = \text{Yard before stop} \\
V_{\text{Limit}}, & S(t) = \text{Yard after stop} \\
\end{cases} \\
R(t) &= \begin{cases} 
R_{\text{free}}, & S(t) = G \\
R_{\text{stop}}, & S(t) = YG \\
R_{\text{stop}}, & S(t) = Y \\
R_{\text{stop}}, & S(t) = YY \\
R_{\text{stop}}, & S(t) = \text{R before stop} \\
R_{\text{stop}}, & S(t) = \text{R after stop} \\
R_{\text{stop}}, & S(t) = \text{Yard} \\
\end{cases}
\end{align*}
\]

The above represents the line speeds varied with the given signals. For example, \( V_{\text{Limit}}(t) \) is equal to \( V_{\text{free}} \) when \( G \) is displayed at the current section \( S(t) \), and \( V_{\text{Limit}}(t) \) follows \( V_{Y_Y} \) when the train is passing through the current section displaying \( YY \). The specific values for \( V_{\text{Limit}}(t) \) are presented in Table 3.

\[
R(t) = \begin{cases} 
R_{\text{free}}, & S(t) = G \\
R_{\text{stop}}, & S(t) = YG \\
R_{\text{stop}}, & S(t) = Y \\
R_{\text{stop}}, & S(t) = YY \\
R_{\text{stop}}, & S(t) = \text{R before stop} \\
R_{\text{stop}}, & S(t) = \text{R after stop} \\
R_{\text{stop}}, & S(t) = \text{Yard} \\
\end{cases}
\]

Similar to the methods of adopting the line speeds, \( R(t) \) is determined by the given signal at the current section. For instance, \( R_{\text{free}} \) is used for \( R(t) \) when the signal is displaying \( G \) at the current section. Detailed explanations on all of the specific parameter values with respect to \( R(t) \) are provided in the following subsection 3.1.

### 2.3.2 Human Behavior-based Train Operation Model (HBTOM)

To incorporate the human error in making a decision on acceleration/deceleration actions in the train-simulator, Human Behavior-based Train Operation Model (HBTOM) considers a stochastic range \( \varepsilon \) of the location in which the train driver determines to take either acceleration or deceleration actions. The HBTOM involves two types of operation methods. When the stopping distance to avoid the train-to-train collision (\( \text{Dis}_{\text{Human}}(t) \)) is greater than the remaining distance in the current block section (\( S_{\text{section}}(t) \)), the train is controlled with DTOM. On the other hand, in the opposite situation, the train is controlled as follows.

\[
\begin{align*}
\text{Dis}_{\text{Human}}(t) &= D(t) - V(t) - \frac{V(t) - \frac{V(t) - V_{\text{Limit}}(t)}{b}}{b_{\text{norm}}} \\
&= \frac{1}{2} b_{\text{norm}} \left( V(t) - \frac{V(t) - V_{\text{Limit}}(t)}{b_{\text{norm}}} \right)^2
\end{align*}
\]

Where \( N_{\text{section}} \) represents the number of block sections in which the subject train passed through, \( \varepsilon(t) \) indicates the train location at time \( t \), \( \varepsilon \) describes a stochastic perception range of the location, where the train driver makes a decision on either acceleration or deceleration actions, which follows a normal distribution with \( \mu = 0 \) and \( \sigma = r_{\text{human}} \). More detailed descriptions of the specific parameter values with respect to \( R(t) \), \( L_i \), and \( r_{\text{human}} \) are presented in the following subsection 3.1.
2.4. Station Operator  
As stated earlier, the station operator is one of the vital components in the proposed train-simulator in considering the dwell time and capacity at the destination station. Along with the variables, the station operator performs to send signal messages to the signal facilities near the destination station upon the current traffic situation. The controlled parameters involved with the station operator are the number of dwell times of each train (\(T_{dwell}\)) and the maximum capacity (\(C_{station}\)) at the destination station. Based on the dwell time and capacity, the station operator can calculate the delay time of each train (\(T_{delay}\)) at the destination station. Detailed information about \(T_{dwell}\), \(C_{station}\) and \(T_{delay}\) is described in the following section 3.1.

3. Results and Analysis

3.1. Simulation Scenario  
The growing demand of railway traffic pressurs the railway system to be more efficient. Accordingly, the train driver is forced to shorten the travel time and to reduce the congestion delays under a physically constrained environment. Higher efficiency requires a shorter headway in driving, while safety requires a conservative headway. The two conflicting objectives inevitably lead to accidents. For example, it can be easily observed that train drivers often pass signals at danger (SPAD), which results sometimes in severe accidents. In order to examine the potential collision risk of the current operational environment through a realistic simulation, a SPAD event is considered as a simulation scenario. Also, based on the proposed train-simulator, we identify collision risks of the signal failure case occurred near a destination station by applying the probability of emergency braking. It is expected that the results show the number of latent risks involved in the naturalistic driving situations since the train-simulator covers the perception range of the location in which the driver makes a decision on either acceleration or deceleration actions. To demonstrate the simulation scenario mentioned above, we need to select specific parameter values involved in the train-simulator. The following table describes the parameter values used in the study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{Limit}^{FG})</td>
<td>270 km/h</td>
</tr>
<tr>
<td>(V_{Limit}^{TY})</td>
<td>230 km/h</td>
</tr>
<tr>
<td>(V_{Limit}^{Y})</td>
<td>170 km/h</td>
</tr>
<tr>
<td>(V_{Limit}^{Y}), (R_{after})</td>
<td>10 km/h</td>
</tr>
<tr>
<td>(V_{Limit}^{Y}), (R_{before})</td>
<td>15 km/h</td>
</tr>
<tr>
<td>(V_{Limit}^{Y}), (R_{free})</td>
<td>10 km/h</td>
</tr>
<tr>
<td>(V_{Limit}^{Y}), (R_{stop})</td>
<td>10 km/h</td>
</tr>
<tr>
<td>(L_{i})</td>
<td>800 m</td>
</tr>
<tr>
<td>(T_{dwell})</td>
<td>10 min</td>
</tr>
<tr>
<td>(C_{station})</td>
<td>2 platform</td>
</tr>
<tr>
<td>(T_{delay})</td>
<td>0–2 min</td>
</tr>
<tr>
<td>(r_{human})</td>
<td>200 m</td>
</tr>
</tbody>
</table>

3.2. Simulation Results  
Based on the simulation scenarios mentioned in section 3.1, speed profiles of KTX and ITX near a destination station in a normal situation are shown below. The black lines in Fig. 3 represent the line speeds simulated with the DTOM and red lines indicate the actual speeds influenced by the perception range of the train driver using the HBTOM.

The speed profiles of the DTOM and HBTOM differ in the cases of both KTX and ITX. In Fig. 3 (a), the signals are installed at 48800 m, 50400 m, 52000 m, 53600 m, 55200 m, and 56000 m, far from the origin station displaying G, Y/G, Y, YY, R, and Yard signal, respectively. The locations where the signals are installed are marked with the black dotted lines in the figures. As shown in Fig. 3 (a), the DTOM well follows the speed limit of each signal, so that the subject train can reduce its speed right after its exposure to a certain signal until the speed of train reaches the speed limit. After taking deceleration actions, the train maintains its speeds as the line speeds. Also, one can observe that dangerous situations such as SPAD events did not occur in the simulation results of the DTOM. On the other hand, it can be seen that the trains reduce their speed in different locations depending on the characteristics of the train driver in the HBTOM simulation. Some drivers well follow the speed limit of each signal showing similar speed profiles to the DTOM but some drivers reduce the speed after a while compared with the DTOM to increase the average speed near the destination station. Since such behaviors are reflected in the HBTOM, the SPAD events are frequently observed in the simulation results. A similar phenomenon is also observed in the simulation result of ITX, as shown in Fig. 3 (b). In the case of ITX, the signals are installed near 51200 m, 52000 m, 52800 m, 53600 m, 54400 m, and 55200 m far from the
origin station displaying G, Y/G, Y, YY, R, and Yard signal, respectively.

The average speed of the HBTOM is greater than the DTOM due to the relatively late deceleration action of the human driver. Such behavior is similar to the driving behavior observed in the previous studies [14, 15]. Similar to the case of KTX, it shows that there are SPAD events observed in the case of ITX. Given these results, it implies that the dangerous situations caused by different human behaviors can be simulated using the HBTOM.

Fig. 4 represents the speed profiles of KTX and ITX near a station when the signal is not operating normally. Fig. 4 (a) shows that the signals located at 49600 m and 50400 m failed, while Figure (b) shows the signals failed at 52800m and 53600m. Due to these, dangerous situations are observed in the HBTOM such as very short distance between the trains or an abrupt stop near a station platform. However, such dangerous situations are not observed in the DTOM since the current operational system is designed to prevent accidents or incidents even when some signals are inoperative. Accordingly, the HBTOM well simulates undesirable as well as normal driving behaviors of the train drivers, in which we can conclude that HBTOM can be used to monitor the latent collision risks.

In the speed profiles shown in Fig. 3 and Fig. 4, unsafe situations such as SPAD events due to undesirable behaviors of the train drivers can be observed using the HBTOM. To further analyze the effect of undesirable behaviors of the train driver, we simulate different opera-
tional situations based on various ratios between the HBTOM and DTOM with certain time intervals of train departures from the origin station. The ratio between the HBTOM and DTOM represents how well the perception errors caused by the actual naturalistic driving characteristics of the human driver are described in the actual operational environment. Fig. 5 shows the probabilities of SPAD event occurrences with respect to the different ratios between the HBTOM and DTOM. As seen in Fig. 5, the SPAD events do not occur when the ratio is below 0.5. It means that there are no unsafe situations when all of the drivers follow the line speeds properly as designed. However, one can easily observe that the probability of occurrence of SPAD events increases as the ratio between the

![Fig. 5 Probability for occurrence of SPAD event](image)

![Fig. 6 Probability of applying emergency braking with respect to ratio between the number of KTXs and ITXs in different time intervals of train departures](image)
HBTOM and DTOM, as well as the time interval of train departure at the origin station increases. These findings imply that the railway safety in the actual operational situations can be evaluated by changes in the ratio between the HBTOM and DTOM. The potential collision risk is highly related to the ratio between the number of high-speed trains and conventional trains since their speed difference likely results in unsafe situations, particularly when the following train is faster than preceding train.

To examine the effect of the mixed ratio between different train types on the railway safety, we conduct an additional simulation to identify the probability of applying emergency braking with respect to the ratio between the number of KTXs and ITXs in different time intervals of train departure as shown in Fig. 6. Similar to the findings of the previous results shown in Fig. 5, Fig. 6 shows that the probability of applying emergency braking increases as the ratio between the HBTOM and the DTOM increases. It can be also seen that the number of the evasive actions decreases as the time intervals of train departures increase.

This result implies that it is safer when only one type of train among either the high-speed train or conventional train is operated. In other words, unsafe situations occur more frequently in the case of the mixed operation with different types of trains. As shown in Fig. 6 (e), for instance, the worst case is observed when the ratio between the number of KTXs and ITXs is 0.5. Considering that the mixed ratio is generally decided for economic reasons and demands, these findings represent that the time intervals of the train departure should be carefully determined for the operations. Especially, the overall performance of the railway safety varies in case of the mixed ratio of KTXs and ITXs with identical time intervals of train departures at the origin station. Hence, the train operating strategy should consider both efficiency and safety.

4. Conclusion

This study developed a train-simulator that incorporates the uncertainty of human driving behavior and its potential collision risk in the current train operation environment. The simulation covers the perception range of the location in which the driver makes a decision on either acceleration or deceleration actions. The train-simulator is used to estimate the latent risks involved in naturalistic driving situations. Based on the simulation scenarios in the SPAD and signal failure events, the train-simulator evaluates the collision risks by means of using the probability of occurrence of SPAD event and applying emergency braking. One of the findings in the simulation study reveals that the HBTOM well describes the undesirable and normal driving behaviors of the train drivers compared to the DTOM when the signal failures occur. Therefore, the HBTOM can be used to monitor the latent collision risks in the actual operational environments. We also observed that the probability of occurrence of SPAD events increases as the ratio between the HBTOM and DTOM, as well as the time interval of the train departure at the origin station increases. It is also observed that the probability of applying emergency braking increases as the ratio between the HBTOM and the DTOM increases. The findings of the simulation results indicate that there is a strong relationship between the number of taking evasive actions and range of the driving behavioral errors. This represents that the train-simulator has a considerable effect on measuring the potential collision risks compared with the existing driving principles without any considerations of the behavioral errors. Furthermore, it is seen that the number of evasive actions decreases as the time intervals of train departures increase, which implies that it is safer when only one type of train among the high-speed train and the conventional train is operated. These findings suggest that the time intervals of the train departure are carefully determined according to the mixed ratio of high-speed trains and conventional trains because high probability of emergency braking occurs when the mixed ratio is between 0.5 and 0.8.

Even though this research showed a substantial benefit of the proposed train-simulator in revealing latent operational risks associated with the perception errors of the train driver, several advanced methodologies should be considered in further study. For instance, one can consider a different probability density function other than the normal distribution for the perception errors. Also, other types of trains can be further considered in the future study. The fixed-block policies used in the current operational environments may be suggested as a moving block system. In the future study, a dynamic headway principle will be considered for a further analysis.

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