Hindawi
Journal of Advanced Transportation
Volume 2018, Article ID 8040815, 14 pages
https://doi.org/10.1155/2018/8040815

*Research Article*

# A Comparison Analysis of Surrogate Safety Measures with Car-Following Perspectives for Advanced Driver Assistance System

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Received 25 July 2018; Accepted 8 October 2018; Published 1 November 2018

Guest Editor: Luc Chassagne



Surrogate Safety Measure (SSM) is one of the most widely used methods for identifying future threats, such as rear-end collision. Various SSMs have been proposed for the application of Advanced Driver Assistance Systems (ADAS), including Forward Collision Warning System (FCWS) and Emergency Braking System (EBS). The existing SSMs have been mainly used for assessing criticality of a certain traffic situation or detecting critical actions, such as severe braking maneuvers and jerking before an accident. The ADAS shows different warning signals or movements from drivers' driving behaviours depending on the SSM employed in the system, which may lead to low reliability and low satisfaction. In order to explore the characteristics of existing SSMs in terms of human driving behaviours, this study analyzes collision risks estimated by three different SSMs, including Time-To-Collision (TTC), Stopping Headway Distance (SHD), and Deceleration-based Surrogate Safety Measure (DSSM), based on two different car-following theories, such as action point model and asymmetric driving behaviour model. The results show that the estimated collision risks of the TTC and SHD only partially match the pattern of human driving behaviour. Furthermore, the TTC and SHD overestimate the collision risk in deceleration process, particularly when the subject vehicle is faster than its preceding vehicle. On the other hand, the DSSM shows well-matched results to the pattern of the human driving behaviour. It well represents the collision risk even when the preceding vehicle moves faster than the follower one. Moreover, unlike other SSMs, the DSSM shows a balanced performance to estimate the collision risk in both deceleration and acceleration phase. These research findings suggest that the DSSM has a great potential to enhance the driver's compliance to the ADAS, since it can reflect how the driver perceives the collision risks according to the driving behaviours in the car-following situation.

## 1. Introduction

Rear-end collision is one of the most frequent traffic accidents on the roads. Common contributing factors for the rear-end crashes include driver's inattention and human misjudgments on the amount of required deceleration in car-following situation. In efforts to prevent the rear-end crash and improve vehicular safety, drivers' judgments must be assisted and guided based on current or upcoming traffic situations. For such matter, various Advanced Driver Assistance Systems (ADAS) such as Forward Collision Warning System (FCWS) and Emergency Braking System (EBS) have been developed based on different data sources, including camera, radar, LIDAR, GPS, and connected vehicle network. The FCWS and EBS are designed to give warning signals or implement braking autonomously by detecting hazardous situations before a collision ahead of vehicle even occurs. One of major concerns to provide the collision warning or implement the autonomous braking in the ADAS is how the criticality of a certain traffic situation for a vehicle is assessed. To deal with the related problems, various assessment approaches have been proposed. One of the representative methods for identifying the rear-end collision risk is Surrogate Safety Measure (SSM). The SSM calculates the collision risk of a certain traffic situation with microscopic traffic parameters such as vehicle speed, acceleration, time headway, and space headway. There have been various efforts in developing SSMs for the FCWS or EBS based on the parametric method. The previous studies on the SSMs can be classified into two types. One is the perceptual approach and the other is the kinematic approach [1]. The perceptual approach-based SSM is designed to measure the collision risk based on the thresholds of perception. The representative of such approach is Time-To-Collision (TTC) [2], which estimates the expected time for two successive vehicles to collide. Some modified TTCs have been proposed, such as Inverse TTC [3], Time Exposed TTC [4], Time Integrated TTC [5], and Modified TTC [6]. On the other hand, the kinematic approach-based SSM is to estimate the rear-end collision risk based on the difference between the required stopping distances of two consecutive vehicles. There have been numerous SSMs based on this this approach, such as Potential Index for Collision with Urgent Deceleration (PICUD) [7–9], Stopping Distance Index (SDI) [10, 11], Stopping Headway Distance (SHD) [12], Crash Index (CI) [13], and Deceleration Rate to Avoid the Crash (DRAC) [14]. More recently, Deceleration-based Surrogate Measure (DSSM) was proposed by considering a human-centered design [15], and such design significantly affects the performance of the risk evaluation since the human-related parameters are strongly related to the situational awareness measure [16]. Similar to the perceptual approach-based SSMS, the kinematic approach-based SSMs are also used for assessing the safety of a vehicle and giving warning signals to the driver. The previous researches demonstrate that these SSMs show good performances in detecting critical events such as severe braking or jerk maneuvers before a collision.

On the other hand, one of the most critical factors of the SSMs employed in the FCWS and EBS is driver's compliance, which is highly correlated with the system reliability [17]. For example, a conservative SSM designed particularly for passive drivers will give frequent alerts to aggressive drivers in most cases. Then, the driver can become desensitized to the nuisance warnings [18]. On the other hand, imminent threat alerts given by an aggressive SSM may lead to missed alarms, which may not provide enough time to avoid an upcoming collision risk [19]. Therefore, drivers become more intended to ignore such system and they can nullify the effects of potential benefits from the system [20]. However, most of the previous studies on the SSMs applied to the FCWS and EBS have focused on discriminating possible collision situations in a subsequent few seconds, rather than tracking the estimated collision risk according to the drivers' driving behaviours in the entire car-following process. Therefore, there may exist inconsistency between the driver's perception of risk and the actual level of hazard.

Thus, there is a need for exploring the characteristics of existing SSMs particularly in terms of such inconsistency. For such purpose, this study aims to analyse and compare the collision risks estimated by different SSMs based on two different car-following theories, such as action point model and asymmetric driving behaviour model. DSSM is specifically is selected as the representative of human-centered design that considers the inconsistency between the driver's perception of risk and the actual level of hazard. TTC and SHD are selected as the representatives of each of the perceptual approach and kinematic approach, respectively, and they are used as the benchmarking points to be compared with DSSM. In fact, DSSM is basically based on the kinematic approaches like SHD. Compared to the SHD, which calculates the collision risk based on the variables obtained from sensor equipped in the vehicle, DSSM calculates the collision risk with more variables such as jerk rate, acceleration, and transition time for the application in Vehicle-to-Vehicle (V2V) communication environment. By comparing the SHD and DSSM, the characteristics of risk estimation with different technology bases (sensor-based and V2V communication-based) can be shown.

Considering the relationship between the driving behaviours and the collision risk estimated by the SSMs provides a foundation for monitoring the reaction of drivers to the collision risk, which can reflect the different preferences of drivers on the collision risk. The detailed explanation on the analysis method is provided in the following section. Then, Sections 3 and 4 describe the comparison results of the three SSMs according to the action point model and asymmetric driving behaviour model, respectively. Finally, brief concluding remarks are provided in the last section.

## 2. Analysis Approach

*2.1. Car-Following Models for Analysis.* To analyze the relationship between driving behaviour and collision risk in car following situation, several traffic variables are considered in this study. The traffic variable includes speed of a subject vehicle, spacing between the subject vehicle and preceding vehicle, and the relative speed between the two consecutive vehicles. There are two types of car-following processes discussed in this paper to examine the different levels of collision risk with the actual driver behaviour.

First one is analyzed in the spacing-relative speed plane, which adopts the perspectives used in action point model [21]. The action point model, which is also known as psycho-physiological car-following model, considers drivers' perception thresholds for a certain minimum value of the stimulus based on the spacing and relative speed [22]. This analysis would show how drivers react differently to the collision risk according to the changes in the spacing and relative speed. In the action point model-based analysis, the state of a vehicle is defined by using both the spacing and relative speed. Therefore, the state of a subject vehicle is not defined solely by the speed in a car-following situation of two consecutive vehicles.

Nonetheless, the speed of subject vehicle shows an important aspect of vehicle' state in a car-following process since the driver determines the acceleration depending on not only the relative speed but also the speed of the subject vehicle [23, 24]. Hence, the second method of analyzing car-following process is suggested to show a different aspect of the car-following process by focusing on a speed of subject vehicle and spacing based on the asymmetric driving behaviour [24]. The car-following process of asymmetric driving behaviour can show how a driver differently reacts to the collision risk when the vehicle is in acceleration phase and deceleration phase.

These two types of car-following processes describe how drivers perceive the collision risk in terms of the spacing, speed of subject vehicle, and relative speed. It is expected that the results of the analysis can explain why drivers show inconsistent choices of headway in car-following situations. However, these two types of car-following processes can describe only some parts of the highly complex human driving behaviours. These two types of car-following processes suit for the human driving behaviours in the stationary traffic state, particularly with the situations that both lead and following vehicles' speed are less than the free flow speed (or speed limit). Since the scope of this study is within such specific cases that have the high possibility of rear-end collision, we extract the car-following cases without any disturbances such as a vehicle cutting in or changing lane for the SSMs analysis.

*2.2. Safety Surrogate Measures for Comparison.* For analysis on the relationship between driving behaviour and collision risk, investigating different SSMs are necessary to be compared. This study considers three SSMs to estimate the collision risks at a given traffic situation, which includes the TTC, SHD, and DSSM. Since these three SSMs have different perspectives on the collision risk, their performances may be different from each other, even in identical traffic situations.

First introduced by Hayward [2], the TTC is one of the most representative indicators for judging the dangerous situation [25, 26]. It estimates the collision risk between two consecutive vehicles by calculating the remaining time before following vehicle crashes into a front vehicle with the assumption that the path and speed of two consecutive vehicles are maintained. The TTC is defined by

$$TTC = \frac{\left[x_{n-1}(t) - x_n(t) - s_{n-1}\right]}{\left[v_n(t) - v_{n-1}(t)\right]} \quad (1)$$

where $v_{n-1}(t)$ is the speed of leader vehicle at time $t$, $v_n(t)$ is the speed of following vehicle at time $t$, $x_{n-1}(t)$ is the location of leader vehicle at time $t$, $x_n(t)$ is the location of following vehicle at time $t$, and $s_{n-1}$ is the length of leader vehicle. For example, a pre-determined TTC threshold value is 2.0 seconds. The current car-following situation is safe when the TTC value is greater than or equal to the threshold value, while the TTC value gets closer to zero as the rear-end collision risk increases.

For evaluating the collision risk, the concept of safe stopping distance has also been used. Methods with this concept calculate the collision risk based on the difference between stopping distances of two consecutive vehicles with full deceleration rate. The methods with such concept calculate the collision risk by assuming that the leader vehicle suddenly brakes with the maximum deceleration rate. The condition that the stopping distance of leader is smaller than sum of stopping distance of the following vehicle and space headway of following vehicle is considered as a dangerous situation. The SHD is a representative safe stopping distance-based method, which can be formulated as follows:

$$SHD = \max\left[-1.47 \times \left(v_{n-1}(t) \times h_n(t) - v_n(t) \times \tau\right) + \left[\frac{v_{n-1}(t)^2 - v_n(t)^2}{30 \times (acc/g \pm Gr)}\right], 0\right] \quad (2)$$

where $h_n(t)$ is the time headway of the following vehicle at time t, $\tau$ is the perception reaction time, *acc* is the deceleration rate, g is the gravity acceleration, and *Gr*, the grade expressed as a percentage. For example, a predetermined SHD threshold value is 20. It is risky situation when the SHD value is greater than or equal to the threshold value, while the current situation is safe when the SHD value is less than the threshold value.

The DSSM is also one of the concepts using the safe stopping distance-based method, which can well represent the individual collision risk in both acceleration and deceleration phases compared to other SSMs by adopting the transition time [15]. The DSSM is a ratio of the required deceleration and maximum deceleration performance of a subject vehicle, which is defined as follows:

$$K = \left[x_n(t) - x_{n-1}(t) + s_{n-1}\right] + \left[2 \cdot v_n(t) + a_n(t) \cdot \tau\right] \cdot \frac{\tau}{2} - M_{n-1,Tran} + M_{n,Tran} \quad (3)$$

$$b_n(t) = b_{max,n-1} \cdot \frac{\left[v_n(t) + a_n(t) \cdot \tau\right]^2}{\left[2 \cdot K \cdot b_{max,n-1} + v_{n-1}(t)^2\right]} < 0 \quad (4)$$

$$DSSM = \frac{b_n(t)}{b_{max.n}} \quad (5)$$

where $a_n(t)$ is the acceleration rate of following vehicle at time $t$, $a_{n-1}(t)$ is the acceleration rate of leader vehicle at time $t$, $b_{max.n-1}$ is the maximum braking rate of leader vehicle, which represents the vehicle's mechanical deceleration performance, $b_n(t)$ is the needed deceleration rate of following vehicle to avoid the accident at time $t$, $b_{max.n}$ is the maximum braking rate of following vehicle, $M_{n-1}$ is the stopping distance of leader vehicle during transition time, and $M_n$ is the stopping distance of following vehicle during transition time, $\tau$ is the perception reaction time. For instance, a predetermined DSSM threshold value is 1. It is an unsafe situation when the DSSM value is greater than or equal to the threshold value, while the DSSM value is less than the threshold value when the current driving situation is safe.

*2.3. Data Description.* For analysis on the relationship between the driving behaviours and the collision risks estimated by the different SSMs, this research uses one of the Next Generation Simulation (NGSIM) trajectory datasets, which is collected from a segment of U.S. Highway 101 in Los Angeles, California, between 7:50 a.m. and 08:35 a.m. on 15 June 2005 [27]. The length of the study site in the

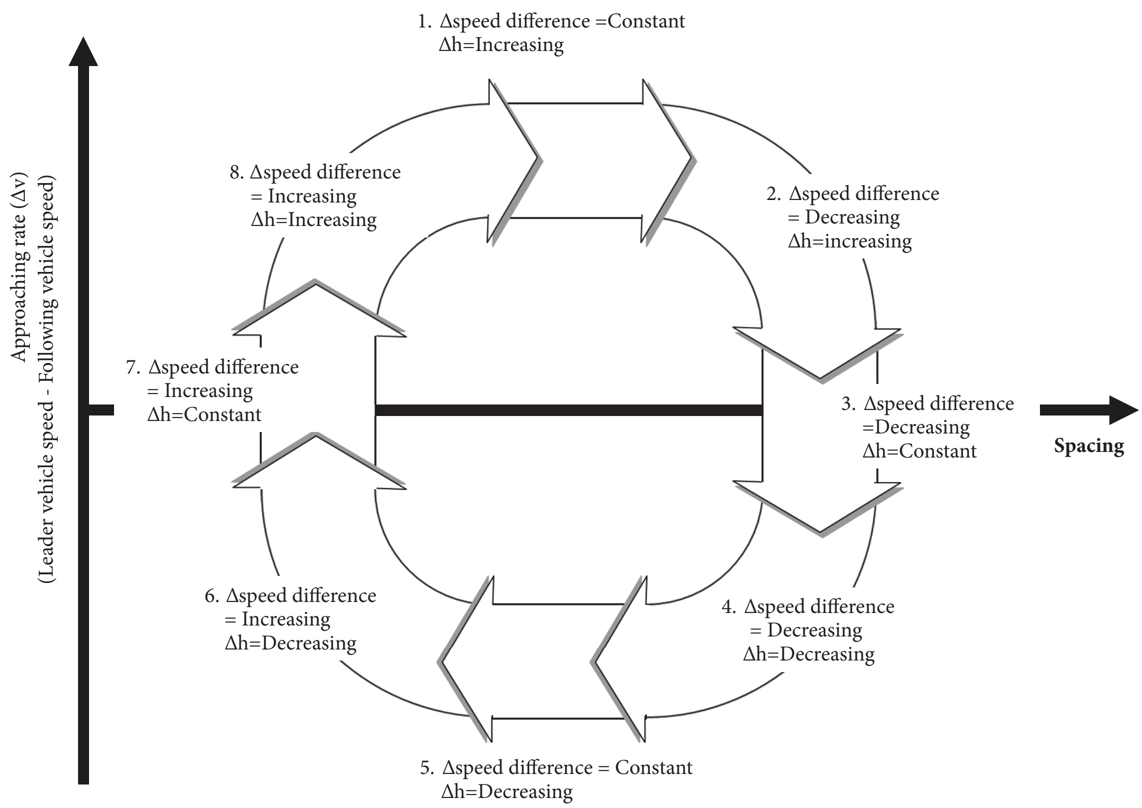



Figure 1: The Classification of driving state of subject vehicle.

NGSIM dataset is 640 m with five main lanes. The data contains microscopic traffic information on individual vehicular movements' trajectories, which includes location, speed, space headway, acceleration/deceleration, and vehicle type at 0.1 sec time intervals. Among the car-following cases in the dataset, 143 car-following cases that do not experience any disturbance such as cut-in and cut-out vehicle when passing through the study site are extracted, excluding motorcycles and trucks.

## 3. Comparison Analysis in Spacing-Relative Speed Plane

*3.1. Action Point Model Perspective.* As the first step of conducting comparison study, this study compares the SSMs with each other from the perspectives of the action point model. In other words, the collision risks estimated by the three SSMs will be described in the spacing-relative speed plane. As stated earlier, the car-following process of the action point model represents the driving behaviour with the psychophysical basis and shows how the driver of subject vehicle adjusts the differences in the locations and speeds between the leader and subject vehicle. In the action point model, a driver's decision is made upon certain perception threshold values. When the speed of preceding vehicle is much greater than the subject vehicle, the state of subject vehicle exceeds the perception threshold of relative speed. Then, the driver of the subject vehicle decides to accelerate. On the other hand, when the speed of preceding vehicle is much less than the subject vehicle, the state of subject vehicle exceeds the perception threshold of relative speed in negative direction. Then, the subject vehicle decreases its speed. The spacing adjustment procedure is arranged similarly in the action point model. When the spacing is much greater than the desired spacing, the state of the subject vehicle exceeds the perception threshold of spacing. Then, the subject vehicle increases the speed to reduce the spacing. In contrast, the state of the subject vehicle exceeds the perception threshold of spacing in negative direction when the spacing is much less that the desired spacing. Then, the subject vehicle reduces its current speed. Based on the two kinds of perception thresholds and driving behaviour, the driver in the subject vehicle makes a decision for either accelerating or decelerating.

Hence, in the action point car-following process, the spacing and relative speed are important variables that directly affect the decision on acceleration and deceleration action. By using these two variables, the state of the subject vehicle can be defined as shown in Figure 1.

The state of the subject vehicle can be described by eight states. The states 1, 2, and 8 represent the situations of when the preceding vehicle is faster. And in states 4, 5, and 6, the preceding vehicle is slower than the subject vehicle. The states 1 and 5 are also the points that the driver makes the decision on acceleration and deceleration. After the state 1, which is called as "catch up" action point, the collision risk is increased

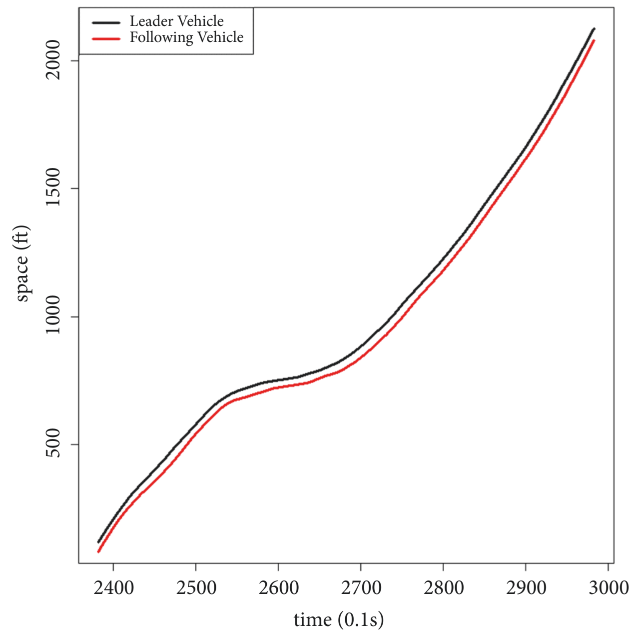



FIGURE 2: The example case for the analysis.

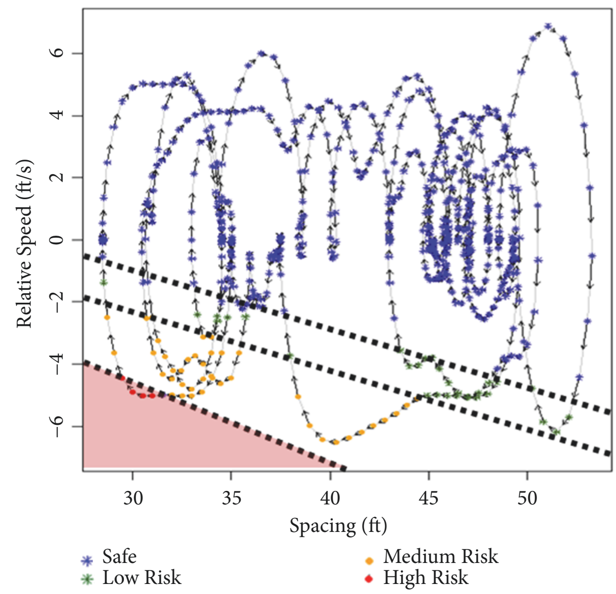



FIGURE 3: Collision risk estimated with the temporal spacing and relative speed (TTC).

due to the acceleration actions. After the state 5, which is called as "release" action point, the collision risk is decreased due to the deceleration actions. In other states, the driver maintains the decision made in the states 1 and 5.

An example case of car-following for the analysis is depicted in Figure 2. In the figure, the black and red lines are the trajectories of the leader and subject vehicle, respectively. One can easily observe that the car-following case meets a shockwave and shows the both acceleration and deceleration behaviours.

*3.2. Car-Following and Collision Risk by TTC.* According to the example case shown in Figure 2, the collision risks estimated by the TTC are shown in Figure 3. This figure shows the relationship between the vehicle spacing and the relative speed. The points in the plane represent the temporal measurements of the two properties and the solid lines with arrows connect the sequence of these points. As we can see in the figure, the temporal measurements draw circles recurrently on the plane during the car-following situation, and it is shown that the low relative speed values with the low spacing values tend to have the high collision risk. In this paper, the collision risks are discretionarily classified into four situations for the quantitative analysis. By the concept of TTC, the risk is considered to be high when the TTC value is low. Thus, the four classified situations considered in this paper are High Risk (TTC ≤ 2.5), Medium Risk (2.5 < TTC ≤ 5.0), low risk (5.0 < TTC ≤ 7.0), and Safe (TTC > 7.0). Note that since there have not been any previous efforts for defining the exact thresholds of the high or low risk at the current stage, the thresholds classifying the risk levels in this study are defined based on the empirical understandings with the given data. In fact, such thresholds may vary depending on the road characteristics or driving environments. Hence, some sensitivity analyses are required to investigate the issue further, but they go beyond the scope of this paper.

As shown in Figure 3, the TTC generally considers that it is safe when the preceding vehicle is faster than the subject vehicle. Hence, it only classifies the states 4, 5, and 6 into the dangerous situations. In TTC, at the similar level of spacing, the collision risk consistently increases as the relative speed decreases. At the similar level of relative speed, the collision risk also consistently increases as the spacing decreases. The level of collision risk is also indicated with different colours in the spacing and relative speed plane. Particularly, the red coloured region indicates that the driving situation is dangerous by the TTC estimation.

In terms of the action point car-following perspective, the collision risks estimated by the TTC do not match well to the action points where a driver changes acceleration and deceleration. In the near perception thresholds, which correspond to the states 1, 2, 3, and 7, the changes in the action are rarely observed. Furthermore, the TTC is not a sensitive measure that has a lack of reflecting the dynamic changes of driving situation, and it misses out some parts of the action points.

*3.3. Car-Following and Collision Risk by SHD.* Similar to the method of using the action point model above, the collision risks estimated by the SHD are shown in Figure 4. Unlike TTC, the risk is considered to be high when the TTC value is also high in SHD. In this paper, the four classified situations based on SHD are High Risk (SHD > 40), Medium Risk (40 ≥ SHD > 0), Low Risk (0 ≥ SHD > -50), and Safe (-50 ≥ SHD). The SHD generally considers that it is not safe when the subject vehicle is faster than the preceding vehicle. The situations with high collision risks determined by the SHD are the states 4, 5, and 6. However, unlike the TTC that

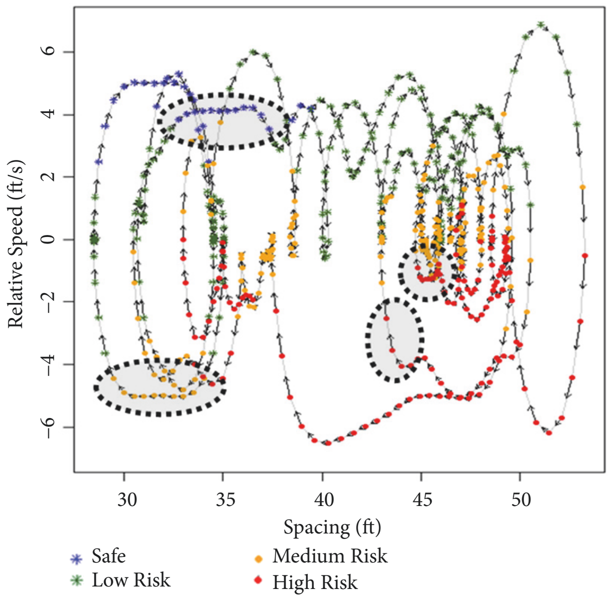



Figure 4: Collision risk estimated with the temporal spacing and relative speed (SHD).

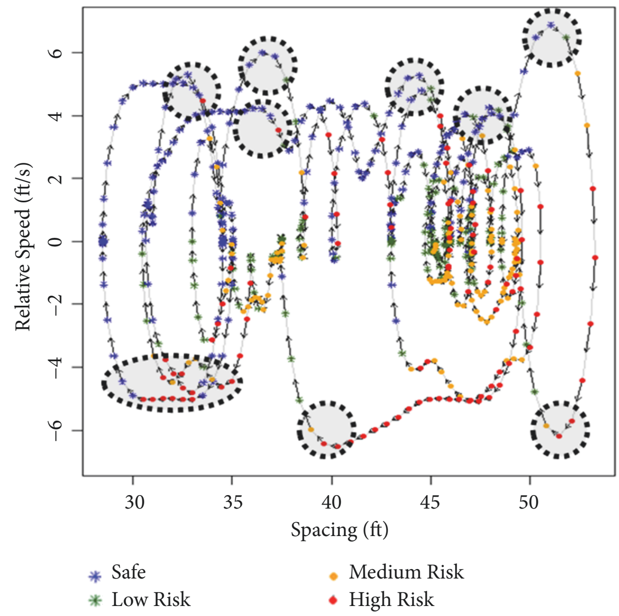



Figure 5: Collision risk estimated with the temporal spacing and relative speed (DSSM).

considers high risk only when the subject vehicle is faster, the high collision risk is determined by the SHD also when the preceding vehicle is faster than the subject vehicle. In terms of the spacing, there is a significant difference between the SHD and the TTC. The high collision risk in the TTC mainly occurs when the spacing is small, but it is widely distributed over the entire spacing regions in the SHD. As the result, the SHD can evaluate the collision risk in the wider range of vehicle states in the spacing and relative speed plane.

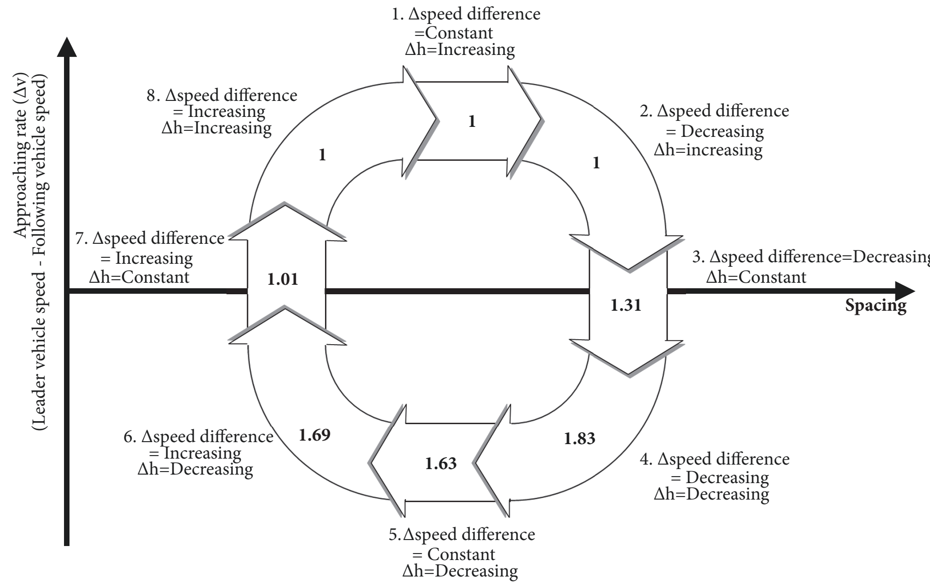
Compared to the TTC, the collision risk in the SHD is more dynamically changed during the car-following process shown in Figure 4. Some corresponding points with the action points are observed, where the driver's driving behaviour is changed due to the excess of perception threshold. The observed action points are marked with the black dotted circles in Figure 4. Before and after the observed action points, the SHD shows approximately one-step difference in terms of collision risk. However, the changing trends of estimated collision risk of the SHD do not match well to the action points of the human driver overall.

*3.4. Car-Following and Collision Risk by DSSM.* Similar to the TTC and SHD, the DSSM considers also that it is dangerous when the subject vehicle is faster than the preceding vehicle, as shown in Figure 5. For the DSSM cases in this paper, the four classified situations are High Risk (DSSM $\geq$ 1.1), Medium Risk (1.1 $>$ DSSM $\geq$ 0.9), Low risk (0.9 $>$ DSSM $\geq$ 0.75), and Safe (0.75 $>$ DSSM). The high collision risk situations are shown in the states 4, 5, and 6. Nonetheless, DSSM shows distinctive differences from other SSMs.

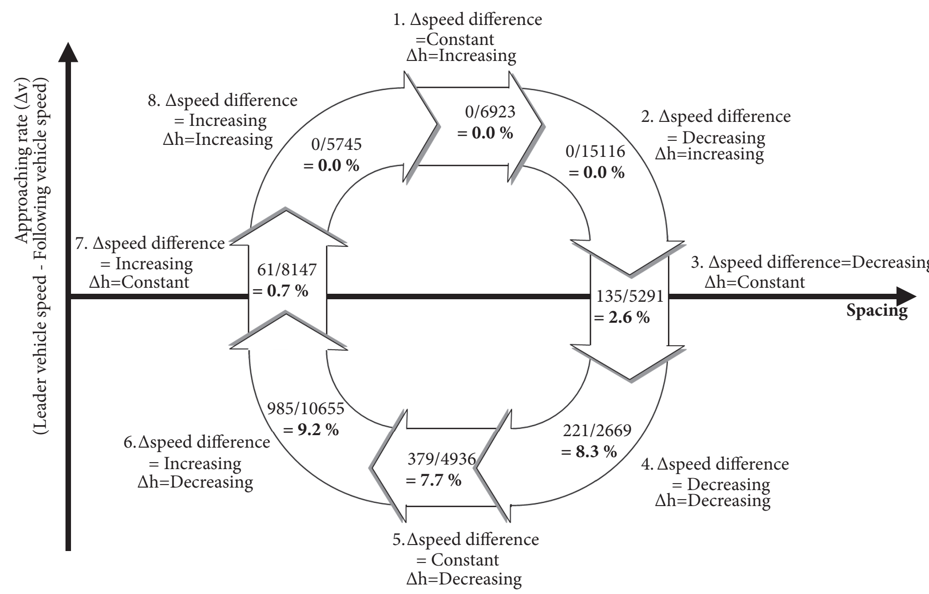
First, the DSSM does not show increasing or decreasing trend only with the relative speed or spacing respectively. In the TTC, the collision risk increases as the relative speed and spacing decrease overall, so that the high collision risk does not occur when there is a large value of the relative speed and spacing. In the SHD, the collision risk generally increases as the relative speed decreases, while it decreases as the spacing decreases overall. Therefore, the high collision risk hardly occurs when there is large relative speed value. On the other hand, the DSSM shows that a high collision risk occurs in all regions, even when the preceding vehicle is faster than the subject vehicle, as shown in Figure 5. Consequently, the DSSM can identify more various dangerous situations than other SSMs in all states of the action point car-following process.

Second, DSSM shows more well-matched results to the human driving behaviour in terms of the action point car-following process. As shown in Figure 5, the collision risk estimated by the DSSM is significantly changed before and after the action points, which are marked with the black dotted circles. After the action points where the preceding vehicle is slower than the subject vehicle, the estimated collision risk is sharply decreased. After the action points, which occur when the preceding vehicle is faster than the subject vehicle, the estimated collision risk of the DSSM shows increasing trend and high collision risk is also observed. This wide perceiving capability of the DSSM beyond the TTC and SHD is from the consideration of vehicles' acceleration in the evaluation of the risk.

*3.5. Comparison of Average Collision Risk and High Collision Risk.* Based on the classified states described as Figure 1, the trends of the estimated average collision risk and frequency of high collision risks are analyzed. The average collision risks of each SSM are calculated with the four classified situations: safe situation, low risk situation, medium risk situation, and




(a) Average collision risk




(b) Frequency of high collision risks

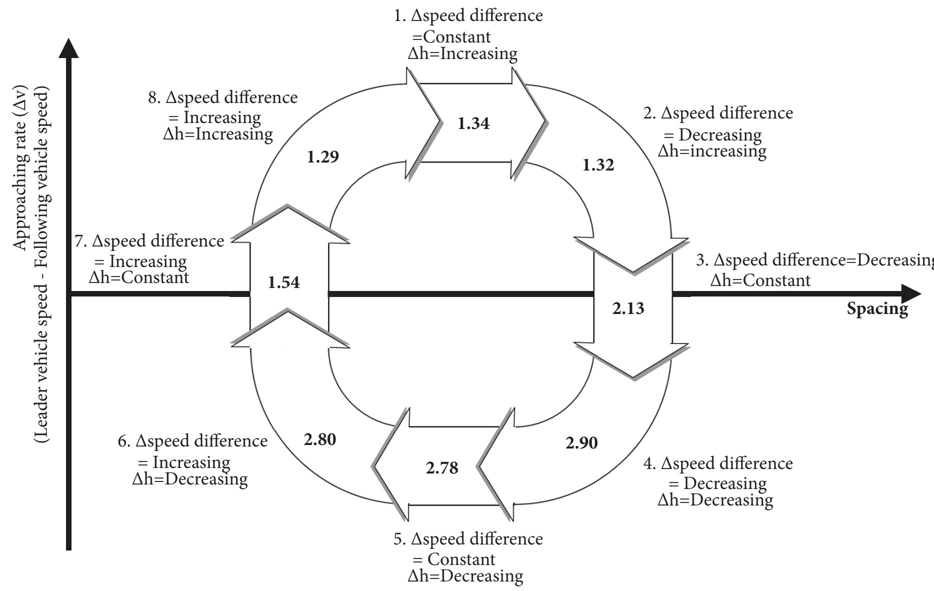
FIGURE 6: The TTC trends on the average collision risk and frequency of high collision risks.

high risk. The four classified situations are graded as 1, 2, 3, and 4, discretionary for the quantitative analysis. The frequency of high collision risks is computed by the same criteria used in average collision risk evaluation, but only the high-risk situations are counted. The number of high-risk situations is divided by the total number of exposure for each classified states.

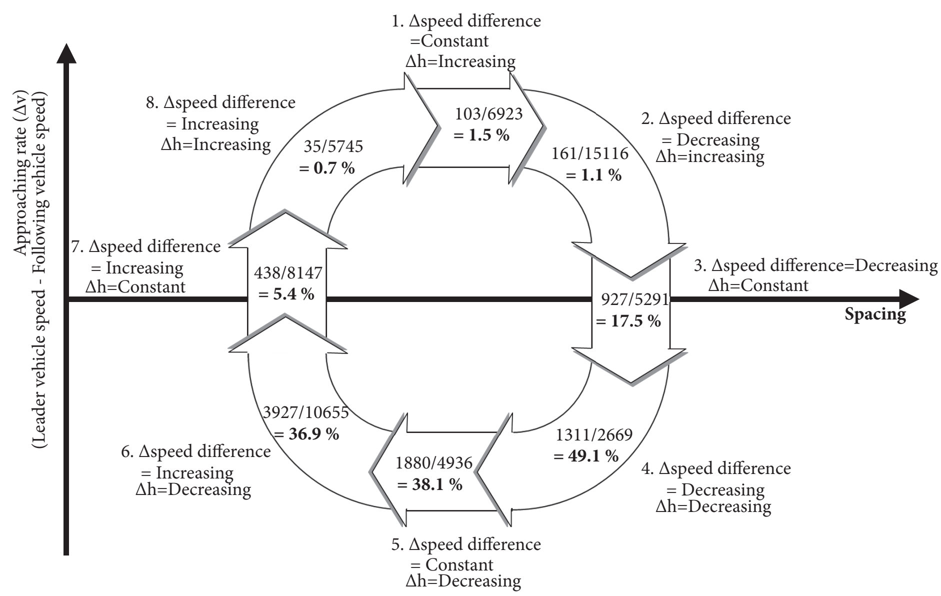
Figure 6 shows the average collision risk and the frequency of high collision risks of the TTC based on the 143 car-following cases. As depicted in Figures 6(a) and 6(b), it can be seen that the TTCs do not show any common behaviours with the action points of the drivers. The average collision risk estimated by the TTC does not show any variations near the states 1 and 5, which are the situations when the drivers decide and change the actions of acceleration and deceleration. No specific relationship between the collision risk and driving actions is observed in the trend of collision risk estimated by the TTC.

Similarly, the SHD can evaluate collision risk in more various states compared to the TTC, as shown in Figure 7.

However, the high collision risks estimated by the SHD are concentrated when the subject vehicle is faster than the preceding vehicle. Moreover, the SHD tends to overestimate the collision risk in these situations, such as state 4. In terms of the action point car-following perspective, the estimated collision risk of the SHD is partially matched to the action




(a) Average collision risk

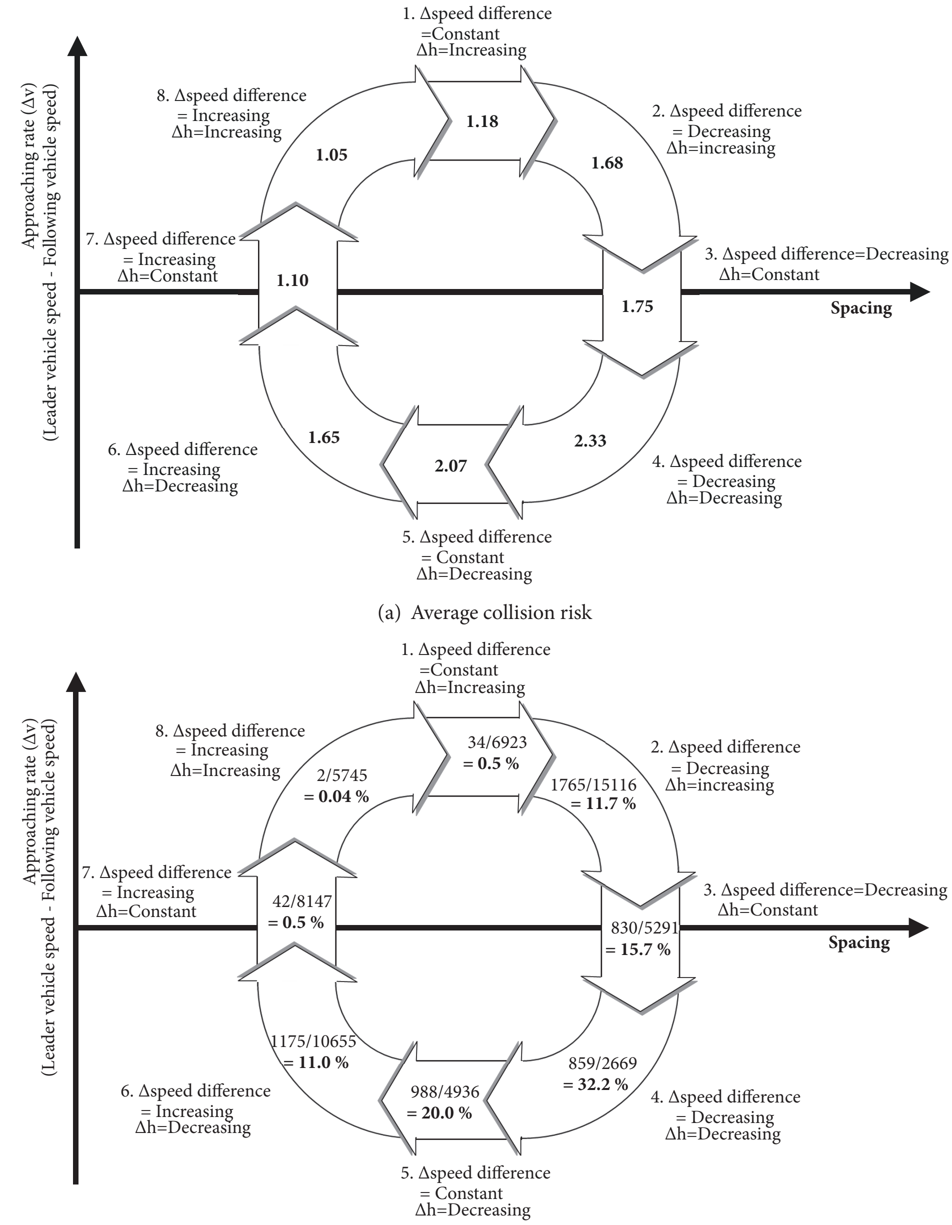



(b) Frequency of high collision risks

Figure 7: The SHD trends on the average collision risk and frequency of high collision risks.

point behaviours of the drivers. In the action point car-following behaviour, the driver decides and changes the actions of acceleration and deceleration near the perception thresholds, which leads to the changes in the collision risks near state1 and state 5. Near state 5, the SHD shows the similar trend to the driving action of human. When the state is changed from 4 to 5, the SHD value decreases even though the variation is not significantly large. When the state is changed from 5 to 6, the SHD value increases. Near the state 1, SHD shows the dissimilar trend to human behaviour. When the state is changed from 1 to 2, the SHD decreases even though the driver is catching up the speed.

In Figures 8(a) and 8(b), the DSSM can evaluate collision risk from more states compared to TTC and SHD. For both analyses, the maximum values are observed in state 4, while the minimum values are observed in state 8. Near these two states, the average collision risk and frequency of high collision risk show the same increasing and decreasing trends. Given this result, the DSSM is the only SSM, in which the severity grade of the collision risk is divided in balance. Therefore, it can be said that the collision risk by DSSM is well matched to the action point behaviour. Overall, the DSSM continuously increases when the state is changed from 1 to 5. And it continuously decreases when the state is changed from




(b) Frequency of high collision risks

Figure 8: The DSSM trends on the average collision risk and frequency of high collision risks.

5 to 1. In detail, near the action points, which are states 1 and 5, the estimated collision risk of DSSM is changed with the similar process of the action point car-following behaviour. After the catch-up action points, which is state 1, the DSSM value rapidly increases. Conversely, near the release action point, which is state 5, the DSSM decreases. Especially, when the state is changed from 5 to 6, more significant decreasing trend of DSSM value is observed compared to that of SHD value due to the release action in state 5. These results coincide with the previous research findings in other car-following models, which is based on the action point driving behaviour [21, 28–32].

## 4. Comparison Analysis in Speed-Spacing Plane

*4.1. Analysis from Asymmetric Behaviour Perspective.* The action point model-based analysis shows well how a driver reacts to the external stimuli by focusing on the relationship between the leader and subject vehicle. However, in the spacing and relative speed plane, it still has a limitation to fully describe the human driving behaviour since it does not consider the absolute speed of the subject vehicle. In order to investigate the effect of such property, we analyze the relationship between the collision risk and the asymmetric driving behaviour. In the asymmetric theory, drivers show different patterns in the acceleration and deceleration phases, and such phenomenon has been observed by several researchers since the 1960's [33–38]. In this theory [24, 39, 40], drivers show two different curves of acceleration curve (A-curve) and deceleration curve (D-curve) with different spacing for the same speed. The A-curve is the boundary curve in the acceleration phase and the D-curve is the boundary curve in the deceleration phase of the car-following situations. In the A-curve, the two consecutive vehicles maintain larger spacing than in the D-curve for the same corresponding speed. The A-curve can be found by connecting the ending points of accelerating actions, and the D-curve can be found by connecting the ending points of decelerating actions. In addition, near the each of the A-curve and D-curve, an acceleration action point line and a deceleration action point line can be observed as well, respectively. The acceleration action point line can be found by connecting the starting points of accelerating actions, and the deceleration action point line can be found by connecting the starting points of decelerating actions.

These accelerating and decelerating actions in the A-curve and D-curve are highly related to the collision risk of the driver. When a driver accelerates to catch up with the leader vehicle's speed during the acceleration process, the driver increases the speed until the collision risk becomes larger than a certain threshold or the desired speed is reached. After that, if the spacing increases and the collision risk drops below certain threshold again, the driver takes acceleration again in order to keep the appropriate spacing. The accelerating actions appear repeatedly to keep the appropriate spacing and collision risk. On the other hand, during deceleration process, the driver reduces the speed until the collision risk is smaller than a certain threshold. After that, if the spacing decreases again and the collision risk is higher than a certain threshold value, the driver decelerates again. The decelerating actions also appear repeatedly in order the keep the appropriate level of collision risk. Based on such logic, a high collision risk would appear near the acceleration and deceleration action point line. Therefore, the estimated collision risk may indicate the timings of the acceleration and deceleration actions.

*4.2. TTC in Speed-Spacing Plane.* Based on the basic relationship between the collision risk and asymmetric driving behaviour, we analyze the three SSMs in the spacing-speed plane. Figure 9 shows the collision risks estimated by the TTC in the spacing-speed plane. The example case shown in Figure 2 is used in these analyses as well.

In the figure, the blue stars, green stars, yellow circles, and red circles represent the safe situation, low risk situation, medium risk situation, and high risk situation, respectively. The dashed lines represent the virtual deceleration action point line, D-curve, A-curve, and acceleration action point line, respectively, from left to right. The dashed lines shift to right or left depending on the driver's psychology on external stimuli and traffic state.

Figure 9 shows the collision risks estimated by the TTC in the spacing-speed plane. As shown in Figure 9, a variation

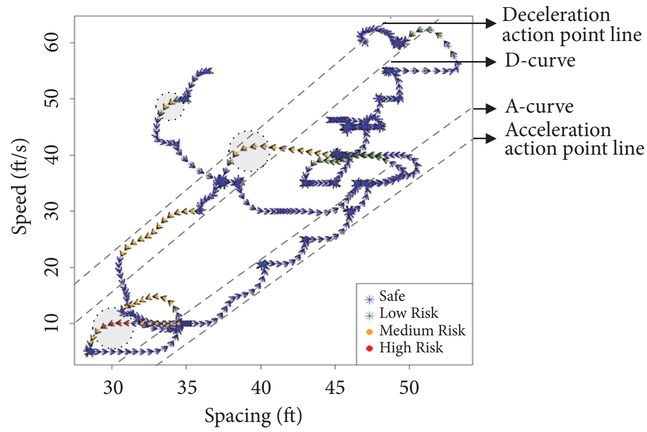



Figure 9: Collision risk estimated with the temporal spacing and speed (TTC).

of the collision risks estimated by the TTC is not large as much as the variation of driver's acceleration behaviours. This result shows that TTC is not a sensitive measure to driving actions. Some high and medium collision risk of TTC is only occurred in the deceleration process. Among these high and medium collision risk of TTC, only the three situations, which are marked with black dotted circles in Figure 9, can describe the human driving behaviour in the deceleration process. In these circled areas, it is observed that the collision risk is high until the state of driver reaches deceleration action point line. After that, the risk decreases as the driver reduces the speed overall. In the acceleration process, the high or medium level of collision risks is not observed, and most of the acceleration processes are considered as the safe situation. In the acceleration process, the leader vehicle is generally faster than the subject vehicle since the subject vehicle accelerates after the preceding vehicle accelerates with response-time delay. Therefore, in this process, the TTC does not properly evaluate the collision risk, because the TTC only evaluates the collision risk when the subject vehicle is faster than the preceding vehicle.

*4.3. SHD in Speed-Spacing Plane.* Figure 10 shows the collision risks estimated by the SHD. Compared to the TTC, the SHD value is more dynamically changed according to the driving action.

The SHD can identify the high collision risk during the acceleration process contrarily to what the TTC can identify only during the deceleration process. The matched results to the driving behaviour during both the acceleration and the deceleration processes are observed and they are marked by the solid and black dotted circles, respectively. In black dotted circled areas, the collision risk is decreased as the driver reduces the speed. After the state of vehicle reaches to D-curve, the driver maintains constant speeds and the SHD value is increased again. In black solid circled areas, the collision risk is increased as the driver increases the speed. After the state of vehicle reaches the A-curve, the driver maintains the constant speed and the collision risk shows the decreasing trend.

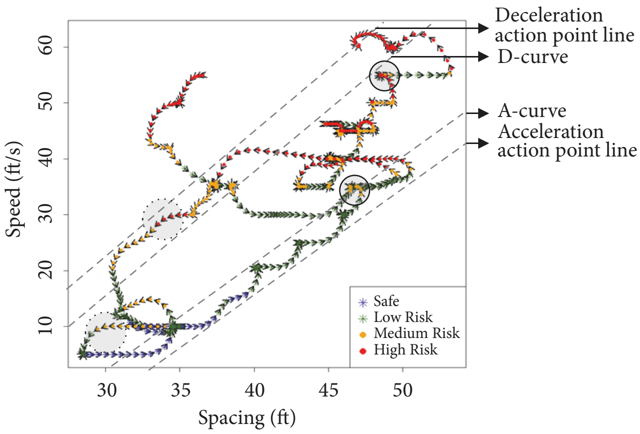



Figure 10: Collision risk estimated with the temporal spacing and speed (SHD).

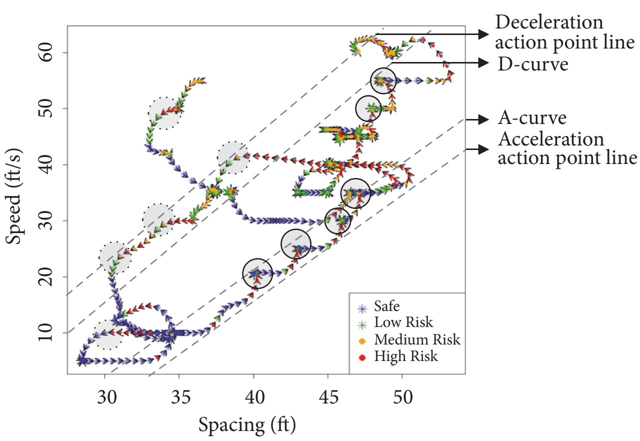



Figure 11: Collision risk estimated with the temporal spacing and speed (DSSM).

Even though the collision risks estimated by the SHD show more matched results to the asymmetric driving behaviour, they still show biased results due to several reasons. First, the SHD always considers the deceleration process as more dangerous situation than the acceleration process. The high collision risk is mainly distributed in the deceleration process and the sensitivity of collision risk to driving action is also high in the deceleration process. Second, the SHD is highly affected by the speed of subject vehicle itself. The collision risk estimated by the SHD generally increases as the speed of the subject vehicle increases overall. Due to these influences, the high collision risk is not observed when the speed of the subject vehicle is low, even though the state of the subject vehicle is near the acceleration action point line and deceleration action point line.

*4.4. DSSM in Speed-Spacing Plane.* Compared to other SSMs, the DSSM shows the most sensitive and well-matched results to the asymmetric driving behaviour, as shown in Figure 11.

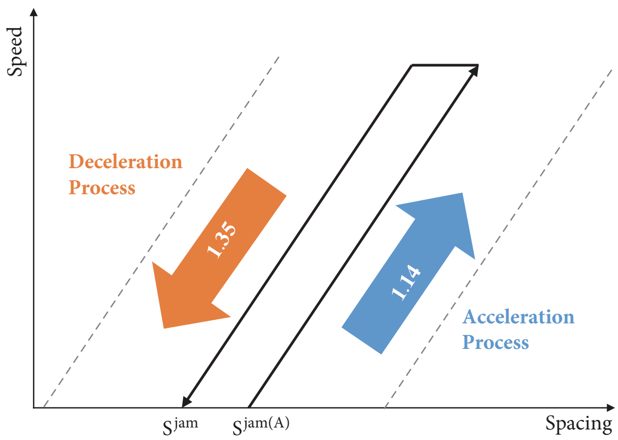
The black dotted circles and black solid circles are the representative cases of the matched situations during the acceleration and the deceleration processes, respectively. In the areas near the black dotted circles in the deceleration process, the high collision risks occur right before the state reaches to the deceleration action point line. The collision risks sharply decrease after the driver starts deceleration action. In the areas near the black solid circles in the acceleration process, the high collision risks occur right before the state of the subject vehicle reaches A-curve. The collision risks decrease right after the state of the subject vehicle reaches the A-curve and as it maintains a constant speed. The collision risks gradually decrease until the state of the subject vehicle reaches to the acceleration action point line.

*4.5. Comparison of Average Collision Risk and Frequency of High Collision Risk.* Figure 12 compares the average collision risk and the frequency of high collision risk of each SSM. The DSSM well captures the high collision risk particularly in acceleration process compared to other SSMs. Except for the DSSM, the TTC and SHD consider the deceleration process as more dangerous situation than acceleration process. The SHD shows the highest average collision risk in both acceleration process and deceleration process with approximately three or four times higher frequency of high collision risk than the TTC and the DSSM. Considering the slightly low successful alarm ratio of the SHD compared to the DSSM in previous research [15], the SHD has a tendency of overestimating the collision risk.

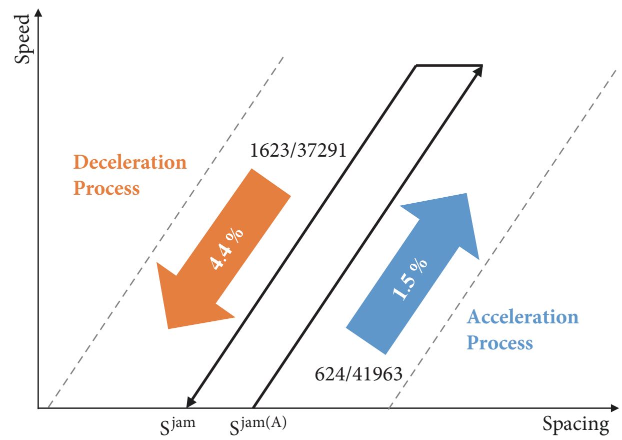
## 5. Conclusion

In order to investigate the relationship between collision risk and human driving behaviour, this study analyzes three different SSMs based upon two different car-following theories, including the action point model and asymmetric driving behaviour model. The three SSMs, including the TTC, SHD, and DSSM, show different characteristics and trend in estimating the collision risk. In the analysis with the action-point model, the estimated collision risks of the TTC and SHD only partially match with the pattern of driver's driving behaviour. The high collision risks are concentrated where the subject vehicle is faster than preceding vehicle, so both SSMs overestimate the collision risk particularly in such situations. On the other hand, one could observe that the DSSM shows well-matched results to action point behaviour of the driver. After the catch up action point, the collision risks estimated by the DSSM rapidly increase. Conversely, near the release action point, the DSSM value shows a decreasing trend. In the analysis with asymmetric driving model, the TTC and SHD show biased collision risks in the deceleration process. Especially, the SHD is highly affected by the speed of subject vehicle itself, so the high collision risk is rarely observed when the speed of subject vehicle is low. DSSM equally evaluates the collision risk during acceleration process and deceleration process and it shows well-matched results to acceleration and deceleration actions near acceleration and deceleration action point line.

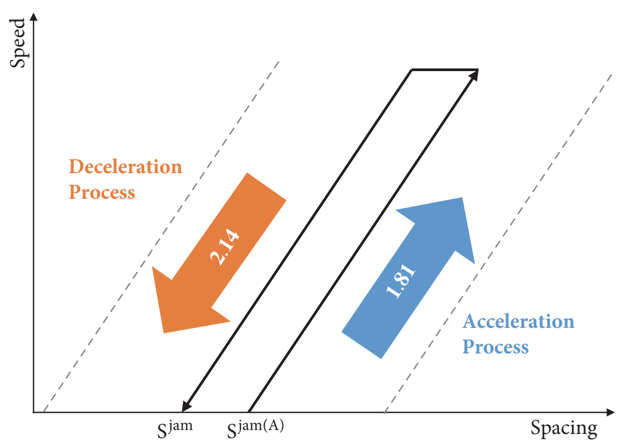
This study provides ample opportunities to design human-centered services of the FCWS and EBS in two



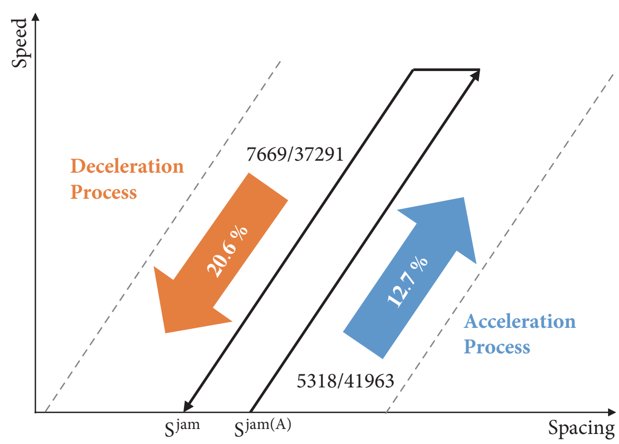

(a) Average collision risk trend and



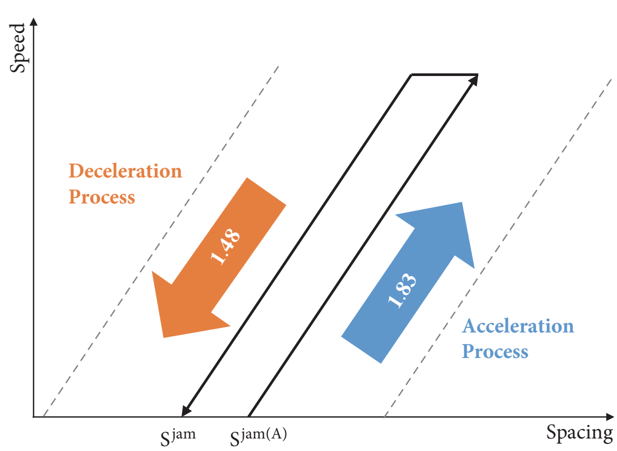

(b) Frequency of high collision risk trend of TTC



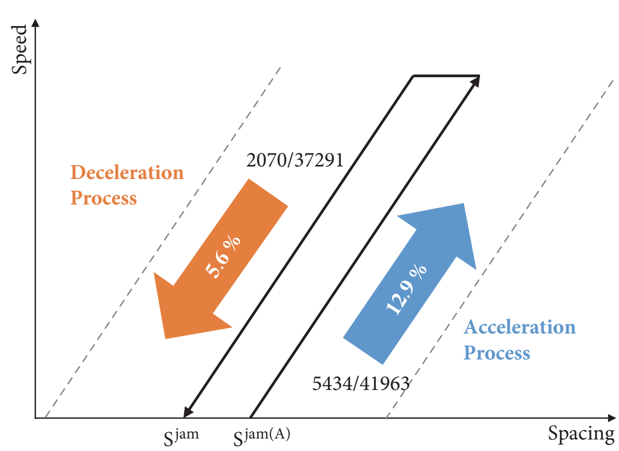

(c) Average collision risk trend and




(d) Frequency of high collision risk trend of SHD




(e) Average collision risk trend and




(f) Frequency of high collision risk trend of DSSM

Figure 12: Each SSM trends on their average collision risks and frequencies of high collision risks.

aspects. First, it can provide an opportunity for significantly reducing the false-alarm ratio of a collision warning system. The SSMs can estimate a more detailed state of a subject vehicle in terms of the collision risks in various traffic situations. The effect of small changes in the collision risks varied with different driving behaviours can be tracked and analyzed continuously. Based on the research findings of this study, not only dangerous situations but also the trend of increasing (or decreasing) collision risks can be identified. By providing warnings before collision risk reaches a higher level, safety-related services can significantly improve the accuracy and give enough time for drivers to prepare for a harsh braking. Second, it can render safety-related services more acceptable to drivers. In order to make a collision warning system be acceptable to human drivers, the judgment on dangerous situations of the system needs to be similar to that of the human drivers. Microscopic analyses on SSMs and driving behaviours would provide the foundation for monitoring the reaction of human drivers to the collision risk. Furthermore, by analyzing the relationship between driving behaviour and collision risk estimated by SSMs, the safety-related services can reflect the different preferences of drivers on the collision risk.

However, this current paper still has a limitation in that the thresholds classifying the risk levels are given based on the empirical understandings with the given data. It is due to that there has not been a previous effort for defining the exact thresholds of the high or low risk so far. In fact, such thresholds for the SSMs may vary depending on the road characteristics like the nature of traffic flow (uninterrupted or interrupted flow) and the free flow speed (or speed limit). The thresholds may vary by different regions or even by different countries. Hence, the results of this current paper shall be revisited later, by considering the variations of the thresholds. Thus, the sensitivity analysis of the thresholds is an essential research topic to be addressed in further studies. Furthermore, the comparative analyses in this paper were done only with the representative SSMs of the perceptual approach (TTC) and kinematic approach (SHD and DSSM). It is suggested also to try other various SSMs while conducting further sensitivity analysis. In addition, the difference among the kinematic approaches like the SHD and DSSM is the selection of the obtainable microscopic variables to be used for the risk calculation, such as the spacing and relative speed, and these variables must be obtainable in real-time. Considering the application of the autonomous vehicles in the near future, in which more detailed information can be obtained in real-time, it is also suggested to develop the existing SSMs further into the more advanced form that can take account into various safety-related variables, such as real-time jerk rate and acceleration.

## Data Availability

The 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.

## Acknowledgments

This research was supported by the Ministry of Land, Infrastructure, and Transport (MOLIT, KOREA) [Project ID: 18TLRP-B146748-01-000000, Project Name: Connected and Automated Public Transport Innovation (National R&D Project)] and the Ministry of Trade, Industry, and Energy (MOTIE, KOREA) [Project ID: 10063147, Project Name: Multi-Level Safety System for Intersection Collision Prevention].

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