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Investigating the Impact of Connected and Automated Vehicles on Signalized and Unsignalized Intersections Safety in Mixed Traffic

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Abstract: Road traffic crashes are a major safety problem, with one of the leading factors in crashes being human error. Automated and connected vehicles (CAVs) that are equipped with Advanced Driver Assistance Systems (ADAS) are expected to reduce human error. In this paper, the Simulation of Urban MObility (SUMO) traffic simulator is used to investigate how CAVs impact road safety. In order to define the longitudinal behavior of Human Drive Vehicles (HDVs) and CAVs, car-following models, including the Krauss, the Intelligent Driver Model (IDM), and Cooperative Adaptive Cruise Control (CACC) car-following models were used to simulate CAVs. Surrogate safety measures were utilized to analyze CAVs' safety impact using time-to-collision. Two case studies were evaluated: a signalized grid network that included nine intersections, and a second network consisting of an unsignalized intersection. The results demonstrate that CAVs could potentially reduce the number of conflicts based on each of the car following model simulations and the two case studies. A secondary finding of the research identified additional safety benefits of vehicles equipped with collision avoidance control, through the reduction in rear-end conflicts observed for the CACC car-following model.

Keywords: connected and automated vehicles; road safety; intersections; time to collision; mixed traffic; SUMO

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1. Introduction

Safety is one of the most important challenges for road transportation. According to the World Health Organization (WHO), there are approximately 1.3 million deaths per year due to road traffic crashes, and traffic deaths are expected to become the fifth most common cause of death by 2030 if the current trend continues [1,2]. Amongst all crashes, human error is a factor in approximately 90% of crashes [1,3]. Connected and Automated Vehicles (CAVs) are expected to significantly reduce road crashes by eliminating human error.

According to the typology defined by the Society of Automotive Engineers (SAE), there are five levels of CAV automation, from level 0 which describes fully manual driving to level 5 which describes fully autonomous driving [4], with the level of human intervention required in the driving task reducing at higher levels of the typology. Similarly, CAVs offer additional benefits over human drivers due to V2V communication [5], which allows vehicles to communicate with other road users and infrastructure. Using these systems CAVs can benefit from safety features, such as Cooperative Adaptive Cruise Control (CACC) to control the longitudinal movement of the vehicles [6].

Due to the automation and connectivity features of CAVs, it is necessary to investigate the effect of CAVs on different aspects of transportation, especially safety. However, because CAVs, particularly those operating at level 5 automation, are very uncommon on the roads, there is limited data available on CAVs. As such one of the current ways to evaluate the safety effects of CAVs is through a simulation framework.

This study investigates the impact of CAVs on the safety of arterial intersections using microsimulation. Previous studies [7,8] have often focused more on modeling the longitudinal behavior of vehicles than on conflict classification methods. These studies classified conflicts using a consistent approach based on the angle between two vehicles at risk and the link information. As such, previous studies lack an alternative method for classifying conflicts. This study addresses this issue by investigating the impact of CAVs on the safety of intersections considering route topology regardless of the angle of vehicles which means that not only positions and speeds of vehicles are effective in determining conflict but also the distance of vehicles to conflict area is an important factor in determining conflicts.

This study uses microsimulation to explore the impact of CAVs on traffic safety in an arterial mixed traffic environment. Microsimulation is based on the driving behavior of CAVs and Human Drive Vehicles (HDVs). To specify the driving behavior of CAVs and HDVs in the simulation environment, car-following models were used, and their parameters were modified. Car following models are selected based on two approaches. In the first approach, the same car following model is used for CAVs and HDVs, and in the second approach, different car following models are used for CAVs and HDVs, and these approaches are intended to answer the following two questions:

(1) To what extent can CAVs affect road safety if we use the same car following models?
(2) To what extent can CAVs affect road safety if we use different car following models for CAVs and HDVs?

Simulations are presented for both signalized and unsignalized intersections with varying penetration rates of CAVs included in the model. Scenarios were selected as they represent common intersection configurations in arterial road environments. Based on the simulation results, safety analysis is carried out to estimate the safety impact of CAVs in the mixed traffic.

The remainder of the paper is organized as follows. Section 2 reviews previous studies on the effects of CAVs on the safety of transportation networks while highlighting the differences between previous research and this study. Section 3 presents the macrosimulation networks, car-following models, and safety analysis methods utilized in this paper. Section 4 demonstrates the results obtained from the simulations. Finally, the discussion and conclusion are presented in Sections 5 and 6, respectively.

2. Literature Review

New technologies, such as Automated Vehicles (AVs) and CAVs, that benefit from Advanced Driving Assistant Systems (ADAS) can improve different aspects of transportation, such as safety, capacity, and stability. Thus, many researchers have been interested in the impacts of these technologies. Literature suggests that fully automated and electrified vehicles can reduce Greenhouse Gas (GHG) emissions [9,10]. Previous studies have also confirmed that CAVs can increase road capacity and reduce congestion, especially when the penetration rate of CAVs is high [11,12]. Furthermore, studies show that CAVs can improve the stability of roads [13]. Moreover, some studies revealed that CAVs have the potential to reduce delays and waiting time at signalized intersections [14,15].

2.1. Previous Studies on the Effect of CAVs on Safety

As mentioned before, human error plays an important role in traffic crashes with most crashes involving some human error, such as speeding, driver distraction, or driving under the influence of alcohol [1]. CAVs are projected to improve safety by eliminating human error. Given that the effects of CAVs on road safety are high, it is necessary to conduct studies to determine the impact of these vehicles on safety. Due to the lack of CAVs data, most studies explore the safety impact of CAVs through simulation. Tibas et al. [16] investigated the impact of AVs on the safety of four roundabouts in Croatia in mixed traffic.

They carried out this research by VISSIM simulator and analyzed the safety results using Surrogate Safety Assessment Model (SSAM) software. SSAM is software to analyze the safety situation of transportation networks based on vehicle trajectory data. They used an identical car-following model (Wiedemann) for HDVs and AVs. They concluded that the number of conflicts increases with the presence of AVs but the rate of increase in conflicts is slight. Morando et al. [17] examined the effect of AVs on the safety situation of signalized intersections and roundabouts. They used two types of AVs which were characterized by conservative and aggressive driving behaviors and were based on Wiedemann car-following. Their results based on SSAM outputs revealed that AVs reduce the number of conflicts in both networks. Virdi et al. [7] carried out research to show the safety impact of CAVs with the help of microsimulation and SSAM outputs. They investigated networks including intersections, roundabouts, and highways. They developed an algorithm for CAVs driving behavior called "Virdi CAV Control Protocol (VCCP)" and used the Wiedemann car-following model [18] for HDVs driving behavior. Their results showed that CAVs can decrease the number of conflicts in all networks substantially and the impact of CAVs on safety is impressive when the penetration rate of CAVs is 100%. In another study, Papadoulis et al. [19] explored the impact of CAVs on the safety of motorways. They developed a bi-directional decision-making control algorithm for CAVs' driving behavior and they used the Wiedemann car-following model for HDVs driving behavior. According to the results which were based on the SSAM outputs, they realized that CAVs can reduce the total number of conflicts by up to 94%. Due to the conflict types, they showed that CAVs increase the number of rear-end conflicts, while CAVs decrease the number of lane-changing conflicts. Arvin et al. [20], examined the effect of CAVs on rear-end collisions in a signalized intersection network. They modified the Wiedemann car-following model to show realistic driving behavior and they used Adaptive Cruise Control (ACC) and the CACC [21–24] car-following model to show CAVs driving behavior. They showed that crashes are drastically reduced and the crash reduction rate for the CACC model is higher than the ACC model. Furthermore, they investigated the impact of CAVs on speed volatility and found that there is a strong correlation between volatility and risk and severity of crashes and found that CAVs reduced the speed volatility substantially. Zhang et al. [8] investigated the impact of CAVs on freeway crash hotspots. They used the Wiedemann car-following model for HDVs and Intelligent Driver Model (IDM) [25] car-following model for CAVs. In their study, two scenarios were defined. In scenario 1, CAVs could change lanes and in scenario 2, CAVs were constrained to managed lanes. Safety analyses were carried out by SSAM. Their results illustrated that in scenario 1, CAVs increased the number of conflicts up to 300%. However, Scenario 2 showed that CAVs reduced the number of conflicts from 63 to 0. Table 1 shows a summary of reviewed studies that investigated the impact of AVs and CAVs on safety. Most of these studies showed that CAVs can improve the safety of roads and reduce crashes. However, these studies used an identical approach to evaluate safety using SSAM software that determines the types of conflicts based on the angle between two vehicles that are at risk and link information [26].

Table 1. Summary of studies (MaxS = the maximum speed of each vehicle during the conflict event, PET = post encroachment time, BDMCA: bidirectional decision-making control algorithm, SSM = Surrogate Safety Measure).

Authors	Network	Car Following Model	SSM	Impact on Safety
Tibas et al. [16]	Roundabouts	CAV: Wiedemann HDV: Wiedemann	TTC, PET, MaxS	Positive
Morando et al. [17]	Roundabouts, Intersections	CAV: Wiedemann HDV: Wiedemann	TTC, PET	Positive
Virdi et al. [7]	Intersections, Roundabouts, Highways	CAV: VCCP HDV: Wiedemann	TTC, PET	Positive
Papadoulis et al. [19]	Motorways	CAV: BDMCA HDV: Wiedemann	TTC, PET	Positive
Arvin et al. [20]	Intersections	CAV: ACC, CACC HDV: Wiedemann	TTC	Positive
Zhang et al. [8]	Freeway	CAV: IDM HDV: Wiedemann	TTC	When Lane changing is allowed: negative Managed lane: positive

2.2. Car Following Models and Networks Used in Previous Studies

Based on Table 1 information, in studies that evaluate the safety impact of CAVs various car-following models have been used to determine the driving behavior of CAVs and HDVs. For determining HDVs driving behavior, the Wiedemann car-following is widely used in many studies [8,16,17,19,27]. To determine the driving behavior of CAVs, a range of models have been considered including the Wiedemann car-following model [16,17], IDM car-following model [8], new driving behavior algorithms [7,19], and ACC and CACC car-following models [17,20,27]. In these studies, the driving behavior of HDVs and CAVs was characterized according to one of two approaches: 1. Identical car-following model for HDVs and CAVs. 2. Different car-following models for HDVs and CAVs. However, these studies did not use these two approaches simultaneously, which can help researchers understand the range of possible changes in safety results. Alongside different car-following models, studies have considered a range of simulation environments [28,29]. However, few studies have considered both signalized and unsignalized intersections instead, tending to focus on only one type.

This paper seeks to address some of the previous methodological limitations by exploring the impact of CAVs on the safety situation of a signalized grid network that consists of nine intersections and an unsignalized intersection. The two scenarios were selected as they represent typical arterial road configurations. To fill the aforementioned gaps, the contributions of this paper are as follows: first, an analysis of safety is carried out considering route topology. Second, safety outcomes are assessed using two different approaches for HDVs and CAVs driving behavior. Finally, different network configurations are explored by considering a signalized grid network and an unsignalized intersection.

3. Methodology

Simulation is a commonly used approach in traffic science that allows researchers to investigate real-world traffic operations. Considering that the driving behavior of vehicles is a factor in analyzing the effects of CAVs on transportation network safety, microsimulation is widely used in studies to assess the impact of CAVs on the safety of roads [16,17,19]. This study investigates the impact of CAVs on the safety of a signalized grid network and an unsignalized intersection using the Simulation of Urban MObility (SUMO) simulator (an open-source microsimulation software) [30]. The methodological steps needed to examine the safety impact of CAVs are shown in Figure 1.

Figure 1. Study framework.

3.1. Car-Following Models

The first step to assessing the safety impact of CAVs is defining the driving behavior of HDVs and CAVs. To define the driving behavior of vehicles, car-following models were used. A car-following model describes how an individual vehicle interacts with the preceding vehicle in a longitudinal direction [31]. Thus, in this research, car-following models were used to demonstrate the behavior of HDVs and CAVs. Two driving behavior definition approaches were used in this study. In the first approach, HDVs and CAVs were defined by an identical car-following model, namely the Krauss car-following model [32], which is the default car-following model used in SUMO and is described in Section 3.1.1. The second approach utilized different car-following models for HDVs and CAVs. In this approach, the Krauss car-following model was used for HDVs, and for CAVs, IDM [25] and CACC [21–24] car-following models were used, which are described in Section 3.1.1, Section 3.1.2, and Section 3.1.3, respectively.

3.1.1. Krauss Car-Following Model

For analyzing the longitudinal movement of vehicles, the Krauss car-following model was employed [32]. The model describes the safe speed of the following vehicle using Equation (1):

$$\mathrm{V_{safe}} = \mathrm{v_l(t)} + \frac{\mathrm{g(t)} - \mathrm{v_l(t)t_r}}{\frac{\mathrm{v_l(t)} + \mathrm{v_f(t)}}{2b} + \mathrm{t_r}} \quad (1)$$

where $\mathrm{V_{safe}}$ is the safe speed, $\mathrm{v_l(t)}$ is the speed of leading vehicle i in time t, $\mathrm{t_r}$ is reaction time(s), $\mathrm{g(t)}$ is leading vehicle gap in time t, b is the vehicle maximum deceleration ($\mathrm{m/s^2}$). $\mathrm{V_{safe}}$ may exceed the speed limit on the road or exceed the vehicle's acceleration limit until the next step [33]. The model describes another speed, called the desired speed (v_{des}), which is a speed that is the minimum speed between safe speed, maximum speed (v_{max}), and a speed when acceleration capabilities (a) are taken into account [33] that Equation (2) shows desired calculation:

$$v_{des} = \min\left[v_{max}, v + at, v_{safe}\right] \quad (2)$$

Since human driving is imperfect, this model defines random error term (ε) which is subtracted from the desired speed [34], and Equation (3) demonstrates speed calculation due to the driver imperfection.

$$v = \max[0, rand[v_{des} - \varepsilon, v_{des}]] \tag{3}$$

In the SUMO simulator to demonstrate the driver imperfection, a parameter is considered called sigma that changes from 0 to 1 (sigma = 0 shows perfect driving). The value of this parameter was 0.5 for HDVs and was 0 for CAVs, as per previous research conducted by Luken et al. [35].

3.1.2. IDM Car-Following Model

The second car-following model which was used for CAVs was the IDM car-following model, developed by Treiber et al. [25]. In comparison with most of the deterministic acceleration modeling, this model is more realistic. To calculate acceleration, IDM creates a balance between two ratios where the first ratio is desired velocity versus actual velocity and the second ratio is desired headway versus actual headway [11]. Equations (4) and (5) show the calculation of acceleration of the subject vehicle in the IDM car-following model.

$$a = a_0[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*(v, \Delta v)^2}{s_0}\right)^2 \tag{4}$$

$$s^*(v, \Delta v) = s_0 + max[0,\ vT + \frac{v\Delta v}{2\sqrt{a_0 b}}] \tag{5}$$

In these equations, a is acceleration, a_0 maximum acceleration, v is current speed, v_0 is desired speed, δ is acceleration exponent, $s^*(v, \Delta v)$ is desired minimum headway, s_0 is current headway, Δv is the speed difference between vehicle and its leader vehicle, T is the desired headway, b is deceleration.

3.1.3. CACC Car-Following Model

ACC and CACC are examples of ADAS which can be effective in improving safety situations. ACC systems provide this feature to automatically follow a preceding vehicle by measuring the distance and velocity of the preceding vehicle using sensors, such as radar, lidar, or video cameras. When there is a preceding vehicle, ACC systems control the speed of the vehicle according to desired headway. In the absence of a preceding vehicle, ACC controls the speed of the vehicle based on the user's desired speed [36]. CACC is a cooperative ACC, which is an extension to ACC systems and benefits from communication between infrastructure and vehicles. Using this communication feature it is estimated that CAVs can improve the safety of transportation networks [20]. The CACC car-following model [21–24,36], which is based on the performance of CACC systems, follows four purposes: 1. Speed control, 2. Gap-closing control, 3. Gap control, 4. Collision avoidance control.

Speed control: speed control model aims to adjust the vehicle's speed according to its desired speed [20]. The communication to infrastructure and vehicles does not affect speed control. Acceleration is calculated as follows using Equation (6):

$$a_{i,k+1} = k_4[v_d - v_{i,k}] \tag{6}$$

In this equation $a_{i,k+1}$ is the acceleration of vehicle i at the time k + 1, v_d is desired speed, $v_{i,k}$ is the current speed of vehicle i at the time k, k_4 is speed gain control which is equal to 0.4 s^{-1} [21]. When the time gap is larger than 2 s this mode is activated [36].

Gap control: In this car-following model, first-order transfer functions show the speed of vehicles that are equipped with CACC in the next time step $k + 1$, as shown in Equation (7):

$$v_{i,k+1} = v_{i,k} + k_5 e_{i,k} + k_6 e_{i,k} \quad (7)$$

In this equation, $e_{i,k}$ is the first derivative of the gap error ($e_{i,k}$) shown in Equation (8) for the $e_{i,k}$ calculation:

$$e_{i,k} = v_{i-1,k} - v_{i,k} - t_d \alpha_{i,k} \quad (8)$$

In Equation (8), t_d is the CACC controller's desired time gap and $\alpha_{i,k}$ is the acceleration at time k. Based on Liu et al. [24], the values of k_5 and k_6 were 0.45 s^{-2} and 0.0125 s^{-1}, respectively. This mode was activated in two situations: 1. Time gap < minimum threshold, 2. Gap < 0.2 m and speed deviation < 0.1 m/s [36].

Gap-closing control: Gap-closing is activated when the time-gap falls below the minimum threshold, and its parameters are derived by turning the current CACC gap controller parameters [36]. According to Liu et al. [24], in this mode, the values of k_5 and k_6 were 0.005 s^{-2} and 0.05 s^{-1}, respectively.

Collision avoidance control: As part of the study conducted by Mintsis et al. [36], collision avoidance control was introduced. During simulations, collision avoidance control helps avoid rear-end collisions. Similar to the gap control mode, the controller maintains a similar logic [20]. In this control mode, k_5 and k_6 were 0.45 s^{-2} and 0.05 s^{-1}, respectively.

After the introduction of the car-following model, several common parameters of car-following models should be modified for HDVs and CAVs. Table 2 shows the common parameters of car-following models for HDVs and CAVs. Minimum headway, minimum gap, and acceleration values were taken from Atkins [5], and deceleration values for HDVs and CAVs were taken from Qiong Lu et al. [37]. Other parameters of the three car-following models which were not modified in this study were set to the default values in the SUMO simulator.

Table 2. Car-following models' parameters.

Vehicle Type (Car-Following Model)	Minimum Headway (s)	Minimum Gap (m)	Acceleration (m/s^2)	Deceleration (m/s^2)
HDV (Krauss)	0.9	1.5	3.5	4.5
CAV (Krauss)	0.5	0.5	3.9	4.5
CAV (IDM)	0.5	0.5	3.9	4.5
CAV (CACC)	0.5	0.5	3.9	4.5

3.2. Safety Analysis

This paper analyzed the safety situation of intersections based on the number of conflicts. The vehicles in the microsimulation environment follow a predefined set of behavior patterns known as a car-following model that avoids collisions [20]. Thus, the microsimulation environment of this paper was a collision-free environment. As such, to measure safety this paper uses time to collision (TTC) which is an important surrogate safety measure in traffic microsimulation. Time to collision according to Hayward [38], is the remaining time before a collision would occur if both vehicles maintained their current paths and kept their speeds constant [39]. In this paper, two different TTC values were considered based on the two different vehicle types. For HDVs, TTC equal to or less than 1.5 s is considered a conflict [7,17,19]. For CAVS, smaller gaps are accepted between vehicles, as such in accordance with Virdi et al. [7], a TTC equal to or less than 0.5 s was considered as a conflict. To obtain safety outputs from the SUMO simulator, the Surrogate Safety Measures (SSM) device output was used. SSM device outputs include information about conflicts, such as type of conflicts, TTC value, the position of conflicts, etc. There are three kinds of conflicts in SSM device outputs, and these conflicts are calculated based on different TTC formulas. The first conflict type is lead/follow which, in previous studies is known as the rear-end conflicts [17,20]. In follow/lead situations, the time-to-collision is defined for time periods in which the follower is faster than the leader and it is given as Equation (9) [40,41]:

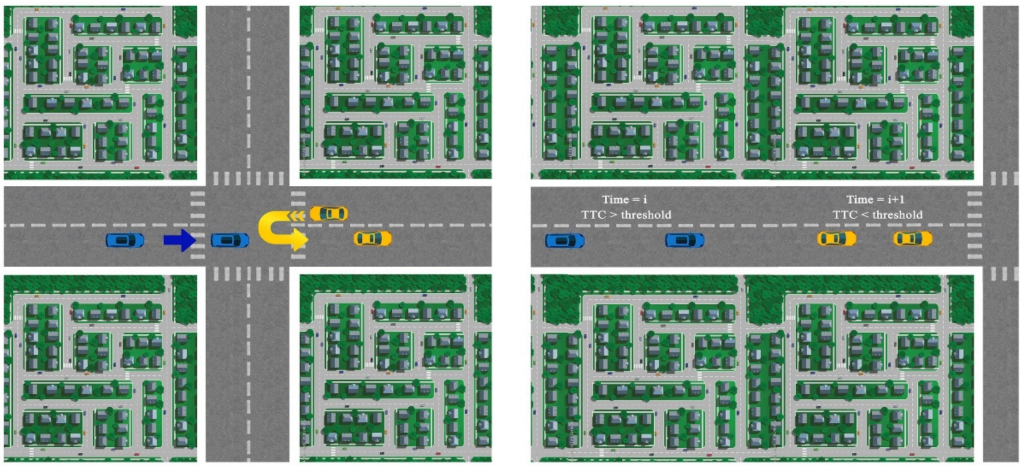
$$\text{TTC} = \frac{((x_{i-1,t} - x_{i,t}) - L_{i-1,t})}{v_{i,t} - v_{i-1,t}} \quad (9)$$

where $x_{i-1,t}$ is the position of the leader at the time t, and $v_{i-1,t}$ is the speed of the leader at the time t, $x_{i,t}$ and $v_{i,t}$ are the position and speed of the following vehicles at the time t, $L_{i-1,t}$ is the vehicle length at the time t. In the lead/follow conflicts, prior to and after conflict points, vehicles pass along the same sequence of lanes [40].

The second and third types of conflicts are crossing and merging conflict. SSM defines these types of conflicts as follows: "if for the case that the expected conflict area exit time of the vehicle A is larger than the expected conflict area entry time for vehicle B, where A is the vehicle with the smaller expected conflict area entry time" [40]. Equation (10) shows the TTC calculation formula for crossing and merging conflicts. In this equation, S_B is B's distance to conflict area entry and v_B is B's current speed. Equation (10) shows that TTC is calculated based on the speed of the vehicle and route topology so that the Distance of the vehicle to the conflict area plays a decisive role in determining potential conflicts.

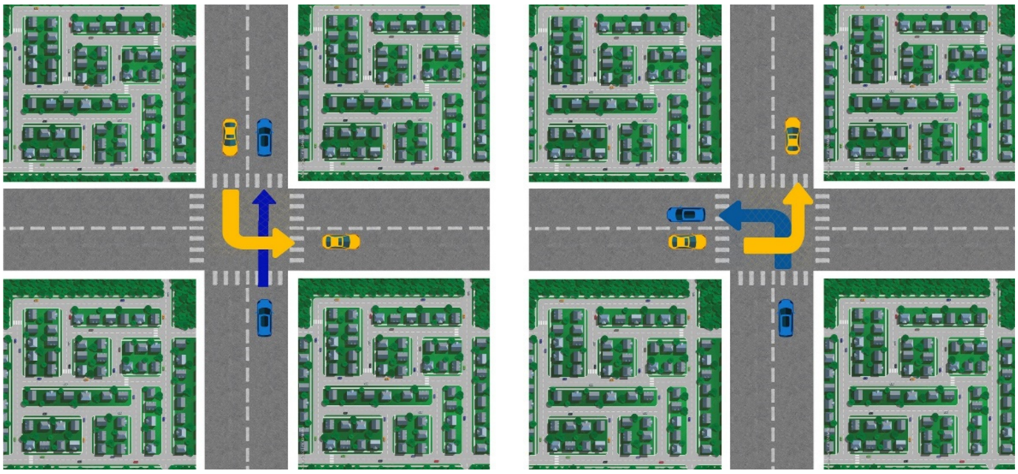
$$\text{TTC} = \frac{S_B}{v_B} \quad (10)$$

The difference between merging and crossing conflicts is that in crossing conflicts, different sequences of lanes are used by vehicles before and after the conflict point but in merging conflicts, before the conflict point, vehicles pass on different lanes, but they pass on the same lane after it [40]. To better illustrate the types of conflicts, examples are shown in Figures 2 and 3. Figure 2a shows an example of merging conflicts. Figure 2b demonstrates an example of lead/follow conflicts that this figure shows two different times and finally, Figure 3 shows two examples of crossing conflicts in two different situations. Time i shows that there are not any conflicts because the TTC is bigger than the threshold. However, time $i + 1$ shows that a conflict because TTC is lower than the threshold. Thus, based on safety definition and conflict types, we analyzed the impact of CAVs on different types of conflicts using the SUMO simulator.



(**a**) (**b**)

Figure 2. Examples of merging and lead/follow conflicts: (**a**) example of merging conflicts; (**b**) example of lead/follow conflicts. Figure 3 shows two examples of crossing conflicts in two different situations.



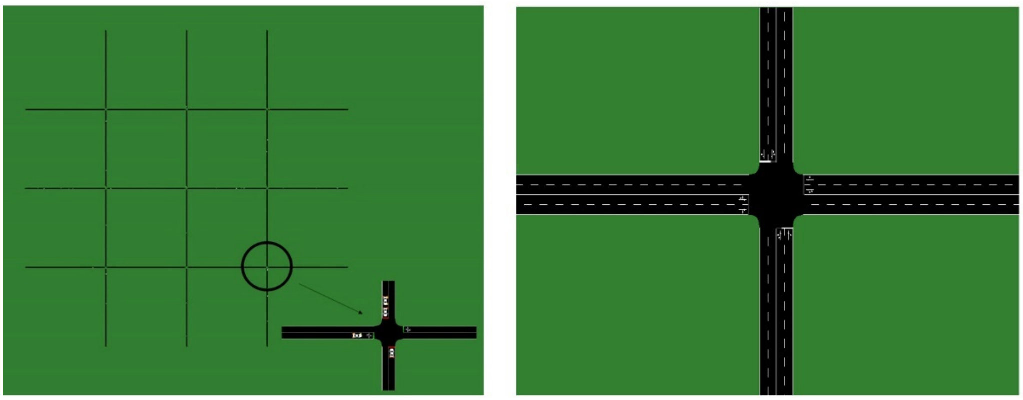
(**a**) (**b**)

Figure 3. Examples of crossing conflict: (**a**) shows crossing conflict occurs when vehicles have different movements; (**b**) shows crossing conflict occurs when vehicles have similar movements.

3.3. Case Studies and Demands

In this study, two different intersection case studies were used. The first case study was a grid network that included 9 signalized intersections with a speed limit of 50 km/h. All the links in the grid network had a 400-m length and run bidirectionally. There was a 90-s cycle time for all traffic lights. The green light time was 43 s, the red-light time was 43 s, and the yellow light time was 4 s. There were four phases at each intersection: 1. a straight phase, 2. Left turn phase, 3. Right turn phase, 4. U-turn phase. Although in many intersections U-turn is not allowed, in this study U-turn phase was added to investigate the impact of CAVs on merging conflicts. In addition, due to the intersection's low-speed limit, left-turns were permitted at the same time as straight traffic at the intersection.

The second case study was an unsignalized intersection with a speed limit of 50 km/h. each link of the intersection had two lanes. Figure 4 shows two case studies. In the grid network, Randomtrip.py (SUMO's built-in tool) was used to route the vehicles randomly. Compared with a grid network demand model with fixed routes, random trips produced a more flexible and homogeneous network [37]. For the unsignalized intersection, three different demands were measured: 1200 veh/h, 1500 veh/h, and 1800 veh/h. The case studies were selected as they represent common arterial intersections, however, it is noted that CAVs will be required to operate in a diverse range of intersections and road environments, however, investigation of alternative configurations was beyond the scope of this analysis.



(**a**) (**b**)

Figure 4. Case studies: (**a**) Signalized grid network; (**b**) shows Unsignalized intersection.

4. Results

This section presents the results that were obtained from simulations and SSM device outputs. To determine the impact of CAVs on safety, scenarios were defined. In this study, for each case study, six scenarios were defined. Each scenario increased the penetration rate of CAVs by 20% from 0% to 100%. Initially, results of the grid network are presented, followed by results of unsignalized intersections.

4.1. Grid Network Results

Figure 5 shows the number of total conflicts based on the results of three car-following models. The analysis demonstrated that CAVs can reduce the number of total conflicts significantly and have the potential to reduce conflicts from 3198 to 0. A summary of the results can also be found in Appendix A. However, the results showed that the impact of CAVs on the number of total conflicts is only realized once the penetration rate of CAVs is more than 50%. One reason for this could be that CAVs have a shorter headway, both when the vehicle in front is a CAV and when the vehicle in front is an HDV, and difference in the headway of the two types of vehicles causes more conflicts when the penetration rate is below 50. From a car-following perspective, Figure 5 shows the number of total conflicts based on the results of three car-following models. In this study, two different approaches were used for CAVs driving behavior that in the first approach, the Krauss car-following was used for CAVs, and in the second approach, IDM and CACC were used for CAVs. Figure 6 illustrates that in both approaches, CAVs reduced the number of conflicts significantly. The Krauss car-following model and IDM car-following model were found to produce similar results, but the CACC car-following model showed a different trend of reducing conflicts.

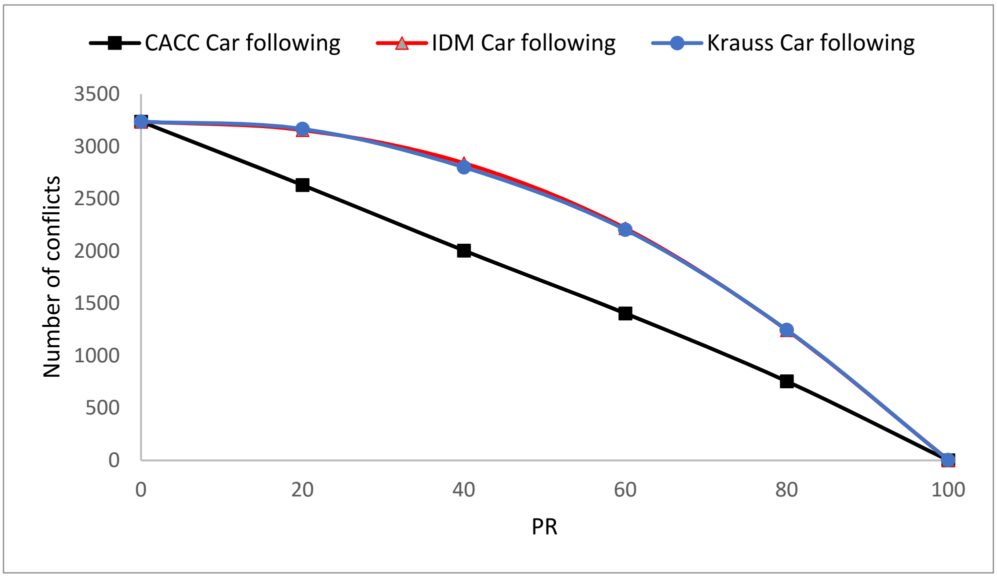


Figure 5. Change in the number of conflicts based on three car-following models.

To understand the reason for this different trend, the impact of CAVs on each type of conflict should be considered. Figure 6 illustrates the impact of CAVs on each conflict type. This figure shows the number of lead/follow conflicts based on penetration rates. Based on the three car-following models results, when penetration rate was lower than 50% and predominant traffic flow was HDVs, the number of conflicts increased significantly, while when penetration rate was higher than 50% and predominant traffic flow was CAVs, the number of conflicts decreased dramatically. The important note is that although all three car-following models showed similar trends in the change in conflicts, CACC car-following model results showed fewer conflicts than other car-following models. The reason for this difference is that, as mentioned before, CACC systems benefit from collision avoidance control which helps vehicles to prevent lead/follow conflicts. Thus, the number of lead/follow conflicts based on CACC car-following was much less than that of the IDM and Krauss car-following model. Figure 6 also demonstrates that CAVs can reduce the number of merging and crossing conflicts significantly especially when the penetration rate of CAVs was 100%, the number of conflicts reaches 0.

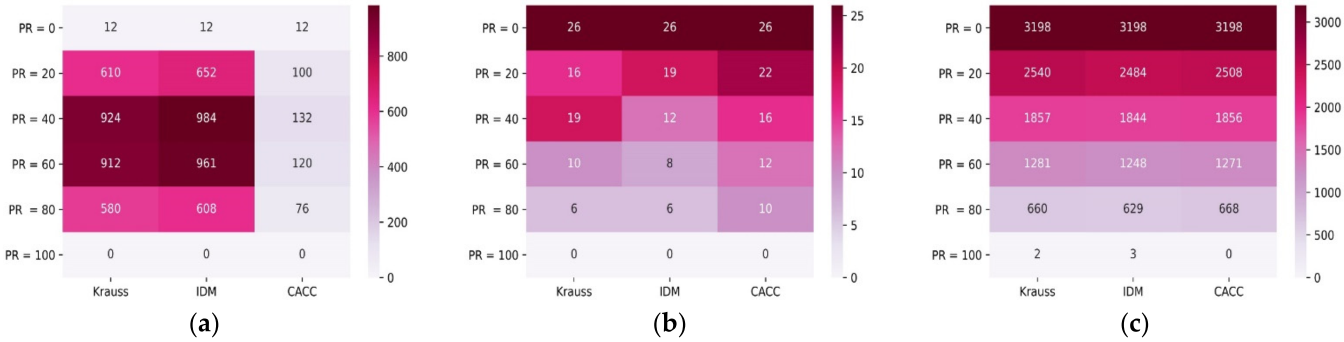


Figure 6. Number of conflicts based on different conflict types: (**a**) lead/follow conflicts; (**b**) merging conflicts; (**c**) crossing conflicts.

Overall, the results of this network illustrate the safety potential of CAVs, and their ability to dramatically reduce conflicts.

4.2. Unsignalized Intersection Results

Based on the outputs of the SSM, the safety analysis is shown in Figure 7. The analysis confirmed that CAVs can reduce the number of total conflicts in each scenario based on different traffic demands. Furthermore, it is evident that CAVs can reduce the number of lead/follow and merging conflicts substantially and CAVs have the potential to reduce the number of lead/follow and merging conflicts up to 0. However, the results of the study show that when the penetration rate of CAVs exceeds 50%, the impact of CAVs on the number of conflicts is impressive. Furthermore, it can be observed from this figure that increasing demand is directly related to increasing the number of conflicts. All three car-following models, based on the two aforementioned approaches, had similar results in the three traffic demands tested. Moreover, Figure 8 demonstrates the number of total conflicts based on three different demands. In each demand, CAVs reduced the number of total conflicts substantially.

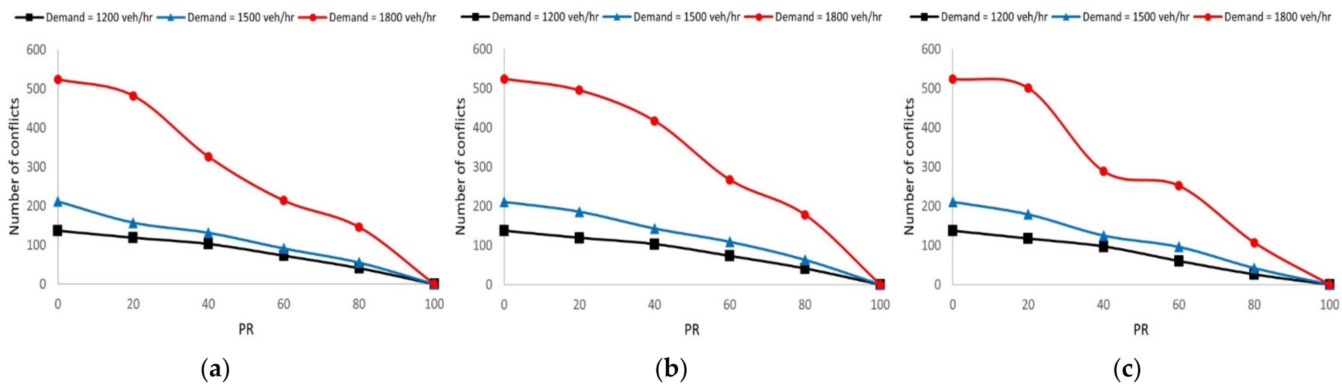


Figure 7. Number of conflicts based on different car-following models: (**a**) Krauss car-following model; (**b**) IDM car-following (**c**); CACC car-following model.

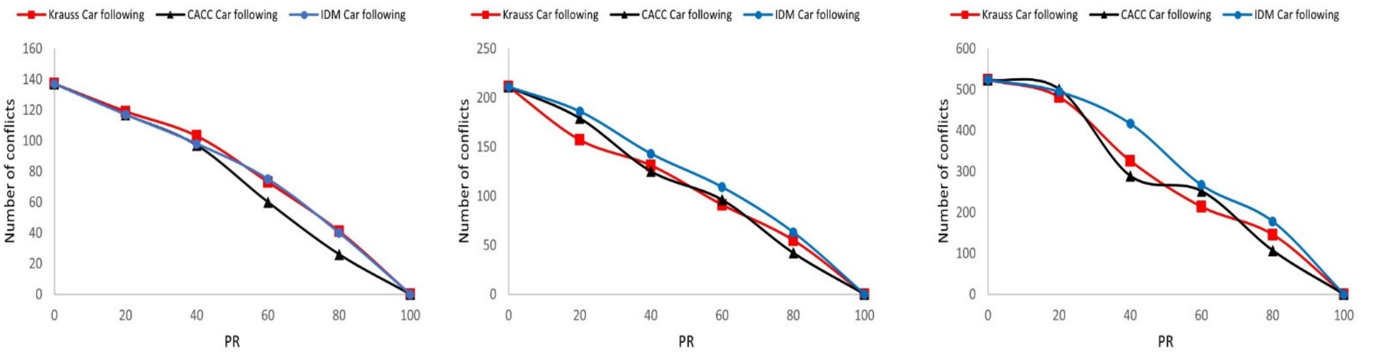
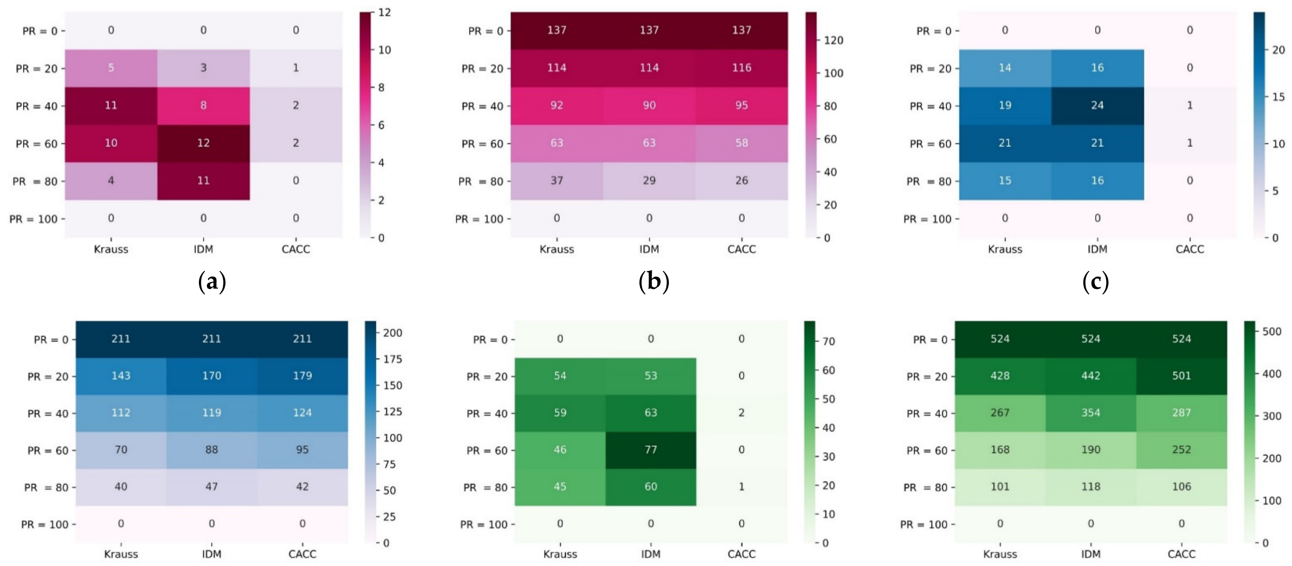


Figure 8. Number of conflicts based on different demands: (**a**) Demand = 1200 Veh/h; (**b**) Demand = 1500 Veh/h; (**c**) Demand = 1800 Veh/h.

Figure 9 demonstrates the effect of CAVs on each type of conflict. This figure shows that there were two types of conflicts in the unsignalized intersection. The first type was lead/follow conflict. Based on the results, CAVs demonstrated the number of conflicts decreased if the penetration rate of CAVs was high (in most cases over 60%) but CAVs increased the number of lead/follow conflicts if the penetration rate of CAVs was low and this trend was true in all three demands. Moreover, three car-following models based on two approaches indicated a similar trend of total conflicts changing but the number of lead/follow conflicts in the CACC car-following model was lower than the number of lead/follow conflicts in the Krauss and IDM car-following models. This difference is because of collision avoidance control of CACC. The second type was crossing conflicts. The results confirmed that the number of crossing conflicts decreased for each penetration rate of CAVs and when the penetration rate of CAVs was 100%, the number of crossing conflicts reached 0. This trend was true in all three demands, and it is evident from the results that when demand increased the number of conflicts increased. In addition, all three car-following models based on two approaches showed a similar trend to reduce the number of crossing conflicts. Based on the results of this study, CAVs are proving to have enormous potential for improving safety throughout these types of networks, as well as reducing conflicts.



(**d**) (**e**) (**f**)

Figure 9. Number of conflicts based on different demands and different car-following model:

(**a**) Demand = 1200 veh/h—Conflict type = lead/follow; (**b**) Demand = 1200 veh/h—Conflict type = Crossing; (**c**) Demand = 1500 veh/h—Conflict type = lead/follow; (**d**) Demand = 1500 veh/h—Conflict type = Crossing; (**e**) Demand = 1800 veh/h—Conflict type = lead/follow; (**f**) Demand = 1800 veh/h/type—Conflict type = Crossing.

5. Discussion

CAVs are expected to reduce traffic crashes by eliminating human error, which is a contributing factor in crashes on transportation networks [3]. This paper investigated the impact of CAVs on traffic safety at intersections. The results of this study show that CAVs can substantially reduce the number of intersections conflicts in the two simulated intersection configurations, with the findings aligning with previous research [20,28] on intersection safety. However, this study presents a key point of difference from previous studies by classification of conflicts based on route topology which, in addition to the speed and location of the vehicles, also pays attention to the distance of the vehicles to the conflict area, as opposed to previous studies which have classified conflicts more based on the angle between two vehicles at risk.

In detail, this study found that CAVs can reduce rear-end collisions at intersections only when the penetration rate of CAVs is high and CAVs are the dominant vehicle in the traffic stream. The findings align with results on rear-end collisions presented by Zhang et al. [8] and demonstrated that as CAV penetration rates increased there was a reduction in crashes, however at lower penetration rates, CAVs can result in an increase in crashes. However, other researchers, such as Khashayarfard et al. [28], have found that CAVs can reduce the number of conflicts even at low penetration rates.

There are two key points of difference that contribute to the differing results. First, different studies have used different driving behavior modes for vehicles, and second, different TTC thresholds have been utilized to evaluate the safety of transportation networks. However, it is evident that when the penetration rate of CAVs is high (especially when the penetration rate is 100%), the number of conflicts decreases. Although this study's approach of crossing conflicts classification is based on route topology and previous studies' classifications are based on the angle of vehicles at risk rather than route topology, the results of this study and previous studies [6,28] confirmed that CAVs reduce the crossing conflicts dramatically. Moreover, this study demonstrated that CAVs reduce merging conflicts at signalized intersections. The effect of this type of conflict is not investigated in the previous studies and it is recommended that future studies should investigate the impact of CAVs on the merging conflicts in different networks configurations. Another key contribution of this result was the use of multiple car-following models in the analysis. Previous research exploring CAVs safety [6,7,17,19] has typically used the same car-following models. This study filled this gap using two different approaches to determine the impact of CAVs on safety. In the first approach, identical car following models were used to show HDVs and CAVs driving behavior, and in the second approach different car following models were used to show HDVs and CAVs driving behavior. These approaches were used to answer two questions which are mentioned in the introduction. The results of the first and second approaches showed that CAVs can reduce conflicts substantially. In addition, a comparison of the two approaches obtained an important result by demonstrating that the CACC car following model results in fewer rear-end conflicts compared to the IDM and Krauss car-following models. The reason for this difference is related to collision avoidance control of the CACC car-following model, which helps CAVs to avoid rear-end collisions. Future research should investigate the impacts of the collision avoidance control of the CACC car-following model on rear-end collisions in other transportation networks, such as highways or freeway on-ramps, which are common crash locations. Furthermore, the results of the impact of CAVs on both signalized and unsignalized intersections revealed that CAVs can reduce the number of conflicts in both networks. This is an important finding given the added complexity of operating CAVs in unsignalized intersections. Albeit further research is required to investigate other road configurations and road environments. Furthermore, the implications on intersection capacity are also an important consideration, particularly at lower penetration rates.

Overall, the results of this study highlight the potential safety benefits of CAVs at signalized and unsignalized intersections and confirms previous findings. Notwithstanding, there are noted limitations of this research that can be addressed in future studies. Notably, the HDVs driving behavior in this study is based on the car following models adopted in the previous studies [4,35,37]. These models represent a simplification of actual driver behavior and there is scope to further develop these models through the calibration of parameters based on real-world data. Similarly, CAV models can be refined as more real-world data becomes available on CAV vehicles and their operating parameters.

Further, while this study focused on intersections, there is potential to explore different intersection configurations and make modifications to the geometry and signal control, which may in term influence the safety benefits of the CAVs. Future research could also explore the impact of CAVs on other networks, such as highways or locations where vehicle weaving occurs. Moreover, different types of driving behavior, such as conservative or assertive driving behavior, and different types of vehicles, such as heavy vehicles, could be simulated to produce more realistic scenarios. Moreover, realistic driving behaviors of CAVs in mixed traffic can be simulated with the help of the vehicular ad hoc network (VANET) that connect groups of moving or stationary cars by way of a wireless system, which would simulator vehicle to vehicle (V2V) communication technology.

6. Conclusions

This paper investigated the safety impact of CAVs on a signalized grid network and an unsignalized intersection through the use of microsimulations. To analyze intersection safety, TTC was used as a surrogate safety measure. Simulations for this study were performed using the SUMO traffic simulator. The results of this study revealed that CAVs can reduce the number of conflicts dramatically especially when CAVs are dominant in traffic. In addition, in comparison with IDM and Krauss, CACC had fewer rear-end conflicts because the CACC car-following model has collision avoidance control which helps CAVs avoid rear-end collisions. Furthermore, the results of CAV implementation in both signalized and unsignalized intersections showed that they can reduce conflicts to zero in both networks. Thus, given the positive effects of vehicles on intersection safety, future studies need to consider more complex models, such as modeling lane changing of CAVs or simulating V2V communications using wireless communications to obtain provide further insight into the potential safety benefits that can be achieved through CAVs.

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Appendix A

Here, numerical results of safety analysis based on SSM device outputs are presented. Tables A1 and A2 show the results of the safety analysis based on SSM device outputs in a grid network and unsignalized network.

Table A1. Results of impact of CAVs on safety of grid network (CFM = car-following model, PR = penetration rate).

CFM	PR (%)	Number of Total Conflicts	Number of Conflicts Based on the Type of Conflict		
			Lead/Follow	Merging	Crossing
Krauss	0	3236	12	26	3198
	20	3166	610	16	2540
	40	2800	924	19	1857
	60	2203	912	10	1281
	80	1246	580	6	660
	100	2	0	0	2
IDM	0	3236	12	26	3198
	20	3155	652	19	2484
	40	2840	984	12	1844
	60	2217	961	8	1248
	80	1243	608	6	629
	100	3	0	0	3
CACC	0	3236	12	26	3198
	20	2630	100	22	2508
	40	2004	132	16	1856
	60	1403	120	12	1271
	80	754	76	10	668
	100	0	0	0	0

Table A2. Results of impact of CAVs on safety of unsignalized intersection network (CFM = car-following model, PR = penetration rate).

CFM	PR (%)	Demand = 1200 veh/h		Demand = 1500 veh/h		Demand = 1800 veh/h	
		Number of Conflicts Based on the Type of Conflict		Number of Conflicts Based on the Type of Conflict		Number of Conflicts Based on the Type of Conflict	
		Lead/Follow	Crossing	Lead/Follow	Crossing	Lead/Follow	Crossing
Krauss	0	0	137	0	211	0	524
	20	5	114	14	143	54	428
	40	11	92	19	112	59	267
	60	10	63	21	70	46	168
	80	4	37	15	40	45	101
	100	0	0	0	0	0	0
IDM	0	0	137	0	211	0	524
	20	3	114	16	170	53	442
	40	8	90	24	119	63	354
	60	12	63	21	88	77	190
	80	11	29	16	47	60	118
	100	0	0	0	0	0	0
CACC	0	0	137	0	211	0	524
	20	1	116	0	179	0	501
	40	2	95	1	124	2	287
	60	2	58	1	95	0	252
	80	0	26	0	42	1	106
	100	0	0	0	0	0	0

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