

Article

Connected Automated and Human-Driven Vehicle Mixed Traffic in Urban Freeway Interchanges: Safety Analysis and Design Assumptions

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Abstract: The introduction of connected automated vehicles (CAVs) on freeways raises significant challenges, particularly in interactions with human-driven vehicles, impacting traffic flow and safety. This study employs traffic microsimulation and surrogate safety assessment measures software to delve into CAV–human driver interactions, estimating potential conflicts. While previous research acknowledges that human drivers adjust their behavior when sharing the road with CAVs, the underlying reasons and the extent of associated risks are not fully understood yet. The study focuses on how CAV presence can diminish conflicts, employing surrogate safety measures and real-world mixed traffic data, and assesses the safety and performance of freeway interchange configurations in Italy and the US across diverse urban contexts. This research proposes tools for optimizing urban layouts to minimize conflicts in mixed traffic environments. Results reveal that adding auxiliary lanes enhances safety, particularly for CAVs and rear-end collisions. Along interchange ramps, an exclusive CAV stream performs similarly to human-driven ones in terms of longitudinal conflicts, but mixed traffic flows, consisting of both CAVs and human-driven vehicles, may result in more conflicts. Notably, when CAVs follow human-driven vehicles in near-identical conditions, more conflicts arise, emphasizing the complexity of CAV integration and the need for careful safety measures and roadway design considerations.

Keywords: urban freeways interchanges; surrogate safety measures; connected automated vehicles; VISSIM; road design



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1. Introduction

Over the past few decades, escalating traffic volumes have had significant effects on road safety, traffic congestion, and fuel consumption [1]. To enhance drivers' performance and mitigate human errors, tools like adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC) have been implemented [2]. However, the transformative innovation expected to profoundly impact these aspects in the coming decades is the advent of connected autonomous vehicles (CAVs). Connected autonomous vehicles integrate digital technology with automated systems to assist or replace human drivers [3]. These vehicles operate autonomously, utilizing sensors and cameras to continuously analyze their surroundings. Additionally, they establish ongoing GPS-based location tracking systems and telecommunications networks [4,5]. This autonomy enables them to execute precise maneuvers, thereby positively impacting both traffic network performance and safety [6].

Despite these advancements, the integration of CAVs in traffic introduces driving challenges, particularly at critical points such as interchanges and intersections, where they still interact with non-autonomous or manually operated vehicles. Microsimulation is a valuable tool for forecasting the potential impacts of CAV circulation [7,8]. It enables the analysis of collaborative behaviors, such as the formation of vehicle platoons, and

provides opportunities for refinement based on implementation experiences in various what-if scenarios [9]. Studies have shown that human drivers in CAV platoons adjust their maneuvers, frequently decreasing their time headways [10,11]. Nevertheless, scenarios characterized by diminished reaction times of human drivers may lead to collisions [12].

The effectiveness of precision maneuvers executed by CAVs is intricately tied to the capabilities of their detection systems and the quality of surrounding infrastructure. Hence, the operational efficiency of CAVs experiences a notable improvement when the roadway infrastructures adhere to high-quality standards [13]. This becomes especially critical at interchanges, where vehicles interact at elevated speeds. Consequently, there is a pressing need to examine potential adaptations and impacts stemming from the collaboration between CAVs and human-driven vehicles.

Country-specific design standards have led to a wide range of geometric layouts for interchanges worldwide [14–16]. Varied design standards may result in differences in safety features and impact factors such as capacity, throughput, and congestion, influencing overall traffic flow dynamics, safety performance, and the efficiency of interchanges.

Building upon this, the study aims to address the question: What is the impact of the coexistence of CAVs and human-driven vehicles on operational and safety performance at freeway interchanges? The research involved collecting and analyzing various geometric interchange configurations in Italy and the US to explore both advantages and disadvantages in the transition to complete CAV driving.

To achieve this goal, the evaluation utilized VISSIM (Version 10) [17] in modeling urban freeway interchanges; the microscopic traffic simulation tool has been coupled with the surrogate safety assessment model (SSAM) [18] to identify potential traffic conflicts.

The study transitions from an interest in understanding the potential evolution of road traffic parameters along the ring roads under mixed traffic conditions involving CAVs and human-driven vehicles. Specifically, the focus is on the geometry of urban freeway interchanges, which exhibit significant variations influenced by both traffic parameters and landscape features. The study delves into the complexity of these interchanges by examining a sample of existing road infrastructures characterized by high heterogeneity. Despite some limitations in the approach used, the research findings underscore the need to improve road policies to optimize and adapt road interchanges for accommodating the next generation of traffic vehicles.

2. Related Research Studies

The efficiency of CAV driving at freeway interchanges may be affected or compromised by human-driven vehicles in traffic [19]. In this context, a potential solution could involve adjusting the access configurations of dedicated lanes, especially at the “turning points” where traffic flow shifts or turns. These areas often play a crucial role in influencing the overall performance and efficiency of the interchange. Updating intersection management and enhancing access configurations at these turning points could potentially serve as a solution to address challenges related to mixed traffic [20,21]. Considering the potential to reduce human errors through CAVs, there is an outlook of decreasing crashes [22]. For high-occupancy vehicles alone, the removal of human mistakes is estimated to eliminate 93–97% of crashes [23].

In this context, to facilitate the transition to CAV driving, the implementation of autonomous vehicle/toll (AVT) lanes could be realized, where CAVs have free access, while human-driven vehicles must pay a toll [24]. To understand the impact of driving next to CAV platoons on the behavior of both human-driven vehicle drivers and CAVs, it is crucial to examine the behavioral adaptation. This assessment should be based on the interaction between CAVs and human-driven vehicles (HdVs), providing insights into the implications of segregating CAVs and human-driven vehicles through dedicated lanes. The examination of behavioral adaptation and its effects on traffic efficiency and safety performances, stemming from the experience of driving with CAVs, drivers’ inclination to transition between automated and manual modes and vice versa, the consequences of such

transitions (i.e., the transition of control), and drivers' choices in car following and lane changing while CAV driving has been defined as "any change of driver, traveller, and travel behaviours that occurs following user interaction with a change to the road traffic system, in addition to those behaviours specifically and immediately targeted by the initiators of the change" by Kulmala and Rämä [25]. Thus, behavioral adaptation encompasses behaviors not only specifically and immediately targeted by the initiators of the change but also those resulting from the interaction among vehicles during driving. Additionally, there is a notable lack of understanding concerning the effects on performance and safety resulting from various design setups of road segments featuring dedicated lanes during maneuvers (such as merging, splitting, transitioning between manual and automated control, and entering or exiting dedicated lanes). The influence of diverse lane utilization policies on driver behavior and, consequently, on traffic performance and safety remains inadequately explored.

A study on behavioral adaptation examined the behavior of drivers with and without ACC experience when driving in ACC mode [26]. When utilizing the ACC system, drivers tend to adopt slightly lower driving speeds and larger time headways. Interestingly, drivers with ACC experience drive at faster speeds than regular drivers and maintain smaller headways in ACC mode. This behavior is attributed to an indirect behavioral adaptation or carryover effect from their experience of driving with the ACC system.

A crucial aspect in the design of dedicated lanes at interchanges involves addressing the carryover impacts of automated driving. As drivers exit these exclusive lanes, they must disengage automation and assume manual control based on either lane utilization policies or their personal choice regarding how to navigate regular lanes. Research indicates that behavioral adaptation persists during manual driving following automation exposure [27]. Chen et al. [28] conducted simulation experiments examining CACC effects on traffic in off-ramp freeway sections. Low CACC penetration degrades safety and operational efficiency, while near 1% penetration significantly improves traffic flow. Increasing the conservative mandatory lane change zone length enhances traffic speed, with optimum performance at 750 m. Excessive zone lengths show diminishing benefits. The findings offer valuable insights for alleviating road traffic congestion, suggesting that directing lane changes can be an effective strategy to improve overall traffic flow efficiency. In terms of selecting time headway in CACC mode, Nowakowski et al. [29] found that male drivers tend to maintain shorter time headways compared to females. Overall, drivers choose approximately 50% shorter time headways in CACC mode than in ACC mode. However, the authors expressed reservations, noting that events were often brief, with only half lasting two to three minutes. According to [30,31], further investigation is warranted to understand drivers' preferences in setting ACC or CACC parameters, considering factors like age, gender, and driving style in mixed traffic scenarios at road interchange facilities. In certain traffic scenarios, human drivers may choose to take control of the vehicle, either switching off the automation mode or activating it.

Based on the above, this study aims to fill scientific knowledge gaps in two key areas of transportation research. Firstly, there is a lack of studies on how human drivers adapt behavior when driving alongside autonomous vehicles and connected autonomous vehicles. Secondly, there is limited exploration of rehabilitation options for interchanges operating with mixed vehicles. Addressing these research areas is essential for improving road safety and optimizing infrastructure in the dynamic context of mixed-vehicle transportation systems. The present study aims to contribute scientific understanding and addressing social implications related to the interactions between CAVs and human-driven vehicles at road interchanges. Employing traffic microsimulation and surrogate safety measures allows for the examination of a variety of complex scenarios, enhancing the replicability of design solutions. Furthermore, the study may facilitate international meta-analysis, offering valuable insights for the development of globally applicable solutions in the intelligent transportation systems domain.

3. Materials and Methods

The first goal of this study is to conduct a thorough analysis and comparison of specific interchanges in Sicily, Italy, and Florida, USA. So far, correlations and distinctions that offer insights into factors pertaining to the design and safety of urban road infrastructure have been investigated.

The chosen case study locations comprise interchanges located on ring-roads within diverse urban settings, adhering to both Italian and American roadway design standards [15,16]. In Italy, the selected interchanges are within the road network of three Sicilian cities—Palermo, Catania, and Messina—while in the United States, the selected interchanges are situated in Florida, functioning as a reference for scalability. Each interchange facility is designated with a code for ease of identification and result interpretation as shown in Figure 1: Interchanges 1A, 2A, and 3A in the road network of Palermo City (Italy); Interchanges 4A and 5A in the road network of Catania City (Italy); Interchange 6A in Messina City (Italy), and Interchanges 1B, 2B, 3B, and 4B in the City of Miami, Florida (USA). Considering that it was not possible to conduct a traffic detection survey, traffic volume parameters, required to model the origin/destination (O/D) matrix, were calculated based on lane capacity, i.e., the conditions in which the maximum hourly volume occurs in a generic roadway section. Therefore, the roadway network was simulated with the most unfavorable conditions both in terms of the level of service and consequent greater interactions between vehicles. Vehicle routes were established using “dynamic assignment” to allow for the generation of dynamic routes between junction nodes rather than static ones. Itineraries were assigned based on the most significant accident projections to be observed. Specifically, Figure 1 shows the layout of each interchange, showcasing features of the urban context such as on and off ramps, allowing for the examination of various elevations. Meanwhile, Table 1 outlines the primary design and operational parameters relevant to each studied interchange.

Table 1. Design and operational features by interchange studied.

Parameter	Interchange ¹									
	1A	2A	3A	4A	5A	6A	1B	2B	3B	4B
Main roadway section width (m)	12.00	12.00	11.00	11.00	11.00	10.5	17.00	15.00	22.00	19.00
Main roadways length (km)	0.75	0.69	0.61	0.56	0.690	0.635	1.15	1.130	2.135	0.74
Main roadways lanes quantity	2.00	2.00	2.00	2.00	2.00	2.00	3.00	3.00	4.00	4.00
Entering ramps	2.00	3.00	2.00	2.00	2.00	2.00	2.00	2.00	6.00	4.00
Exit ramps	2.00	5.00	2.00	2.00	2.00	2.00	4.00	2.00	6.00	6.00
interchange land use (km ²)	0.25	0.12	0.14	0.16	0.26	0.27	0.52	0.27	0.55	0.53
Bridges	1.00	2.00	1.00	1.00	1.00	2.00	2.00	4.00	2.00	9.00

¹ the interchanges are codified as shown in Figure 1.

VISSIM Modeling

Building upon the information provided in the introduction section, a case study sample was chosen, comprising 10 freeway interchanges situated in urban areas. Section 4 will delve into the specifics of each interchange. The initial phase of this study involved integrating each freeway interchange model into VISSIM software (Version 10) [17]. Vehicle routes were configured using the “dynamic assignment” option, which was preferred for its capability to generate dynamic itineraries between junction nodes rather than static ones [32].

In order to incorporate CAVs into the simulation model, a new vehicle category corresponding to cars was configured. The calibration phase involved assigning driving behavior parameters specific to autonomous driving. These parameters encompass four types of behavior that CAVs can adopt, considering factors such as driving aggressiveness and the availability of roadway context data.

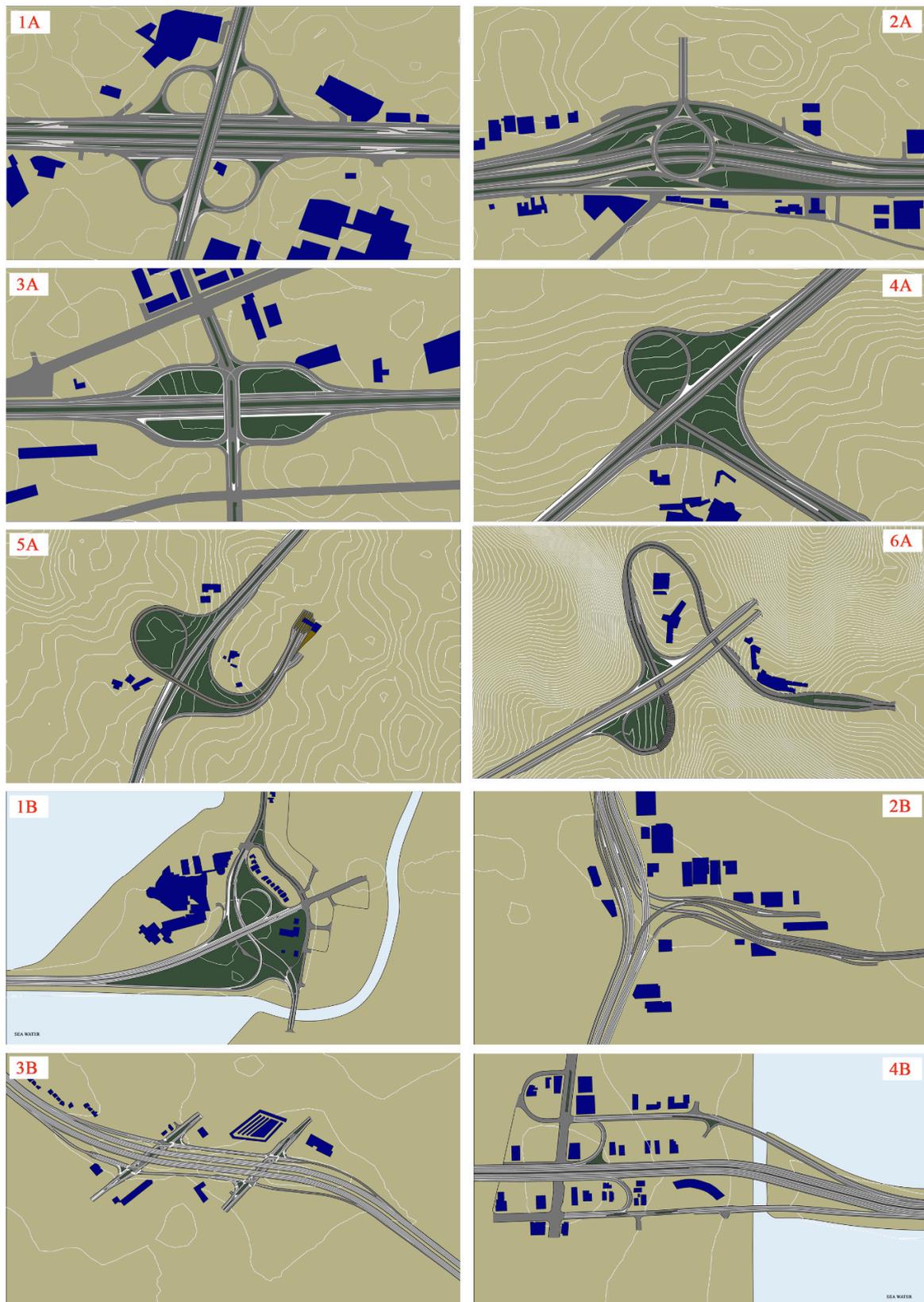


Figure 1. Sketches of the road interchanges within the investigated sample. A code is associated with each interchange facility as follows: Interchanges (1A–3A) in the road network of Palermo City (Italy); Interchanges (4A,5A) in the road network of Catania City (Italy); Interchange (6A) in Messina City (Italy); Interchanges (1B–4B) in the City of Miami, Florida (USA).

Table 2 displays the driving behavior parameters utilized concerning aggressive driving tendencies. In order to simulate a mobility context with highly efficient CAVs, the “all knowing” typology was selected.

Table 2. Driving behavior parameters in relation to aggressive driving way.

Wiedemann's 99 Parameters		Real Safe	Cautious	Normal	All Knowing
CC0	(standstill distance) (m)	1.5	1.5	1.5	1
CC1	(mean headway time) (s)	1.5	1.5	0.9	0.6
CC2	(following variation) (m)	0	0	0	0
CC3	(threshold for entering following) (s)	−10	−10	−8	−6
CC4	(negative following threshold) (m/s)	−0.1	−0.1	−0.1	−0.1
CC5	(positive following threshold) (m/s)	0.1	0.1	0.1	0.1
CC6	(speed dependency of oscillation) (1/ms)	0	0	0	0
CC7	(oscillation acceleration) (m/s ²)	0.1	0.1	0.1	0.1
CC8	(standstill acceleration) (m/s ²)	2	3	3.5	4
CC9	(acceleration with 80 km/h) (m/s ²)	1.2	1.2	1.5	2

Consequently, the desired acceleration/deceleration and speed distributions were established, as depicted in Figure 2, where a behavior parameters setting is shown in terms of speed and acceleration/deceleration, basically due to the differences between CAV and HdV speed limit observations and acceleration/deceleration maneuver trends. HdVs do not respect speed limits as precisely as CAVs, and the latter operate with gradual speed increases or decreases, while HdVs are subjected to driver reactions that affect the way a desired speed or acceleration/deceleration is achieved. So, it can be observed that the spread is minimized, and the plots demonstrate how CAVs strictly adhere to the speed limit.

Operations at full capacity were simulated, as the introduction of CAVs into traffic is anticipated to encourage operating the entry mechanism at the highest possible level of utilization. According to [9], utilization is defined as the ratio of the number of entering vehicles (i.e., the throughput) to the maximum number of vehicles that each entry lane could accommodate (i.e., the capacity). Capacity calculations relied on capacity models and adjustment factors for connected and autonomous vehicles as suggested by the *Highway Capacity Manual* (HCM) [33]. In VISSIM, the integration of CAVs into the road interchange model was completed by configuring speed distribution functions and driving behavior parameters based on [34] and specific assumptions discussed by [35].

The values of the driving behavior parameters for both CAVs and human-driven vehicles were determined through the author's evaluation, incorporating insights from [34–36]. Also, each reported parameter indicates a specific value of following behavior belonging to the Wiedemann's 99 (W99) car-following model [37–39]; these are detailed in Table 3.

The traffic micro-simulator was coupled with the SSAM software to measure traffic conflicts [18]. Specifically, the VISSIM simulation process generates results that can be imported into the SSAM provided by [18]. The surrogate measures of safety, widely recognized for explaining the safety performance of road facilities through the vehicle trajectories provided by traffic micro-simulators [18,40], are integral to understanding safety dynamics. In this context, the SSAM reads trajectory files generated by VISSIM. By utilizing surrogate measures such as time to collision or post-encroachment time, the SSAM can evaluate the probability of conflict occurrence. Following the logic of SSAM, conflict events (i.e., conflicting vehicle pairs) are systematically listed, encompassing conflicts from preceding steps. For each interchange, eight trajectory (*.trj) output files were extracted from VISSIM and processed by SSAM, utilizing parameter thresholds to identify potential high severity conflicts and their specific locations within each sample interchange.

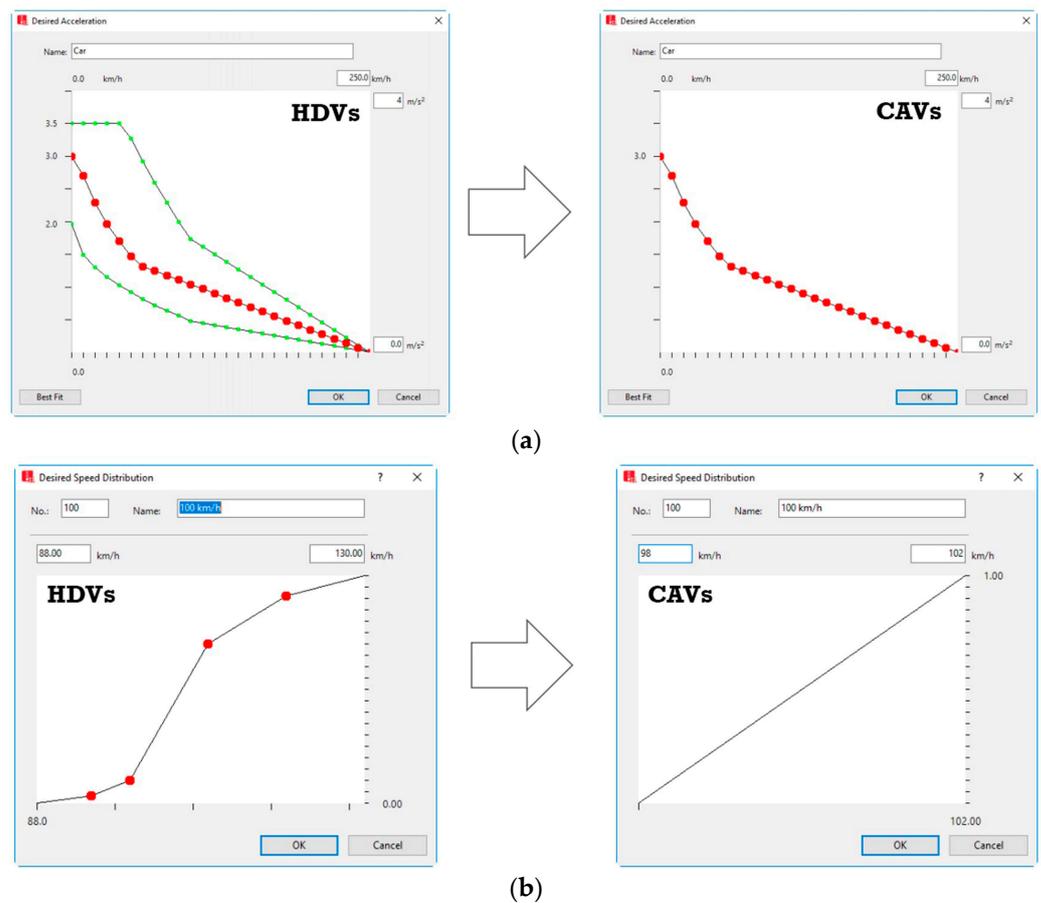


Figure 2. Examples of (a) desired acceleration settings with the range variation in green for HDVs; (b) speed distribution settings.

Table 3. Driving behavior parameters, defaults, and fine-tuned values for CAVs and human-driven vehicles.

Wiedemann's 99 Parameters		Default Value	CAV Value	HdV Value
CC0	(standstill distance) (m)	1.50	1.00	1.50
CC1	(mean headway time) (s)	0.90	0.60	0.90
CC2	(following variation) (m)	4.00	0.00	4.00
CC3	(threshold for entering following) (s)	−8.00	−6.00	−8.00
CC4	(negative following threshold) (m/s)	−0.35	−0.10	−0.35
CC5	(positive following threshold) (m/s)	0.35	0.10	0.35
CC6	(speed dependency of oscillation) (1/ms)	11.44	0.00	11.44
CC7	(oscillation acceleration) (m/s ²)	0.25	0.10	0.25
CC8	(standstill acceleration) (m/s ²)	3.50	4.00	3.50
CC9	(acceleration with 80 km/h) (m/s ²)	1.50	2.00	1.50

It was determined that evaluation parameters significantly impacting potential conflicts among vehicular trajectories are the time-to-collision (TTC) and post-encroachment time (PET) [41]. It is observed that conflicts are more probable with smaller values of TTC and PET, with a TTC of zero indicating a collision. It is crucial, however, for the TTC to be shorter than the PET [18].

The upper limit for the time-to-collision (TTC) was set at 1.5 s, consistent with the default TTC value. Alternative threshold values below 1.5 s led to reduced overlap for the vehicle pair in the projection timeline, resulting in a revised maximum TTC threshold. It is important to highlight that the SSAM continuously updates the time-to-collision (TTC) values for each vehicle pair, ensuring that the projection timeline remains free of overlaps.

However, a collision occurs if the projection reaches zero with overlapping vehicles. In such cases, conflicts are considered resolved once the TTC value exceeds the threshold again [18]. Conversely, the threshold for the post-encroachment time (PET), representing the time interval between one vehicle exiting and another entering the conflict area, was adjusted to 2.50 s, in contrast to the default value of 5.00 s [18]. PET is associated with a conflict timestep, enabling the recording of the final PET value after a conflict concludes, even if the corresponding time-to-collision (TTC) value is below its threshold. Setting the minimum values for TTC at 0.3 s and PET at 0.50 s was necessary to address processing errors, as zero values were identified and removed [18,41]. The conflict type parameter allowed classification of conflicts based on the conflict angle, representing the hypothetical collision between the trajectories of conflicting vehicles: a rear-end conflict occurs if the absolute value of the conflict angle is less than 30 degrees and a crossing conflict occurs when the absolute value of the conflict angle exceeds 80 degrees, otherwise a lane-changing conflict occurs [42]. To clarify, a rear-end conflict occurs when two vehicles are in the same lane simultaneously, whereas lane changing involves two vehicles that have switched lanes. In the examination of each case study, trajectory files for each scenario underwent individual analysis using the SSAM. This method resulted in the initial identification of crucial areas at the interchanges, classifying potential conflicts into three main groups based on the conflict angle values between vehicular trajectories, as mentioned previously. To prevent unrealistic maneuvers, other surrogate safety measures related to driving behavior were kept at their default values.

Car following models are crucial for defining the driving behaviors of vehicles, and consequently, they were configured differently for human-driven vehicles and CAVs. This differentiation is made because it is anticipated that CAVs can follow the leading vehicle more closely and have shorter reaction times. The subsequent discussion in Section 5 is grounded in both the outcomes of traffic simulations and road safety analyses. This is attributed to the fact that potential traffic conflicts with significant severity can be linked to low values of TTC (time-to-collision) and PET (post-encroachment time) [18]. The selection of value thresholds aligns with the findings presented in [43]. To ensure a valid safety estimation, the time-to-collision (TTC) and post-encroachment time (PET) thresholds were adopted as evaluation parameters, as they are widely used in the freeway context and prevalent in the safety analysis literature [44].

The results of the potential traffic conflict analysis were utilized for road safety assessment, with special consideration given to CAVs based on insights provided by [45]. As is well known, potential traffic conflicts serve as the foundation for the application and modeling of the safety performance functions (SPFs), as elaborated in Section 5. The results revealed a significant increase in rear-end potential conflicts, exceeding 90%, compared to other conflict types. This is primarily attributed to the presence of on and off ramps, where capacity conditions and queuing situations often arise. In many documented cases, a higher concentration of CAVs resulted in elevated instances of rear-end conflicts, as previously discussed by [46], highlighting the heightened vulnerability of CAVs to such types of conflicts. To conduct safety analysis, trajectory output files from the VISSIM simulations were transferred into the SSAM software. Notably, the selected interchanges represented diverse design standards from two different countries, each characterized by varying traffic volumes. The findings were presented using a normalization factor, facilitating the comparison of potential conflicts for each interchange [40]. Figures 3 and 4 depict the quantity and types of conflicts for each interchange, with conflict quantities standardized to 1000 vehicles entering the bypass area. The CAV penetration rate was varied, and it was anticipated that rear-end conflicts would dominate, given that simulations considered the maximum vehicle capacity for each entry lane or ramp, operating in segments with low headway values.

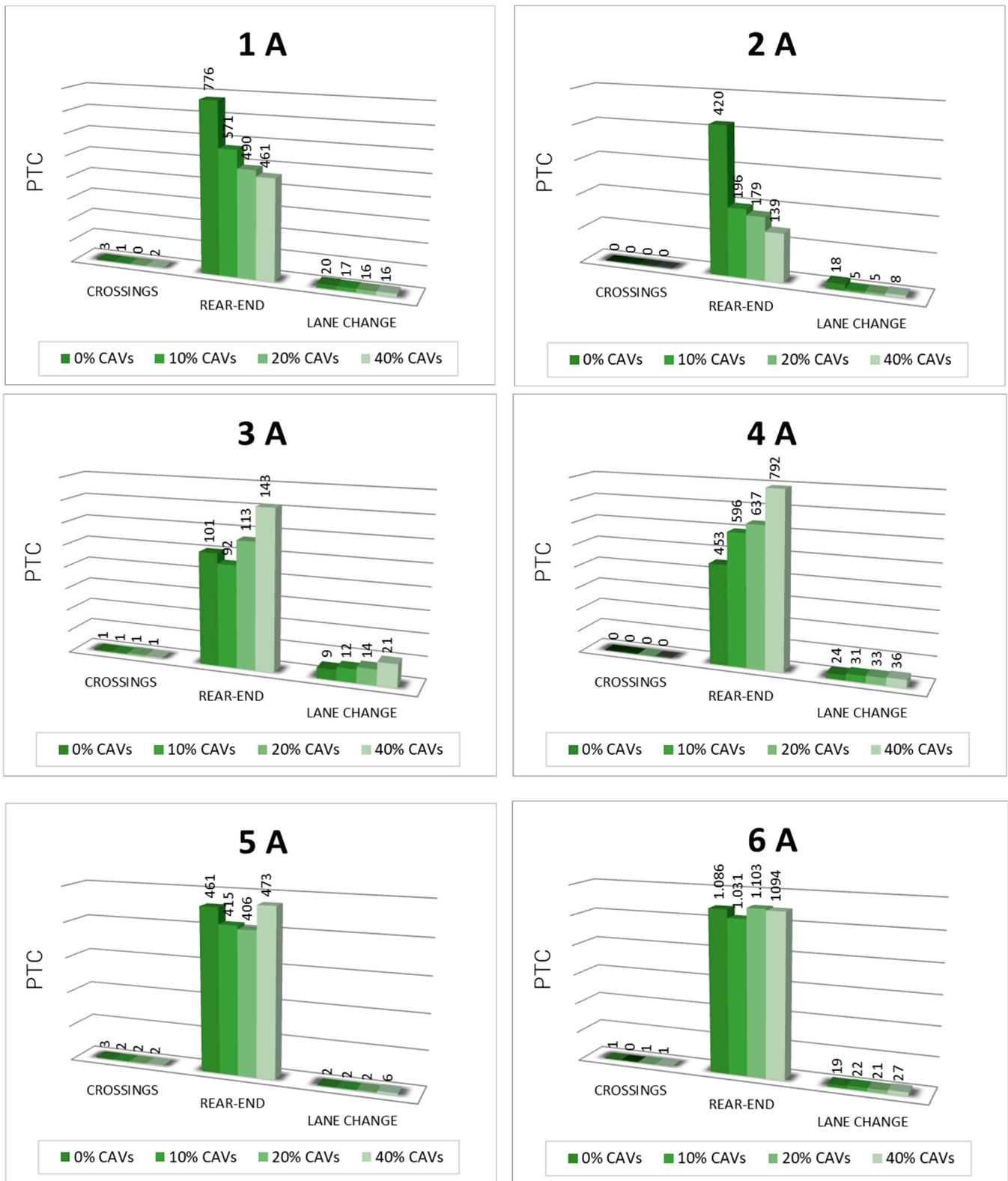


Figure 3. Potential traffic conflicts (PTCs) for 1000 entering vehicles at Italian interchanges under varying CAV rates. **Note:** A code is associated with each interchange facility in Figure 1 as follows: Interchanges (1A–3A) in the road network of Palermo City (Italy); Interchanges (4A,5A) in the road network of Catania City (Italy); and Interchange (6A) in Messina City (Italy).

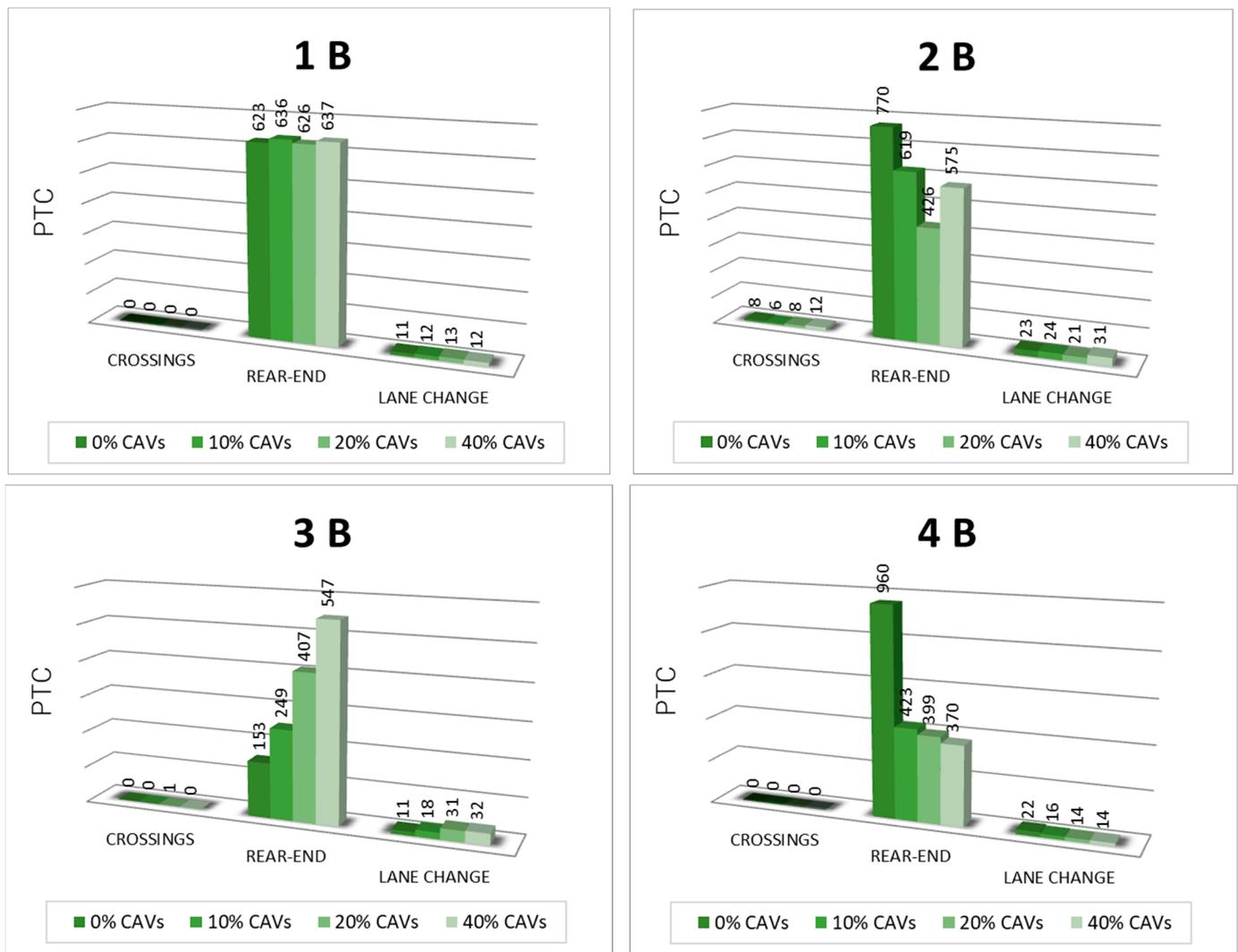


Figure 4. Potential traffic conflicts for 1000 entering vehicles at US interchanges under varying CAV rates. A code is associated with each interchange facility in Figure 1 as follows: Interchanges (1B–4B) in the City of Miami, Florida (USA).

Rear-end potential conflicts are notably elevated compared to other types, primarily due to the propensity for queuing along on- and off-ramps when traffic conditions approach capacity.

Interchanges 1A, 2A, and 4B show a gradual decrease in rear-end potential conflict, while 3A, 3B, and 4A are characterized by an increase. Rear-end potential conflicts results to be gradual for samples 3B–4A from 0% CAVs, while 3A shows a minimum initial decrease for 10% CAVs that does not affect the increasing trend. Samples 5A and 2B are characterized by the 40% CAV threshold that leads from a gradual rear-end decrease to a sudden increase, while 6A and 1B do not show significant outputs, even if the geometrical layouts are similar but are characterized by different operating schemes.

To provide a comprehensive safety assessment of interchange performance, with and without CAVs, the ex ante safety standards for the case studies were scrutinized. To achieve this, the ISATe tool [47] was applied to estimate crashes with a higher probability of resulting in fatalities.

Figure 5 displays potential crashes derived from the ISATe analysis tool applied to each interchange within the entire sample. As described in further detail in the following

text, a safety performance function frequency has been estimated for 0% CAVs and different CAV penetration rates.

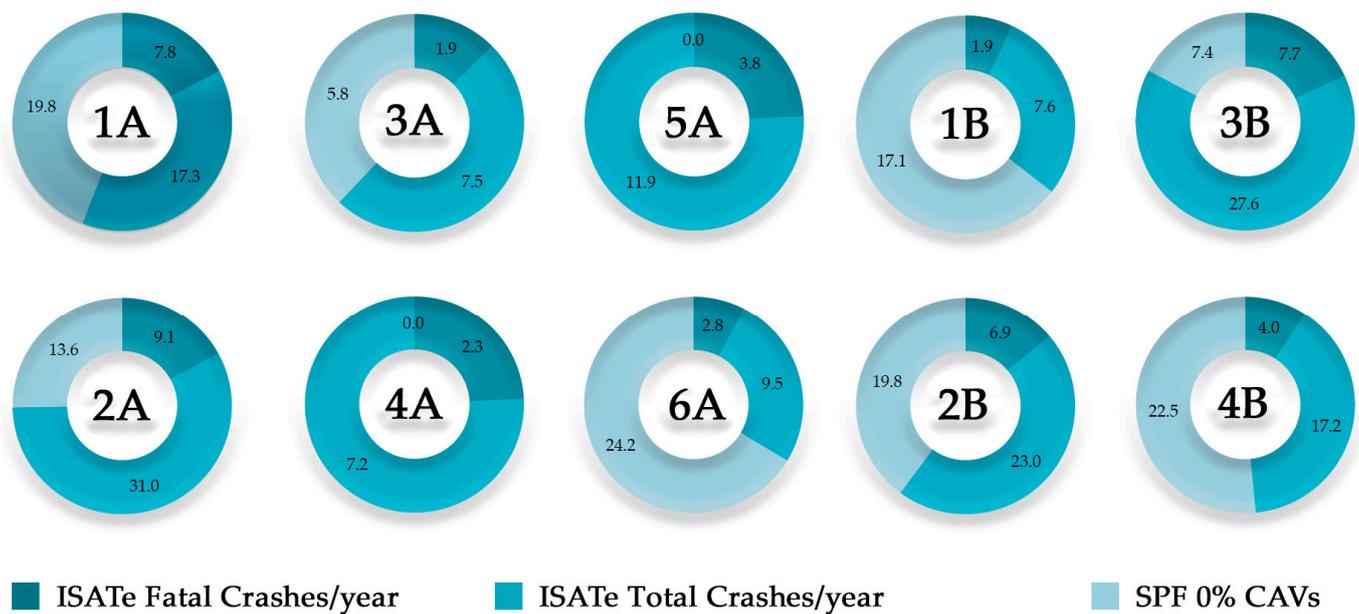


Figure 5. The crash estimates derived from the application of Interchange Safety Analysis Tool Enhanced (ISATe) for the entire sample with 0% CAVs. Note: (1A–6A) and (1B–4B) are the interchanges in Figure 1.

However, it must be emphasized that ISATe outputs are solely linked to geometric layout parameters and AADT values [48]. Consequently, the results exclusively pertain to the road network operations without CAVs in traffic.

Crashes calculated by ISATe exhibited significant variability owing to the characteristics of the sampled interchanges [49]. These findings hold true for both the Italian and North American groups of interchanges, as well as for the sample as a whole.

Furthermore, the results obtained concerning potentially fatal crashes are typical and are usually associated with the type of intersection under investigation. This circumstance affirms, on one hand, the feasibility of utilizing an “international” sample, and on the other hand, underscores the necessity to validate presumed characteristics such as the geometry of the junction, specific traffic conditions, and the susceptibility/adaptability to the presence of CAVs in traffic. These observations could be further enriched through an in-depth study of the urban context characteristics where each junction is installed.

To incorporate the penetration rate of connected and autonomous vehicles into the network models of the sampled interchanges, we sought a correlation between predicted collisions and predicted conflicts. For this purpose, the methodological framework provided by [50] was employed to forecast the number of conflicts and collision types. This framework involved a two-phase nested modeling process wherein a Poisson–gamma safety performance function (SPF) is utilized. This SPF uses traffic volume as an exposure parameter to predict conflicts, which are then employed in another Poisson–gamma SPF to predict collisions.

The traffic conflicts obtained from the SSAM were used for the application and modeling of SPFs. Following the methodology outlined in [50], the expected collision frequency as a function of average hourly conflicts was calculated using Equation (1):

$$E(Y) = a_0AHC^{a_1} \tag{1}$$

where $E(Y)$ is the expected collision frequency, AHC is the average hourly conflicts, $\ln(a_0)$ is equal to -1.1991 , and a_1 is equal to 0.626 . This equation is functional not only because

this study was based on conflict prediction techniques but also because traffic conflicts represent a more appropriate predictor parameter for crashes, due to the fact that they are related to vehicle interactions. Then, it is possible to obtain expected collision frequency for a specific site based on specific site conflicts frequency and confidence level parameters (a_0, a_1).

Subsequently, the previously reported equations were applied for each scenario. The results of the expected yearly crash frequency at the examined intersections are depicted in Figure 6.

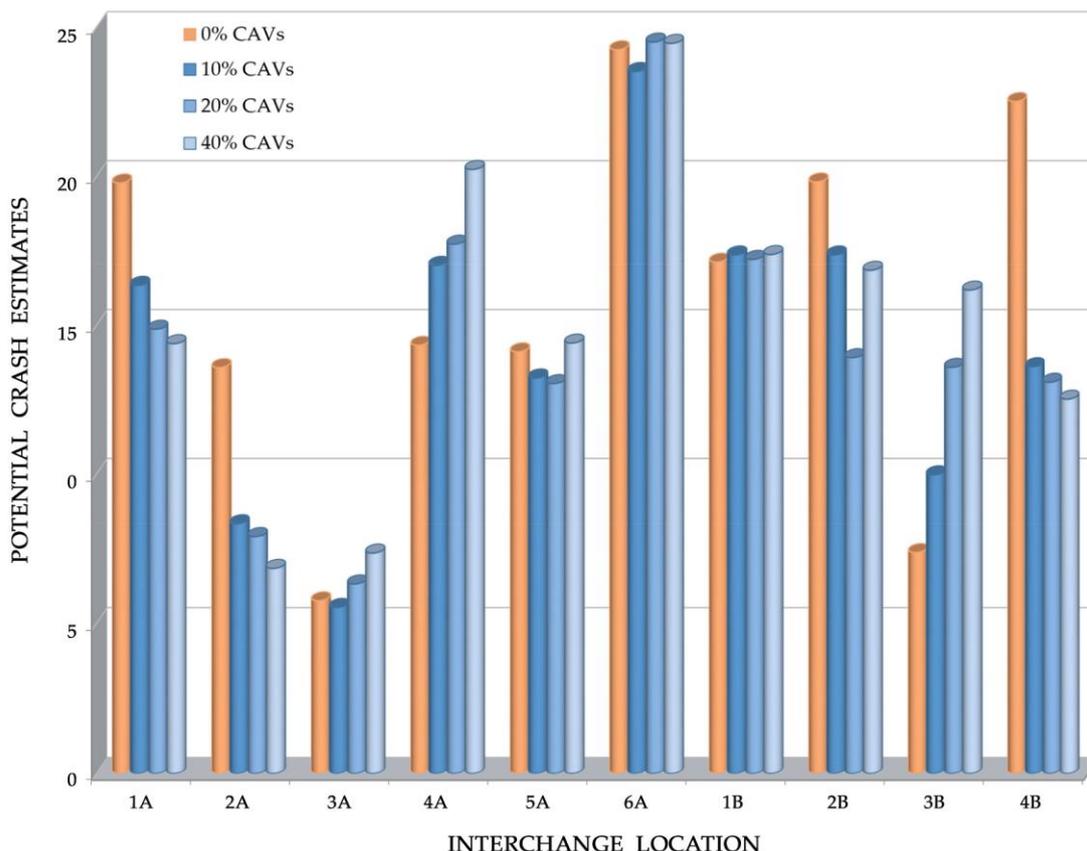


Figure 6. Yearly crash frequency estimates from Equation (1) related to CAV penetration rate at the sampled interchange.

4. Results

Anticipated disparities between the SPF outcomes and the ex ante modeling of ISATe arise from variations in road environment input data. SPF results are influenced by potential conflicts identified in microsimulation trajectory (trj) files, whereas ISATe predictions are derived from roadway geometrical and traffic volume data. Nonetheless, Figure 5’s findings illustrate how distinct conditions at each interchange can result in varying sensitivity to the presence of CAVs, both in terms of absolute values (i.e., number of estimated collisions) and relative values (i.e., between different junction layouts), as discussed in the following paragraphs.

In Figure 7, presented below, an overarching view is depicted, illustrating the potential traffic conflict plot for all investigated interchanges. These plots, directly generated by the SSAM model, predominantly indicate the positions of potential traffic conflicts involving rear-end collisions and lane changes within the considered intersection. Notably, for the analyzed sample, the potential traffic conflict of crossing type remains relatively low. However, a noteworthy observation arises when comparing the traffic volumes of North

American junctions, which were higher than at Italian ones; despite this, the potential conflict rates appear like those found in Italian interchanges.

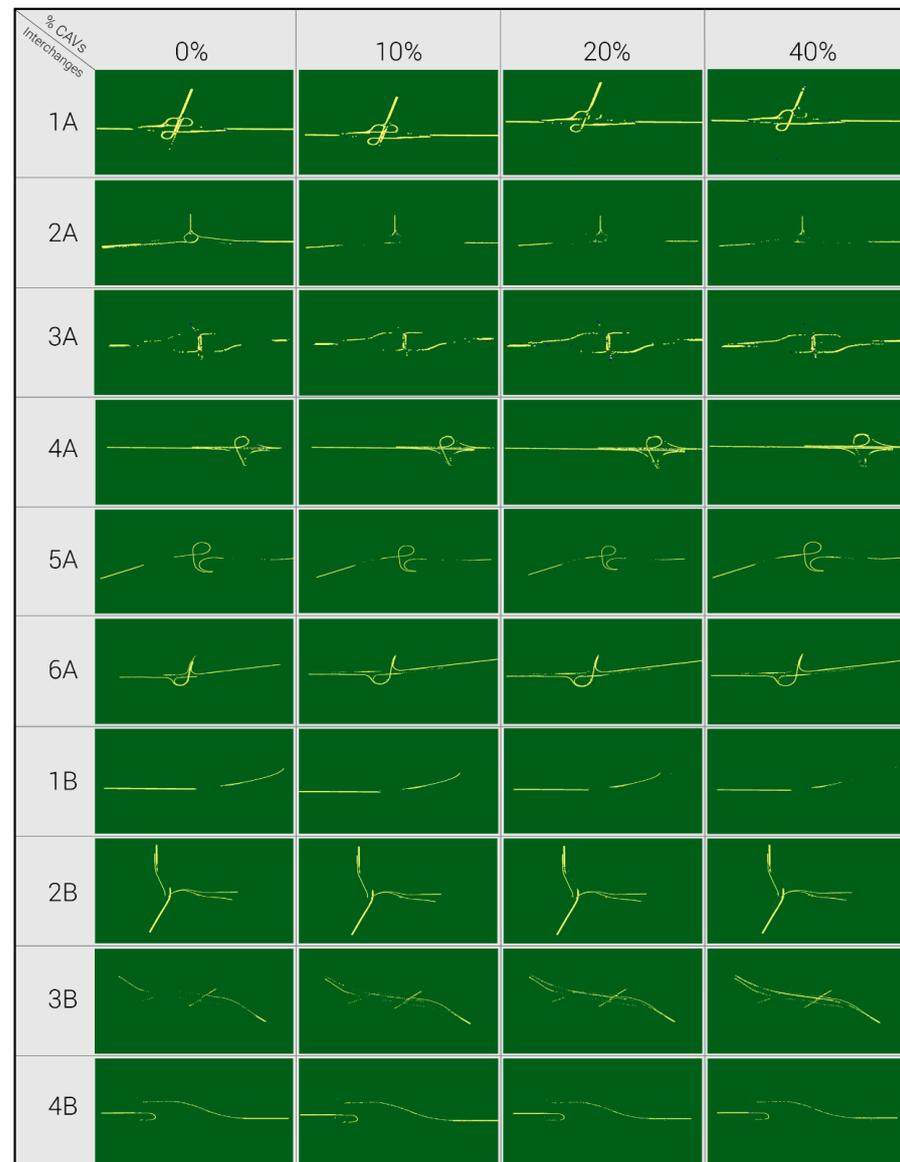


Figure 7. Location of potential rear-end traffic conflicts in interchanges with varying CAV rates.

The larger dimensions of North American interchanges, even with elevated traffic volumes, afford both human-driven vehicles and connected autonomous vehicles the ability to pre-determine the ramp for entry. This is facilitated by the option to maneuver across a greater number of lanes than the standard two lanes observed in Italian interchanges. Furthermore, despite the greater number of lanes in North American (average 3–4 lanes on main roadway) interchanges, potential lane-change conflicts also exhibit similar quantities.

In samples 1A, 2A, and 4B, characterized by a two- and three-lane main roadways, respectively, a gradual decrease in rear-end potential conflict can be attributed to long extensions on/off-ramps that lead to an interchange area that, compared to the entire interchange extension, is characterized by reduced speeds due to reduced radius curves. Therefore, CAVs are able to slow down traffic flow significantly in advance by exploiting ramp lengths, reaching the curved interchange area with reduced speed, and thus minimizing rear-ends potential conflicts. The greater presence of CAVs proportionally affects the impact on the overall slowdown harmonization of traffic flow close to the curved interchange areas.

As regards the increase in potential rear-end conflicts for samples 3A, 4A, and 3B, it is important to highlight that 3A and 3B belong to diamond interchanges category, where the prevalence of straight segments and the minimal presence of curves in interchange areas lead vehicles to increase their desired speed and are then subjected to a non-gradual slowdown in the interchange areas. For sample 4A, rear-end conflict increases are due to the queue formation in and close to ramps, due to high traffic volumes on interchange areas.

Ultimately, samples 5A and 2B are characterized by a 40% CAVs threshold that from a gradual rear-end decrease causes a sudden increase, and considering that interchanges layout are not comparable, this aspect needs to be further explored.

The increase in CAV penetration further leads to a rise in potential conflicts, as an overlap occurs between the decision-making capacity of CAVs (which choose their route well in advance) and human-driven vehicles that occasionally perform maneuvers due to sudden driver decisions. Consequently, in these areas, a high percentage of CAVs does not contribute to the reduction in lane-change conflicts.

Overall, Figure 8 shows the framework of the research model described above. Specifically, the methodological path should be explained using a real case study, as it should be possible to design the simulation environment and to then reach the appropriate safety analysis.

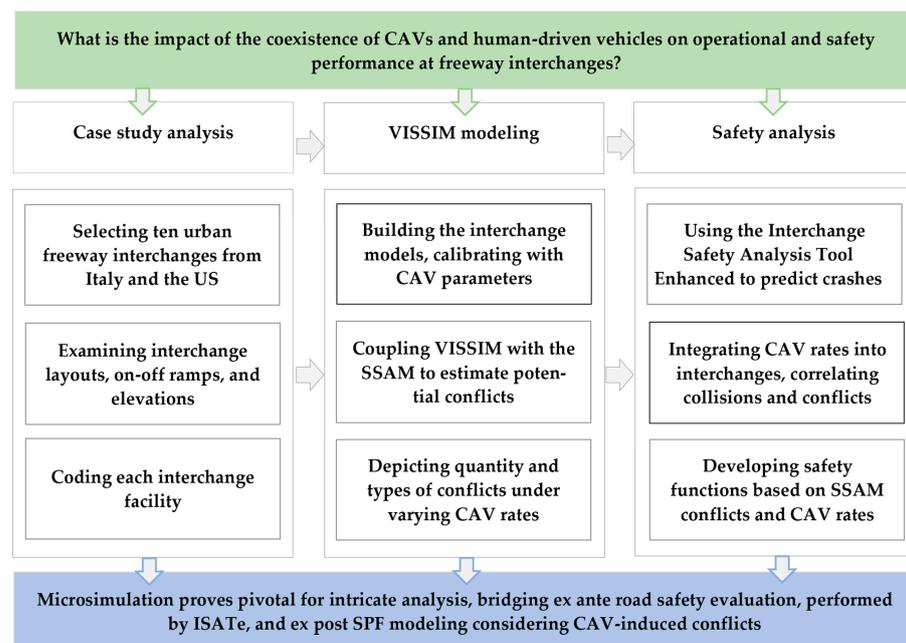


Figure 8. Methodological path of the study analysis.

5. Discussion

Results related to traffic safety estimation emphasize the analysis of conflict numbers and the application of the SSAM. The key performance indicators associated with varying penetration rates of CAVs have been shaped by the contextual analysis of the roadway network, spanning intersections and freeway roadways in prior studies. For instance, in the context of freeway traffic, a decrease in conflict numbers was noted [51], mirroring a similar trend observed with the implementation of a longer headway time [52]. Notably, achieving a 100% CAV penetration rate on freeways resulted in a remarkable 90% reduction in conflicts [53]. Intersection scenarios presented significant outcomes, particularly with the presence of 100% CAVs facilitating the mitigation of crossing conflicts [54].

Concerning other types of intersections, such as signalized intersections and roundabouts, a documented reduction of 65% in conflicts has also been observed [55]. However,

it is crucial to highlight that in a roundabout environment, an increased percentage of CAVs may correspond to a heightened frequency of conflicts [56].

Although safety analysis using the SSAM is a consolidated methodology in road safety literature, it is necessary to highlight some critical issues due to the fact that this approach was developed before the implementation of CAVs, then avoiding their driving behavior and capabilities. Compared to human-driven vehicles, CAVs are able to share precise and complex data, such as close vehicle maneuvers, in real time with surrounding vehicles and infrastructure devices with much shorter reaction times. However, it is questionable whether they are enough accurate to carry out CAVs circulation assessment, which is why it would be necessary to develop dedicated SSAM parameters for CAV behavior, according to their automation/connectivity levels based on field data or driving simulator results. One of the aspects that should be studied in depth is related to the possibility of combining the planning of lateral positions with the optimization of the longitudinal trajectory, especially for maneuvers aimed at changing lanes or merging [57]. For example, when a lane change is simulated, rather than a convergence or divergence maneuver, considering the reduced gaps that CAVs can keep, in addition to the V2V or CACC systems, it is not certain that a crash risk would be established [58,59], but the SSAM will inevitably detect a potential rear-end or lane-change conflict.

6. Conclusions

The exploration of road interchanges and the integration of the latest generation of connected and autonomous vehicles (CAVs) is on the road. The significance of the CAV penetration rate is evident for both operational efficiency and safety features at specific road facilities. However, providing a general rule regarding the realistic consequences of CAVs on freeway bypasses remains challenging. The sample selected for this study, as detailed in Section 4, serves as a valuable starting point to elucidate the intricate relationship between interchange working conditions and safety standards.

The presence of ramps adjacent to the main transit corridor, featuring multiple lanes and additional parallel lanes external to the main ones, contributed to a smoother behavior for CAVs as enrollment increased. In certain scenarios, a reduction in potential rear-end conflicts has been observed. Additionally, intersections with auxiliary road arteries facilitated a reduction in dangerous interactions, primarily involving rear-end collisions with CAVs.

While this approach requires optimization, as methodologies in the literature were predominantly applied to smaller intersections with lower operating speeds and reduced vehicle numbers, this study emphasizes the necessity for safety preventive analyses in freeway and ring road interchanges due to the circulation of CAVs. The study suggests potential solutions that must be subjected to further analysis and trials, such as reducing lane width to increase the quantity and capacity of lanes and widening roadway sections. The former would benefit CAVs with precise lane-keeping systems but could lead to the increased potential for lane-change conflicts for traditional motor vehicles (MVs). The study also confirms the relationship between the trend of rear-end conflicts at 0% CAVs and 40% CAVs for Florida junctions.

CAVs exhibit consistent speed in zones near ramps, arriving with gradual slowdowns, unlike MVs that tend to accelerate in entrance and exit ramps, resulting in sudden slowdowns and evasive maneuvers. The configuration of an extended interchange layout significantly influences the number of potential conflicts, even with the presence of CAVs, and plays a crucial role in accommodating higher traffic volumes.

Considering the challenges associated with a 40% penetration of CAVs, each roadway interchange may have a specific threshold triggering cooperation difficulties with MVs.

Microsimulation emerges as the essential modeling tool for such analyses. Despite its complexity, this approach promises to link the ex ante evaluation of road safety, as seen in ISATe application, and the SPF modeling for ex post evaluation, which can consider potential traffic conflicts arising from CAV operations.

Our findings recommend implementing auxiliary lanes on arterial roads to reduce longitudinal traffic conflicts, particularly for CAVs in rear-end scenarios. This study also underscores the need for further tool development to efficiently analyze diverse urban morphologies and geometrical configurations, minimizing the potential conflicts in mixed traffic operations.

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