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Developing geometric criteria to ensure Minimal Risk Conditions for highly automated vehicles

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ABSTRACT

Connected and Automated Vehicles (CAVs) represent a transformative technology with the potential to significantly enhance road safety and improve mobility for all users. However, it is important to recognize that CAVs are not infallible; there will inevitably be situations in which these vehicles must come to a stop to ensure safety. This designated stopping location is called the Minimal Risk Condition (MRC). Achieving MRC should be a standard operational capability for SAE Level 4 + vehicles, which necessitates that the automated system performs a safe Dynamic Driving Task (DDT) fallback when required, especially in instances where the human driver may not be prepared to take control of the vehicle.

This study proposes various solutions to facilitate MRC, including the use of hard shoulder, Emergency Refuge Lane (ERL), and Safe Harbor (SH). Initially, we examine the advantages and disadvantages of each solution, followed by an assessment of their respective capacities – experimental for ERLs and analytical for SHs. Based on these evaluations, some geometric design criteria and diverse solutions applicable to various highway types and interchanges are proposed.

This work represents an important first step in addressing a critical topic that will receive further attention in the coming years, as the requirements for these zones are defined more precisely in relation to CAV penetration rates and Operational Design Domain (ODD) limitations. Consequently, it is essential that road and interchange design guidelines should be updated and adapted to incorporate these new facilities effectively.

1. Introduction

Connected and Automated Vehicles (CAVs) are a promising technology that has the potential to significantly improve road safety and mobility. By 2022, 638,000 automated vehicles were estimated to be on the road worldwide, while by 2030, sales of this type of vehicle are estimated to account for 12% of the entire automotive sector (ERF, 2020). In this context, it is expected that by 2035, 20%, 24%, and 29% of the global fleet of these vehicles will be in Europe, China, and the United States, respectively. Furthermore, the level of maturity in the market for this type of vehicle varies greatly within the same region (ERF, 2020).

Despite the uncertainty related to connected and automated mobility, progress continues to be made in studies and developments, as well as in discussions between various stakeholders. One of the critical areas where progress is necessary is in the interruptions and terminations of ODD-compatibility zones.

To this regard, one of the issues currently under discussion is closely related to the configuration and design of roads. It concerns the areas where automated vehicles that need to reach a Minimal Risk Condition (MRC) can be safely accommodated. According to Sever and Contissa (2024), Automated Driving Systems (ADS) need to be capable of achieving a Minimal Risk Condition (MRC) in adverse situations, highlighting the need to develop adequate infrastructures that facilitate this process.

Several alternatives have been put forward, from less safe to safer: the use of the outside hard shoulder, the provision of emergency lay-bys, and the development of new safe stopping areas outside the main roadway (Transport Systems Catapult, 2017; Liu et al., 2019; SAE, 2021; Garcia et al., 2022); in addition to using existing service or rest areas.

As with any new technology, CAVs also present new challenges and risks. One of the key challenges for CAVs is maintaining safe operation when the vehicle is unable to operate autonomously. Depending on the

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SAE level of the Automated Driving System (ADS) (SAE, 2021), this may happen under different circumstances:

- SAE1 and SAE2: when the system disengages and suddenly transfers control to the human driver.
- SAE3: when the system detects a soon necessity of transferring control to the driver (Takeover Request, TOR).
- SAE4: when the vehicle approaches the end of a road segment that meets its Operational Design Domain (ODD) (Request to Intervene, RTI) or presents a system failure.
- SAE5: when the vehicle presents a system failure.

For SAE levels 1 to 3, the human driver is responsible for being ready to take control of the vehicle. However, this is not the case for SAE levels 4 and 5, as the system should be able to autonomously operate the vehicle in a limited Dynamic Driving Task (DDT) without human intervention.

Implementing MRCs requires CAVs to continuously monitor and adapt to changing conditions. For example, a CAV encountering severe weather might initially stop at a designated spot but may need to move if conditions worsen. The vehicle's ADS should be capable of reassessing the situation and deciding whether to remain in place or move to a safer MRC, considering both the mid- and long-term risks. In this decision, possible sensor failures or mechanical issues should also be considered, ensuring that the chosen location minimizes overall risk to passengers and other road users.

It is also important to recognize that an ADS must account for factors beyond just the Minimal Risk Condition. The maneuver to reach this condition – Minimal Risk Maneuver, MRM – should also be taken into account. An ADS should ensure that both aspects are comprehensively optimized, ensuring the vehicle reaches a safe stop by executing the safest possible maneuver.

To address the complexities of CAV operations when the automated driving system (ADS) is unable to continue a journey, the concept of Minimal Risk Event (MRX) has been introduced (BSI, 2024). MRX combines the Minimal Risk Condition (MRC) and the Minimal Risk Maneuver (MRM) into a single framework. This new approach considers the trigger events that initiate these maneuvers, optimizing the decision-making process to achieve the lowest overall risk. This integrated concept is essential for managing real-world complexities and enhancing the safety and reliability of CAVs.

The MRX framework provides a structured methodology for evaluating and mitigating risks associated with both the maneuver and the stopping condition. By incorporating a detailed analysis of potential triggers and corresponding responses, MRX enables the ADS to handle a wide range of emergency scenarios effectively. This approach is particularly crucial as CAVs become more prevalent and operate in increasingly complex environments. As such, the development of geometric design criteria and solutions for highways and interchanges must consider the MRX framework to ensure that CAVs can achieve a minimal risk state in various operational conditions.

Depending on the SAE level (1 to 3 or 4 and 5), either the human or the Automated Driving System (ADS) should take the vehicle to a Minimal Risk Condition (MRC) if the Dynamic Driving Task cannot continue. This MRC is defined by the SAE as a 'stable, stopped condition to which a user or an ADS may bring a vehicle after performing the DDT fallback in order to reduce the risk of a crash when a given trip cannot or should not be continued' (SAE, 2021). To summarize, ADS for SAE levels 4 and 5 should always be able to reach an MRC after a RTI or system failure, while other levels are not required to. The latter might be able to reach an MRC under certain conditions but not under any circumstance. The fallback function of an Automated Driving System (ADS) to achieve an MRC is called a Minimal Risk Maneuver (MRM).

Facilitating Minimal Risk Conditions (MRCs) on roads involves classifying these conditions based on inherent risks associated with specific road layouts, traffic volumes, and environmental factors. For instance, MRCs may range from designated parking areas (lowest risk) to in-lane stops that completely block traffic (highest risk). Following the Report from BSI (BSI, 2024), the proposed classification additionally includes MRCs such as laybys, hard shoulders, soft shoulders, side roads, and bus or cycle lanes, from lower to higher risk. Each class is evaluated for risk modification factors like location-specific geometry, current conditions (e.g., weather, traffic density), and vehicle-specific factors, including passenger load and cargo type. This approach aims to ensure CAVs select the safest possible stop location based on real-time and pre-mapped data.

The Minimal Risk Condition must ensure safety while minimizing disruption to traffic operations; for instance, stopping the vehicle within the lane should be avoided.[1] Parking on the hard shoulder –if possible– could be a possibility but nearby traffic could pose a risk. Moreover, the shoulder may not be a possible refuge if it is too narrow or is limited laterally by obstacles such as barriers.

Safe Harbors (SH) are another option for MRCs as designated parking areas. These are located outside the main carriageway, taking advantage of ramps or inner areas at interchanges. They offer more space for a higher number of parking stalls and are less likely to be obstructed by obstacles (Garcia et al., 2022). On the other hand, reaching a safe harbor is not immediate for a vehicle and would depend on how limited its Dynamic Driving Task and the proximity of the Safe Harbor is.

An intermediate solution is an Emergency Refuge Lane (ERL), which is more accessible than safe harbors –it has direct access to the main carriageway through the hard shoulder but is still exposed to traffic–. Another limitation of an ERL is its limited capacity to accommodate vehicles. The ERL is similar to the current Emergency Refuge Area (ERA) or laybys but leaves the shoulder free and allows more than one parked vehicle. In England (Highways England, 2020), the regulation of emergency areas for smart freeways (with variable speed limits) leaving the shoulder to be opened to traffic at peak hours is similar to ERL but only for one vehicle.

The ERL should be outside of the clear zone (a buffer, measured from the edge of the traveled way to the near edge of the ERL), but by locating it outside the hard shoulder, a separation of at least the width of the shoulder is provided. This solution would be safer than stopping the vehicle on either the hard shoulder or the current Emergency Refuge Areas (ERA).

The installation of SHs and ERLs depends on the type of road, traffic volume, available space, and, of course, market penetration of SAE level 4 vehicles (although lower levels of automated vehicles could also seek refuge there). On rural limited-access highways, safe harbors could be located at the unused space between exit and entrance ramps. On urban/suburban limited-access highways with less available space, safe harbors could be located at highway exit ramps, which sometimes provide access to nearby services. Emergency Refuge Lanes could be provided on both freeway exit ramps and main roadways as Emergency Refuge Areas (ERA) of greater length and, therefore, greater capacity.

A vehicle performing in a limited Dynamic Driving Task should decide where to reach an MRC, according to several parameters such as the DDT limitations, proximity to safe harbors or emergency refuge lanes, traffic volume, type of road, weather condition, proximity to destination or critical areas, etc. In fact, the vehicle should also consider the maneuver to reach the MRC in the decision. This maneuver is called "Minimal Risk Maneuver" (MRM) (Karakaya and Blenger, 2023). Some recent studies and even regulations reflect some thresholds or limitations for the speed and acceleration of these maneuvers (European Commission, 2022), but there is a lot still to develop in this field.

Regarding parking design criteria, there is very little literature about safe harbors and emergency refuge lanes for automated vehicles. In order to determine their design and capacity, it is necessary to review some concepts about parking design. To this regard, it should be noted

[1] Insert Video.

that requirements for parking geometry in guidelines contain ambiguous, sometimes even contradictory information that may adversely affect the level of road safety (Mikusova et al., 2020).

According to the classification of parking layouts of Wolshon and Pande (2016), ERLs can be considered parallel parking layouts, while SHs can be defined as angled parking layouts. The convenience and comfort of parking stalls depend on two issues: (i) the width of the parking space and the convenience for people getting into and out of the automobile and (ii) the ease of the turning movements required to park and "unpark" an automobile, which is determined by the module and parking angle as well as the width of the parking space. As stall width increases, the module can be a little smaller to maintain the same overall comfort of turning into the stall. Also, the required module decreases as the angle is reduced from 90 degrees.

Rotating the stall distorts the space required to park the car. The problem is exacerbated the farther the angle is from 90 degrees (see Fig. 1). At 70 degrees, 23 cm (9 in) on each side of the aisle, or a total of 46 cm (18 in) of space, is wasted when the stall is rotated, which may not be available at all locations so would not be preferred.

Concerning parallel parking, a stall width of 2.4 m (8 ft) is typically recommended, although AASHTO (2018) states that a stall width of 2.1 m (7 ft) is acceptable on streets with speed limits at or below 50 km/h (30 mi/h). However, the dimensions of the parking stall will mainly depend on the type and the size of the design vehicle, being this term defined differently worldwide.

Thus, when designing parking lots, it becomes necessary to determine the width of the trajectory, the size of the maneuvering space, and geometric parameters. This requires modeling the dynamics of design vehicles, which is a time-consuming process and not sufficiently mastered by road designers (Mikusova et al., 2020).

This fact, coupled with the lack of reference documents on these issues is often the cause of unreasonable design decisions, which either lead to an overestimation of the estimated cost of facilities or fail to provide optimal operating conditions for vehicles.

Additionally, it is important to note that CAVs are commonly equipped with Advanced Driver Assistance Systems (ADAS), a set of innovative technological solutions that are integrated into vehicles to improve the safety of both the driver and passengers and other road users, including pedestrians and cyclists, as well as enhancing the driving experience.

Particularly, the Rear Cross Traffic Alert (RCTA) plays an important role in the context of the studied phenomenon. RCTA system uses sensors –mainly medium-range radars– and computer processing to detect hazards approaching from the side as the ego vehicle reverses into moving traffic (BSI, 2022). This system can complement rearview cameras and rear automatic braking by preventing potential backing crashes that these other parking assistance systems are not designed to detect (Cicchino, 2019).

However, the range and accuracy of the system mainly depend on the location of the radars, which are usually installed on the rear bumper (Patole et al., 2017) with an angle of 30 degrees (see Fig. 2), and the angle of the parking layout. This means that a 90-degree parked vehicle would have no problems at detecting approaching traffic even from the parked position, but as the angle of park gets lower, the system requires the vehicle to move back a specific distance to initiate traffic detection.

This study goes a step further by proposing new geometric design criteria to facilitate the installation of Emergency Refuge Lanes (ERL) along main highways and Safe Harbors (SH) at interchanges, analyzing their strengths and weaknesses. Both MRCs are classified as the safest solutions by BSI (BSI, 2024).

The paper is divided into six sections. After the introduction, the methods for exploring the new geometric criteria in ERLs and SHs are described. The findings of the experimental data collection on ERLs and the analysis of the diversity of geometric criteria in SHs are then discussed. As a result, new geometric criteria for the design of ERLs and SHs are presented. Moreover, possible locations for these solutions are discussed, as well as the capacity of SHs. Finally, the paper concludes with the most relevant recommendations and suggests where further research should be focused.

2. Methods

The research methodology was divided into two main parts: (a) experimental data collection for the operational and geometric analysis of ERLs; and (b) selection of geometric design criteria for the definition of SHs.

2.1. Geometric design criteria for ERLs

The design of Emergency Refuge Lanes (ERLs) is critical for ensuring the safe accommodation of automated vehicles during instances where they must achieve a Minimal Risk Condition (MRC). A comprehensive methodological framework was developed to establish effective geometric design criteria for ERLs. This framework encompasses data collection, analytical evaluation, and validation of design parameters.

Data collection consisted of a combination of parking maneuver simulations and field studies in a real road environment. The data gathered focused on vehicle behavior during simulated stopping maneuvers after the corresponding lane change, specifically examining approaching speeds, deceleration rates, stopping distances, and final relative positions of the vehicles.

Analytical methods included statistical analysis of the collected data

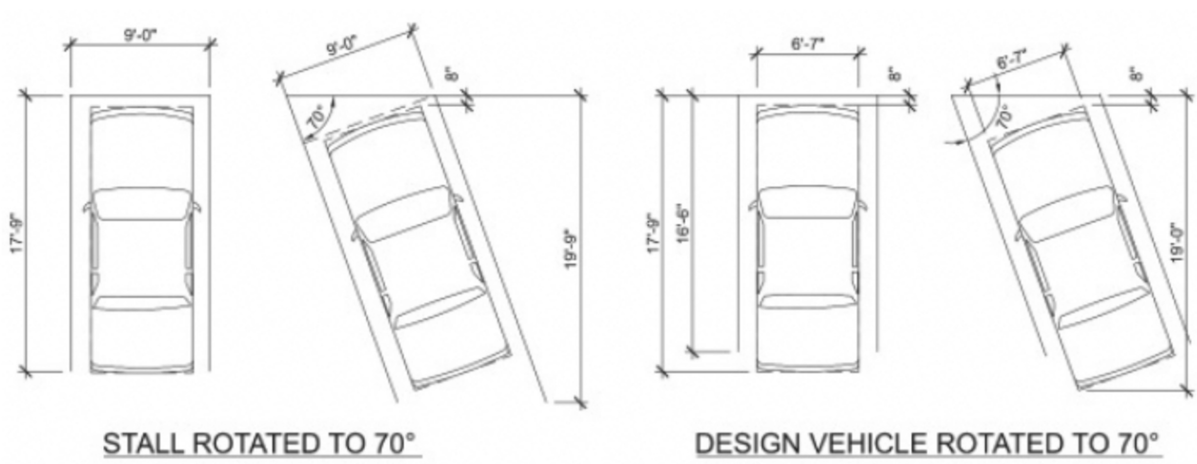
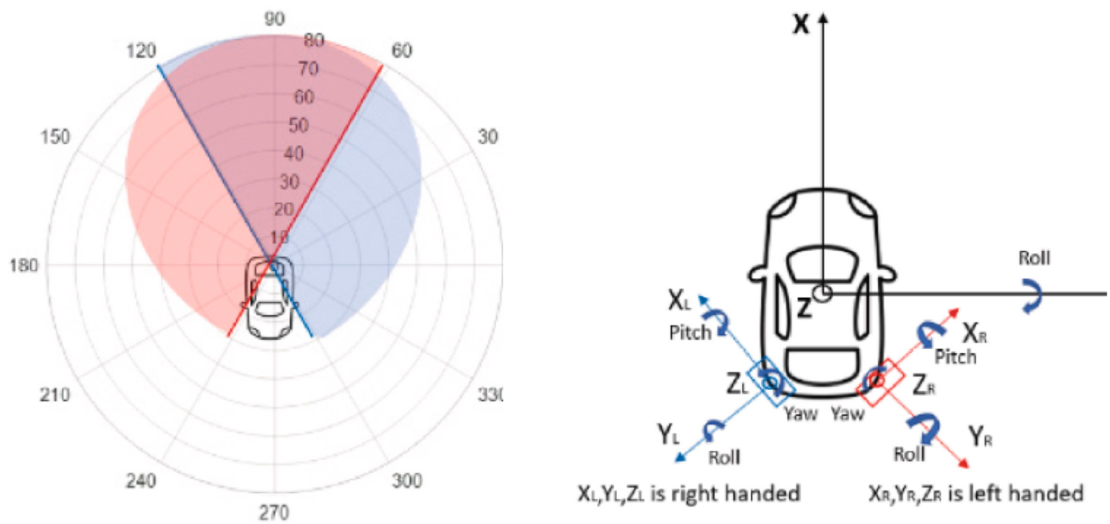


Fig. 1. Rotation of stall for angled parking (Wolshon and Pande, 2016).



(a) (b)

Fig. 2. RCTA system: (a) radar system field of view (FOV) and (b) radar alignment (Park and Yu, 2021).

to determine optimal geometric dimensions for ERLs, such as lane width, length, and positioning relative to the main carriageway. This analysis utilized both experimental data and existing guidelines to derive design criteria that enhance safety while minimizing disruption to normal traffic flow.

Considering that the CAV that needs to search for an MRC will not directly access the ERL from the main carriageway –since it will be developing Minimal Risk Maneuvers (MRMs) by driving, if possible, on the hard shoulder– the speed of accessing the ERL while searching for a free slot should never exceed 30 km/h (18.5 mph). This assumption aligns with the concept of degraded ADS performance, ensuring that the vehicle is not completely immobilized when the ADS performance is compromised (BSI, 2024).

Fig. 3 shows the analyzed maneuver during data collection, which can be divided into three stages: (1) the automated vehicle (yellow car) moves towards the parked car (blue car) at a steady approaching speed (v_a); (2) the automated vehicle initiates a stopping maneuver consisting of a single lane changing action from a speed equal to v_a; and (3) the automated vehicle comes to a stop. Conceptually, this process is similar to a pit stop of a Formula 1 vehicle, but at a much slower speed.

The data collection involved a human driver performing the stopping maneuver on the ERL at various approaching speeds, targeting speeds of 10, 20, and 30 km/h, which reflect the characteristics of CAVs in an MRM.

The data collection was developed by using three SAE 2 vehicles: (i) Audi Q2 2016 with Driving Assistance Pack; (ii) Volkswagen Tiguan 2016 with Driving Assistance Package; and (iii) BMW Series 3 GT 2016 with Driving Assistant Package. These vehicles were selected because they presented a significant difference in length, with the Audi Q2 being the shortest vehicle (4.208 m) and the BMW Series 3 GT the longest one (4.824 m), with the Volkswagen Tiguan having an intermediate length (4.509 m). Each car was driven by its owner and equipped with a Garmin VIRB Elite video camera to record the maneuver, monitor the approaching speed, and identify the time at which the stopping maneuver begins and ends. Additionally, an external fixed video camera was used to record the maneuver and check the transverse positions of the automated vehicles while moving toward the parked car and after completing the stop.

Every SAE 2 vehicle performed ten maneuvers for each approaching speed estimating the average value for the following variables: (i) *gap*, estimated as the distance between the parked car and the automated vehicle after the stopping maneuver; (ii) lateral distance (d_L), estimated as the transverse distance between the right edge of the ERL and the axle of the automated vehicle at its final position; (iii) time required to perform the stopping maneuver (t), estimated as the difference in time from beginning and to end of the maneuver; and (iv) deceleration rate (d), estimated as the approaching speed divided by the time (t). The width of the ERL (w_{ERL}) and the approaching lane (w_a) were 2.7 m and 2.5 m, respectively, the latter simulating a typical width of a hard shoulder of a freeway, while the former was the width of the parking lane used as the scenario for the observations.

An ideal stopping maneuver is defined as one in which the driver (or

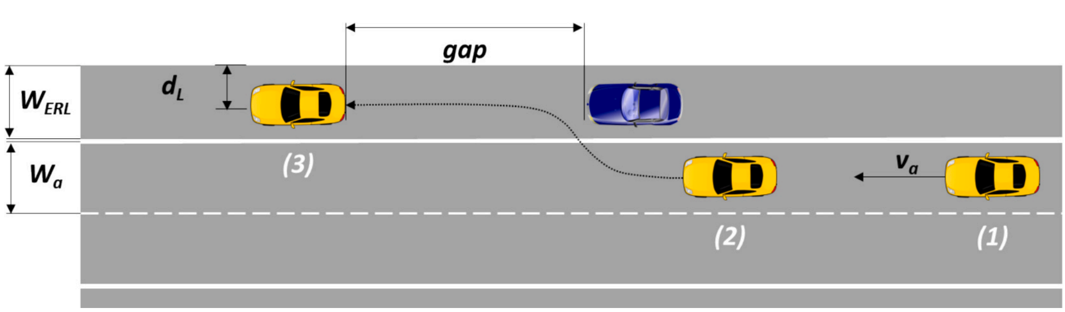


Fig. 3. Field data collection scheme.

the vehicle for levels 3, 4, and 5) is able to move parallel to the ERL while approaching the parked car –along the shoulder–, performs the stopping maneuver just when overtaking the parked car, and finishes the maneuver with the vehicle centered transversely in the ERL. However, ideal maneuvers are expected not to be observed due to the variability of driver behavior or potential inoperable or malfunctioning sensors or automated driving systems. Therefore, an adjustment of the observed gap based on the lateral distance is proposed to be able to compare the findings of the study and estimate the slot length (Fig. 4).

The transverse speed (v_t) of the maneuver can be estimated as the transverse displacement (d_t) divided by the time required to perform the stopping maneuver (t). Then, the time required to reach the center of the ERL from the final position (Δt) can be estimated as the offset between the vehicle and the center of the ERL (Δd_t) divided by the transverse speed (v_t). Moreover, the length traveled (l) by the vehicle in each maneuver can be estimated assuming a uniformly decelerated motion, with the initial speed being the approaching speed (v_a) and the deceleration rate (d). Thus, the average longitudinal speed (v_l) is estimated as the length traveled (l) divided by the time required to perform the maneuver (t). The additional gap (Δgap) is proposed to be estimated assuming the vehicle would keep traveling at v_l during Δt. Therefore, the slot length (SL) is calculated as the sum of gap, Δgap, and vehicle length.

2.2. Geometric design criteria for SHs

The geometric design of Safe Harbors (SHs) is essential for providing automated vehicles with secure locations to achieve a Minimal Risk Condition (MRC) when confronted with operational challenges. Given that SHs are not yet established as standard features in road design, this study employs a methodological framework based on a literature review and existing guidelines for conventional parking facilities to develop effective geometric design criteria for SHs.

This analysis focused on key geometric parameters that are critical for the effective design of SHs, including stall length (SL), stall width (SW), and parking angle (θ). The review indicated that while a stall width of approximately 2.5 m is commonly accepted, the ideal stall length varies based on the types of vehicles typically using these areas. For this study, a minimum stall length of 4.55 m was proposed to effectively accommodate a range of vehicle sizes.

Analytical methods were based on synthesizing design principles derived from the literature and existing guidelines. This included modeling the geometric configurations of SHs to assess their potential effectiveness in accommodating connected automated vehicles (CAVs). The design criteria were tailored to ensure automated vehicles' safe entry and exit while minimizing risks to other road users.

In addition, considerations were made regarding the functionality of Advanced Driver Assistance Systems (ADAS), such as Rear Cross-Traffic Alert (RCTA) systems, in SH design. The angle of parking (θ) and aisle width (A) were also identified as critical factors influencing maneuverability and visibility within these designated areas. Fig. 5 illustrates the measures of parking stalls and their relationship to the parking angle,

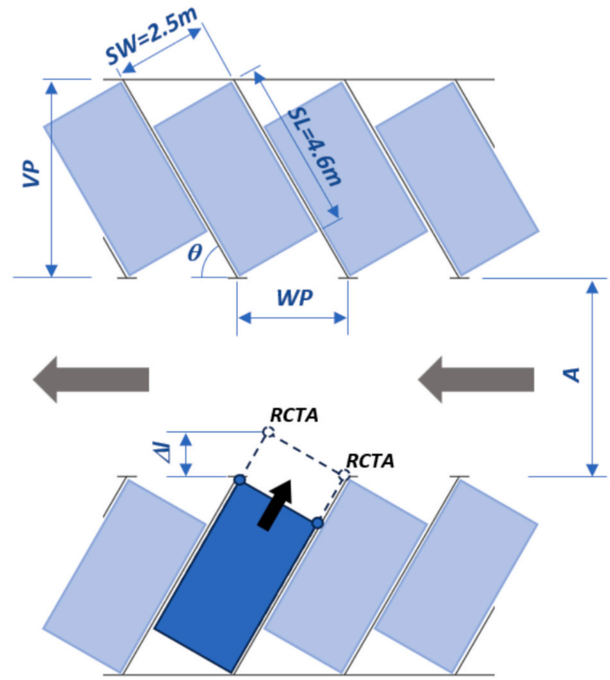


Fig. 5. Measures of the parking stalls and relation to the angle of the park (backward distance required for the RCTA to work is also indicated).

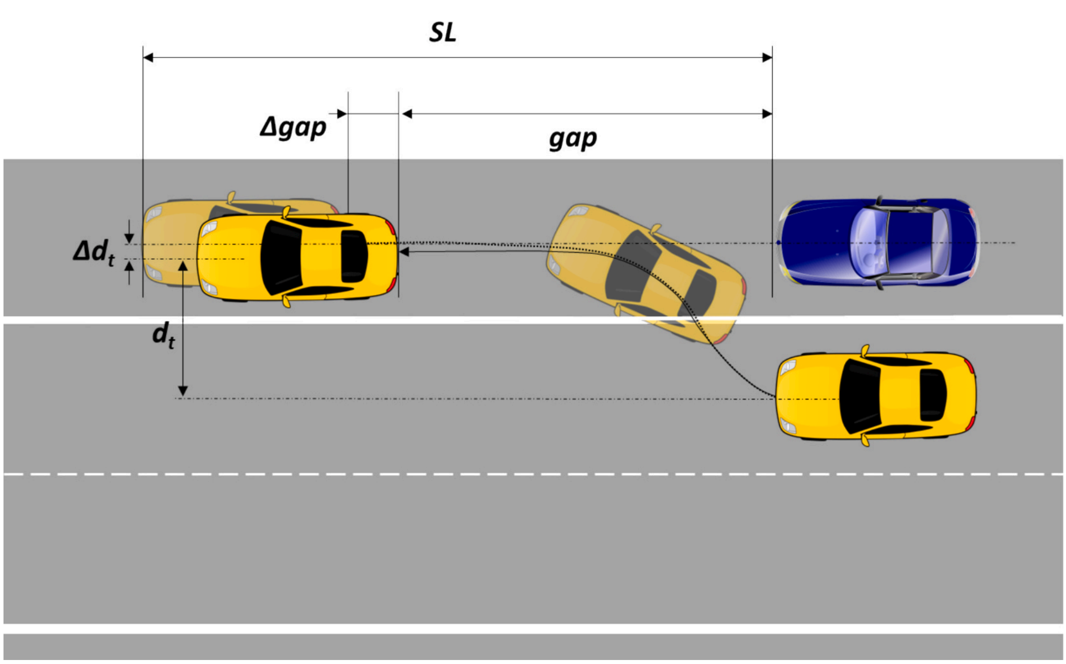


Fig. 4. Estimation of slot length (SL).

further emphasizing the geometric considerations necessary for effective SH design.

By leveraging established parking design standards or criteria and new automated vehicle requirements, this comprehensive methodology proposes robust geometric design criteria for Safe Harbors that enhance automated vehicles' safety and operational efficiency, facilitating their integration into the existing highway infrastructure.

3. Results

3.1. Emergency refuge lane

Table 1 shows the mean and the standard deviation of the variables observed during the experimental data collection for each automated vehicle and approaching speed, as well as those estimated for data homogenization. These are the speeds of the CAV once the vehicle has decelerated along the shoulder from the adjacent roadway while performing each minimal risk maneuver.

Overall, the *gap* increases with the approaching speed and for each automated vehicle. Nevertheless, the transverse displacements are significantly different among vehicles. Although VW Tiguan and BMW 3 GT tend to park more centered on the ERL as the approaching speed increases, the transverse position of Audi Q2 was similar regardless of the approaching speed, with an approximate d_t of 0.25 m towards the shoulder (see Fig. 6). VW Tiguan experienced a d_t of less than 0.10 m at approaching speeds of 20 and 30 km/h while the minimum d_t for BMW 3 GT was 0.245 m at an approaching speed of 30 km/h. The greater values of d_t for BMW 3 GT could be explained by its higher dimensions in comparison to the other vehicles. In Fig. 6, the size of the circles represents the variability of vehicle centering. To this regard, VW Tiguan showed a higher dispersion than the other vehicles.

Despite some differences in deceleration, it was clear that the deceleration rate decreases with the approaching speed. Lower deceleration values in BMW 3 GT were associated with smoother trajectories resulting in less centered final positions in the ERL. *Δgap* reflects how similar the maneuver performed by the vehicle is to the ideal maneuver, so that the higher this value is, the further it is from the ideal maneuver. According to the adjustment described in the Methods section, *Δgap* increases with the value of *vehicle centering*, so the highest values were obtained for BMW 3 GT and the lowest for VW Tiguan, with intermediate values for Audi Q2 (see Fig. 6).

One of the main findings of the experimental study in terms of geometric design criteria for ERLs is the slot length (*SL*). Fig. 7 presents *SL*, calculated as the sum of the *gap, Δgap*, and *vehicle length*, as a function of the *approaching speed*. As expected, a greater length of the slot is required as the approaching speed and the vehicle length increases. In conclusion, it is required a minimum slot length of 13 m (42.65 ft).

For SAE level 4 and 5 vehicles with extensive sensor failures or malfunctions, even more space may be required. Moreover, the gap distance should be checked with the local tow truck fleet to ensure that adequate room remains for a tow truck service vehicle to pull in front of the disabled vehicle in cases where the vehicle must be relocated for repairs.

3.2. Safe harbor

According to the literature review, *SW* can be considered 2.5 m (*8–9*). However, there is no consensus on *SL* due to the standard or design vehicle is different around the world. In this study, a *SL* of 4.55 m has been used. To this regard, it should be noted that *SL* does not influence the capacity of the SH since it depends on the width projection (*WP)* which, in turn, depends on *SW* and *θ*.

Wider parking stalls should always be provided for vehicles carrying disabled occupants who use a wheelchair. Thus, there should be sufficient space for the person to exit the vehicle.

In terms of capacity, the angle of park increases the required width projection (*WP*) and vehicle projection (*VP*) length as indicated in Fig. 5 and in equations (1) and (2).

$$WP = SW/\sin\theta \quad (1)$$

$$VP = SL\cdot\sin\theta + SW\cdot\cos\theta \quad (2)$$

The RCTA is usually placed at the corners of the vehicle's rear bumper (Patole et al., 2017). This means that a 90 degrees parked vehicle would have no problems at detecting incoming vehicles even from the parked position, but as the angle of park gets lower, the system requires the vehicle to move backward a distance Δl expressed in equation (3) (see also Fig. 5).

$$\Delta l = SW\cdot\cos\theta \quad (3)$$

Fig. 8 shows how the angle of the park impacts the capacity of the parking lot and the additional rear distance for the RCTA to work properly. Angles between 60 and 70 degrees provide a very good compromise between these parameters and parking maneuverability. Lower angles dramatically reduce the number of parking stalls and require a wider central lane (aisle) for the RCTA. Higher angles provide even better solutions, but the capacity benefits are marginal compared to a clear drop in maneuverability. Very low angles of parking are dashes since parallel parking would be a better option than angled parking.

Angles between 60 and 70 degrees offer a very good balance between maneuverability and capacity. Higher angles would increase the width of the intermediate lane, while lower values dramatically reduce the parking lot's capacity. For those angles, the effective width of the aisle lane would only be reduced to facilitate the performance of RCTA by a

Table 1
Summary of variables observed and estimated in the experimental data collection.

		$v_a = 10$ km/h			$v_a = 20$ km/h			$v_a = 30$ km/h		
		Audi Q2	VW Tiguan	BMW 3 GT	Audi Q2	VW Tiguan	BMW 3 GT	Audi Q2	VW Tiguan	BMW 3 GT
gap (m)	Mean	4.712	4.809	3.609	5.589	6.319	3.909	6.222	7.323	5.048
	St. deviation	0.373	0.583	0.235	0.488	0.619	0.309	0.936	0.591	0.245
d_t (m)	Mean	2.337	2.378	2.189	2.372	2.514	2.232	2.336	2.526	2.333
	St. deviation	0.066	0.137	0.036	0.042	0.135	0.064	0.035	0.116	0.014
Δd_t (m)	Mean	0.263	0.222	0.411	0.228	0.086	0.368	0.264	0.074	0.267
	St. deviation	0.066	0.137	0.036	0.042	0.135	0.064	0.035	0.116	0.014
d (m/s^2)	Mean	0.521	0.522	0.324	1.152	1.318	0.906	1.869	1.883	1.070
	St. deviation	0.035	0.070	0.039	0.071	0.161	0.107	0.135	0.096	0.020
Δgap (m)	Mean	0.849	0.778	2.263	1.297	0.482	2.805	2.122	0.588	3.018
	St. deviation	0.270	0.423	0.349	0.265	0.694	0.325	0.373	0.876	0.436
Adjusted gap (m)	Mean	5.560	5.587	5.872	6.886	6.801	6.714	8.344	7.911	8.066
	St. deviation	0.545	0.423	0.220	0.504	0.532	0.255	0.927	1.233	0.681
SL (m)	Mean	9.768	10.096	10.696	11.094	11.310	11.538	12.552	12.420	12.890
	St. deviation	0.545	0.423	0.220	0.504	0.532	0.255	0.927	1.233	0.681

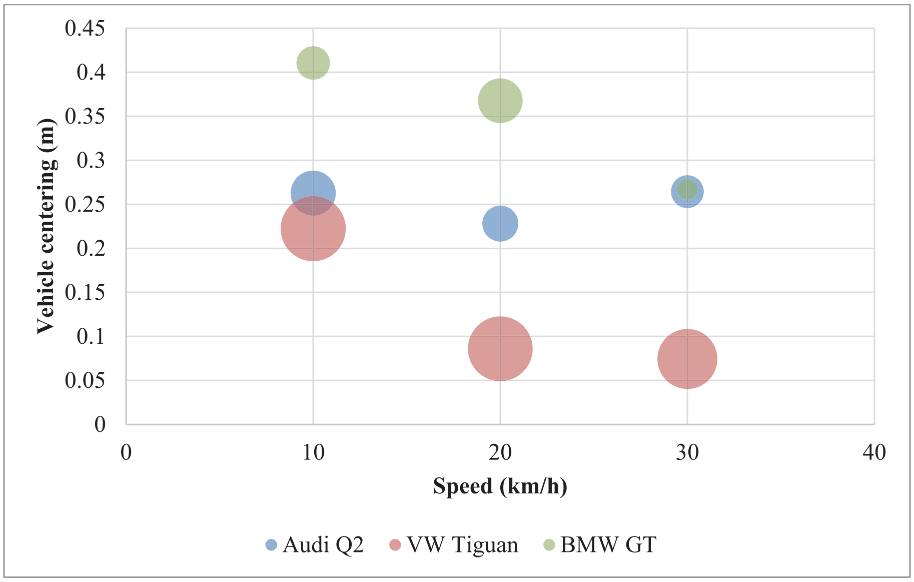


Fig. 6. Vehicle centering on ERL as a function of approaching speed.

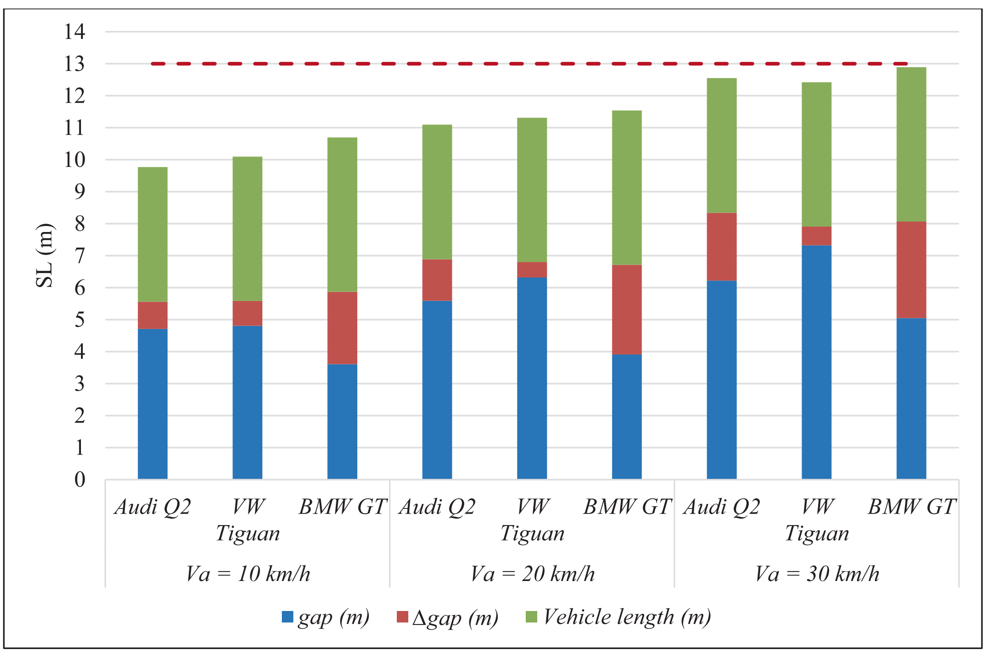


Fig. 7. Slot length on ERL as a function of approaching speed.

maximum of 1.25 m, leaving enough clearance for the approaching vehicle.

The Safe Harbor should be displaced parallel to the main road, leaving the exit ramp where vehicles have reduced their speed to 30 km/h. This can be easily determined using kinematic equations and a constant deceleration rate of 3.4 m/s2 (without using a perception and reaction time because the vehicle is developing minimal risk maneuvers looking for a parking stall), leading to 45 m (if approaching at 70 km/h) or 31 m (if 60 km/h).

Before entering the first parking stalls, some aisle length should be provided to reduce the speed to 0 km/h, resulting 10.2 m for deceleration. Moreover, some additional length should be left for the superelevation transition. 25 m are proposed to provide an additional safety margin, allowing a deceleration of almost 50 km/h from the exit ramp to 0 km/h. In addition, 10 more meters should be necessary to accommodate the entrance curve (with a radius of 50 m) to the parking aisle.

A mirrored situation can be applied to merge the entrance ramp, increasing the speed from 0 to 40 km/h, so at least 20 additional meters are necessary. This would only apply to the last two parking spaces because the rest would have more distance and could reach a higher speed or do so with a lower acceleration rate (< 3.4 m/s2). In the same way, 15 additional meters should be necessary to accommodate the exit curve (with a radius of 50 m) from the parking aisle.

Fig. 9 shows the general layout of a safe harbor and the required radii/lengths to accommodate speeds. The minimum offset of the central lane from the right line of the main carriageway should be 10 m to allow the shoulder width, the berm, and the left vehicle projection. With this minimum or greater offset, a barrier or guardrail will likely be needed between the parked vehicles and the main roadway to provide a safe

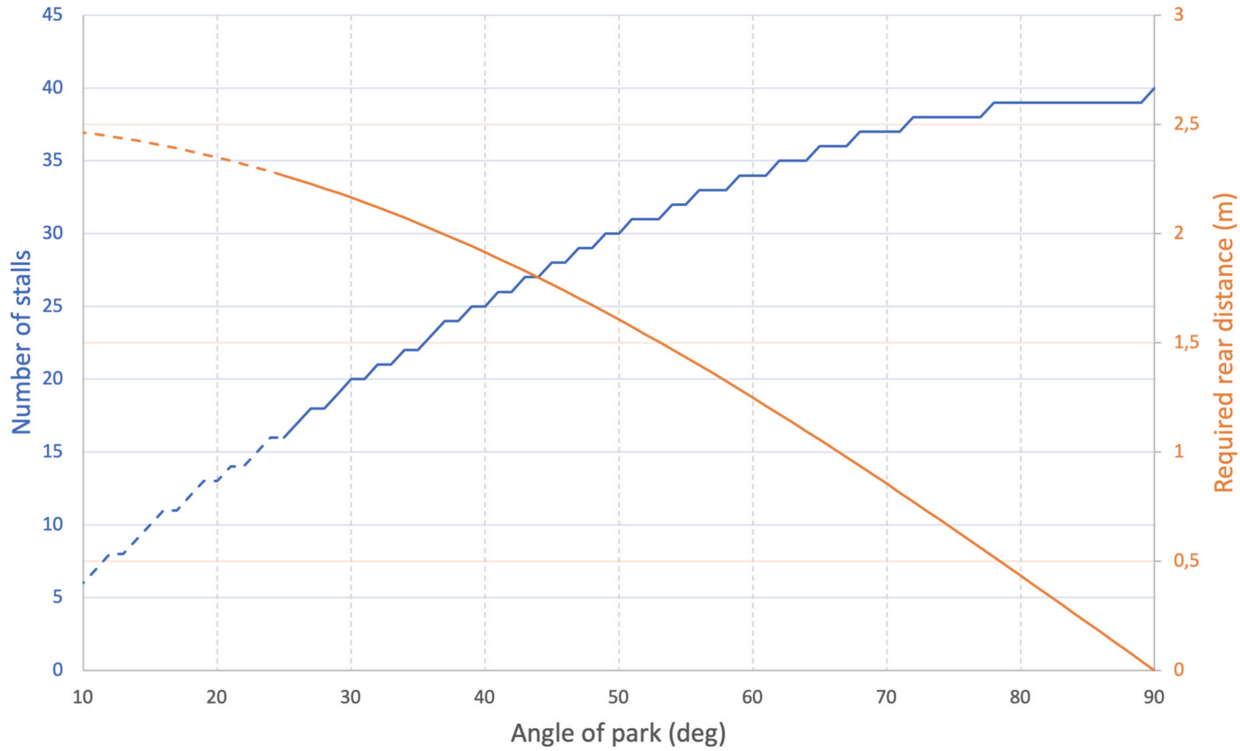


Fig. 8. Effect of the angle of park on the capacity and additional length required for the RTCA (Dl) of the parking lot (one side).

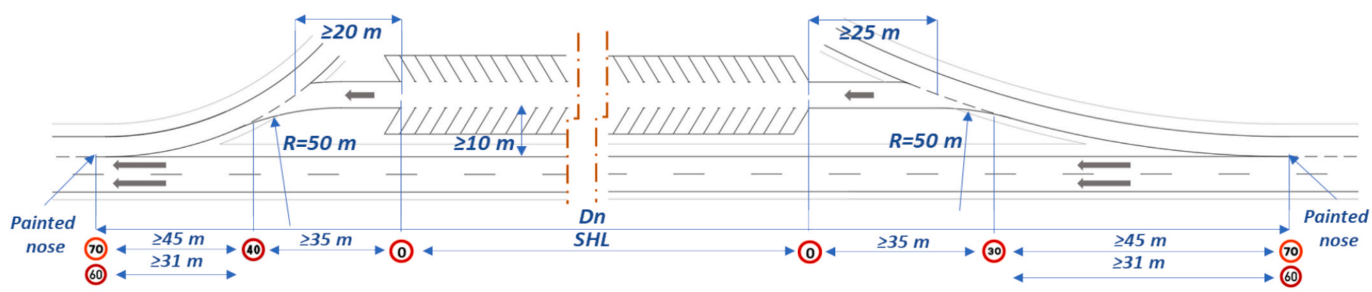


Fig. 9. General configuration of a Safe Harbor between an exit ramp and an entrance ramp.

clear zone.

A critical factor in the capacity of the safe harbor is the distance between painted noses (D_n). This minimum value is regulated by most existing guidelines, as shown in Table 2.

Finally, using moving skates, a tow truck should operate within the space corresponding to the aisle width (A).

4. Geometric design proposals

Considering all previous restrictions regarding the dimensions, angles, and gaps for the parking stalls, the design of Emergency Refuge Lanes and Safe Harbors can be proposed. Given their diverse geometry, these are treated separately.

Table 2
Minimum and desirable distances between exit and entrance ramps at freeway interchanges (distance between painted noses).

Guideline	Dn (ft / m)
Green Book (US)	500 ft / 150 m (minimum)
Texas DOT Roadway Design Manual (US)	500 ft / 150 m (minimum)
	750 ft / 225 m (desirable)
Instrucción de Trazado 3.1-IC (Spain)	415 ft / 125 m (minimum)
	830 ft / 250 m (desirable)

4.1. Emergency refuge lane

Refuge lanes should be located next to the shoulder, without any separator or barrier, so they can generally be built without increasing the right-of-way. A fundamental condition is that shoulders should be wide enough and continuous. The following maneuvers should be supported:

- To reach a free safe slot: deceleration along the shoulder and lane changing (along the initial taper or just before a free parking slot).
- To re-enter the main road: lane change to the shoulder (along the final taper or the gap to the following parking slot) and accelerate along it.

The ERL should be located to allow the performance of Minimal Risk Maneuvers (MRM), by providing the deceleration distance along the shoulder before the ERL begins, i.e., between the speed limit of the main carriageway and the assumed approaching speed (30 km/h). The same applies to the required acceleration distance along the shoulder once the ERL ends, between the stopping position (0 km/h) and the speed limit of the main carriageway. The configuration is shown in Fig. 10, and the total length of the ERL can be calculated using equation (4).

$$(n-1)\bullet SL + LV + TPL1 + (TPL2 + TowS) \leq TL \leq n\cdot SL + TPL1 + TPL2 + TowS \quad (4)$$

Where *TL* refers to the total length of the ERL, *n* is the number of parking slots, *SL* is the slot length, *LV* is the vehicle length, *TPL1* refers to the length of the initial taper, *TPL2* refers to the length of the final taper, and *TowS* is the tow truck space to allow it to be entirely off of the shoulder.

Taper dimensions are generally established at guidelines and should be at least the same length as the gap required to change the lane considering an initial speed of 30 km/h. Considering the results obtained from the observations, the minimum length of the tapers should be 8 m. The minimum width of the ERL (*w*) is 2.5 m, but 3.0 m is recommended. Consideration should be given to adding a minimum 1 m wide shoulder to the ERL for people walking after getting off their CAVs.

The slot length (*SL*) should be at least 13 m considering the results obtained from observations. This length applies to most vehicles, but for vehicles longer than 4.8 m (BMW 3 GT), the approaching speed to the slot should be slightly lower than 30 km/h. ERLs could be located alongside basic segments of freeways (Fig. 11) or collector/distributor roads (Fig. 12), depending on the situation.

Before choosing the location of the ERL, obstacles on the margins, such as drainage elements, structure piles, signs, etc., should be considered, as well as the availability of deceleration/acceleration distances along the shoulder before/after the ERL.

Longitudinal elements such as ditches or safety barriers may be displaced to the new margin of the road. Large curves are not a limitation to deploying these refuge lanes. It is important to clearly indicate that the ERL is not an additional running lane. For this purpose, a double dash longitudinal line separating the ERL from the shoulder, which remains free, and a bracket marking in each slot is proposed. Only one broken line is proposed as an extension of the final taper.

4.2. Safe harbor

Unlike ERLs, Safe Harbors require larger areas, such as those located at the interior of existing interchanges. Again, providing enough length for the vehicles to reduce/increase speed is necessary. In most cases, part of this maneuver can be hosted in the existing ramp (see Fig. 9). Additional lane segments should be added to completely reduce the speed to reach parking stalls. The exit section may not only connect to an on-ramp but also to an intersection or another collector/distribution road, providing that vehicles can re-enter the main highway.

In partial or complete cloverleaves, EX/EN ramps intermediate area is delimited by a sharp and a smooth controlling curve, respectively (Fig. 13). *Dn* tends to be shorter than in other cases, diminishing the capacity of the safe harbor. Moreover, safe harbors can usually be located at both sides of the interchange.

A barrier or guardrail should be included between the parked vehicles and the main roadway (purple dotted line).

In trumpets, the exit ramp tends to be larger, due to a higher radius of the controlling curve, increasing the distance between painted noses (Fig. 14). This is very advantageous for safe harbors. This advantage only exists at one of the sides of the main road, although other configurations may be placed at the other side.

Finally, diamonds generally present two smooth exit and entrance ramps, but with an intermediate crossing road at a different level. There are two possibilities in this case:

- The abutments of the intermediate bridge are too close to the main road. In this case, the safe harbor (at each side of the interchange) has to be located just after the exit ramp, connected to the intermediate crossing road so that vehicles could easily re-enter the main road through the roundabout (see Fig. 15). The larger area is usually an advantage for the design of the safe harbor, but the curve to connect the safe harbor to the crossing road may reduce the length for the facility.
- The abutments present enough space for the safe harbor to continue beneath the bridge. This is not the usual case but benefits the capacity of the safe harbor. With it, the exit lane can be connected to the entrance ramp. This could be an important consideration for future interchange design.

Adding two shoulders with a minimum width of 1 m should be considered for people walking around after they leave their CAVs. Some stalls should be adapted for impaired CAV passengers, too.

Finally, given the additional free space inside many interchanges, additional services such as vertiports, for new aircraft capable of vertical take-off and landing (VTOL), or electric vehicle charging stations could be added, as can be observed in Figs. 13-15. Considering the curvilinear triangular shape of the free space behind the SH, it would be easy to include the design of a vertiport, as it is usually circular. Several vertiport design guidelines have been recently published by the European Union Aviation Safety Agency (EASA, 2022) and Federal Aviation Administration (FAA, 2022). In addition, an area should be provided for passengers to leave their vehicles and rest, considering their mobility as pedestrians.

5. Discussion

5.1. Balance between safety and frequency of MRC facilities

Three possibilities to host vehicles at MRC have been proposed: (i) hard shoulder, (ii) ERLs, and (iii) Safe Harbors. The hard shoulder is the riskiest but most available solution. In fact, it would be a permanent solution for out-of-ODD vehicles due to severe weather conditions, as well as the best solution for vehicles with the most limited DDT. On the other hand, safe harbors provide a far-from-traffic solution that would be ideal and the safest for vehicles that could reach them. However, their availability is the lowest, since they must be located at interchanges. Emergency Refuge Lanes are an intermediate solution, not very close to the traffic stream but with a higher availability than safe harbors.

Road authorities should decide what combination of solutions is the best for each road facility, balancing (a) the risk of stopping a vehicle beside the traffic stream, and (b) the proximity of the ERL or Safe Harbor –which is another kind of risk: having CAVs performing a limited DDT until one of these zones is reached–.

Fig. 16 shows one example of how these solutions could be placed along a road facility (hard shoulder on red; ERL on green; SH on yellow).

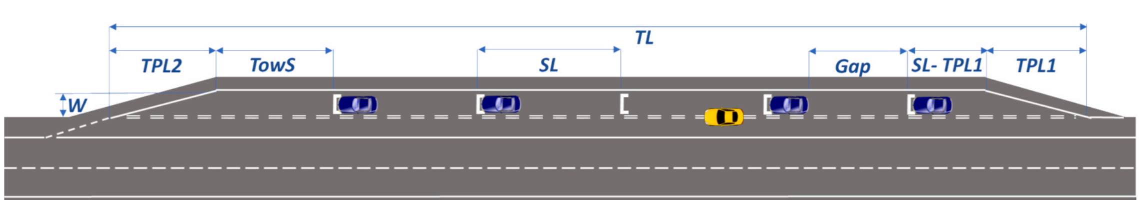


Fig. 10. Distribution of parking slots in an Emergency Refuge Lane.

Fig. 11. ERL along a basic freeway segment, located between two drainage systems.

Fig. 12. ERL along a collector road. In this case, the area within a trumpet is proposed.

Fig. 13. Safe Harbor located in a half-cloverleaf.

Fig. 14. Safe Harbor located in a trumpet.

Fig. 15. Safe Harbor located in a diamond interchange and connected to a secondary road.

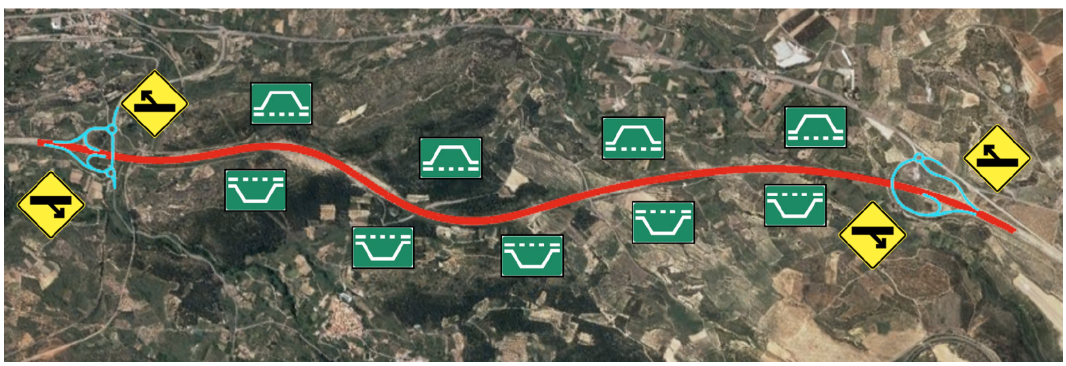


Fig. 16. Example of all three solutions along a road (García et al., 2022).

Under severe weather conditions that exceed the limits of the Operational Design Domain, automated vehicles are expected to execute Minimal Risk Maneuvers consisting of two steps: (1) moving toward the right shoulder, and (2) traveling along it at very low speed until an available ERL slot is found. In this context, the critical operational issue is the lateral merging of vehicles into a shoulder traffic stream already operating under degraded conditions. Since vehicles approach ERLs at very low speeds, the slot length derived from the experimental observations inherently reflects these degraded operational conditions. Similarly, acceleration processes after leaving the ERL are not expected to generate significant conflicts, as vehicles can progressively accelerate along the shoulder before re-entering the lane. Additionally, the minimum longitudinal distance between the downstream end of an ERL and the beginning of a ramp deceleration lane should be sufficient to allow acceleration from standstill to the prevailing highway speed, which introduces an additional geometric design consideration for ERL placement near interchanges.

Although the experimental assessment was limited to passenger cars, the longitudinal dimensions derived for ERL slots suggest that heavy vehicles could potentially be accommodated by occupying two or three consecutive slots, without requiring a geometric redesign. This observation indicates a certain degree of scalability of the ERL concept to mixed traffic compositions, although dedicated validation for heavy vehicles would still be required.

5.2. Capacity of a safe harbor

Once the advantages of safe harbors at interchanges have been reviewed, a critical question arises for every given interchange: could a safe harbor be located in it? What would the capacity be? While a detailed design could answer this issue, there is a faster way by using some mathematical expressions.

The length of the safe harbor parking lot (*SHL*) can be estimated based on the distance between the painted noses (D_n), offset to the safe harbor lane (D_{offset}), ramps controlling curves radii (R_{EX} and R_{EN}) and the deceleration/acceleration buffer lengths (L_{EX} and L_{EN}). Using basic trigonometry and avoiding the effect of the 50 m radius tangencies for simplification purposes (Fig. 9), the length is determined as shown in Equation (5). The number of stalls can be easily obtained by dividing *SHL* by *WP* and multiplying its floor by 2.

$$SHL = D_n - L_{EX} - L_{EN} - R_{EX}\cdot\sin\left(\mathrm{acos}\frac{R_{EX} - D_{offset}}{R_{EX}}\right) - R_{EN}\cdot\sin\left(\mathrm{acos}\frac{R_{EN} - D_{offset}}{R_{EN}}\right) \quad (5)$$

This expression shows that the most important factor is the distance between painted noses (D_n), followed by the controlling curves radii of the exit and entrance ramps. Table 3 shows how all three variables impact the number of parking stalls, considering an offset of 10 m and $WP = 2.9$ m (i.e., park rotation of 60 degrees).

This expression provides an easy way of determining whether a safe harbor can be installed in an interchange where the exit ramp precedes the entrance one. A safe harbor solution would not be justified if the number of parking stalls is comparable to or lower than that provided by an ERL solution (e.g., near 7 for $Dn = 125$ m). As a result, safe harbors should not be installed at interchanges with very strict distance between painted noses (e.g., 125 m). If this distance is near 150 m, trumpet or diamond interchanges are discouraged since their smoother ramps lead

Table 3
Number of parking stalls in a Safe Harbor as a function of *Dn* and radii of ramps.

Dn = 125 *m*

Exit ramp radius (m)	Entrance ramp radius (m) 50	60	80	100	120	140	160	180	200
50	12	10	6	4					
60	10	8	4	2					
80	6	4							
100	4	2							
120									
140									
160									
180									
200									

Dn = 150 *m*

Exit ramp radius (m)	Entrance ramp radius (m) 50	60	80	100	120	140	160	180	200
50	30	28	24	20	18	14	12	10	8
60	28	26	22	18	16	12	10	8	6
80	24	22	18	14	12	8	6	4	2
100	20	18	14	12	8	6	2		
120	18	16	12	8	6	2			
140	14	12	8	6	2				
160	12	10	6	2					
180	10	8	4						
200	8	6	2						

Dn = 200 *m*

Exit ramp radius (m)	Entrance ramp radius (m) 50	60	80	100	120	140	160	180	200
50	64	62	58	56	52	50	46	44	42
60	62	60	56	52	50	48	44	42	40
80	58	56	52	50	46	44	40	38	36
100	56	52	50	46	42	40	38	36	32
120	52	50	46	42	40	36	34	32	30
140	50	48	44	40	36	34	32	30	26
160	46	44	40	38	34	32	30	26	24
180	44	42	38	36	32	30	26	24	22
200	42	40	36	32	30	26	24	22	20

Dn = 250 *m*

Exit ramp radius (m)	Entrance ramp radius (m) 50	60	80	100	120	140	160	180	200
50	100	96	92	90	86	84	82	78	76
60	96	94	90	88	84	82	80	76	74
80	92	90	86	84	80	78	76	72	70
100	90	88	84	80	78	74	72	70	68
120	86	84	80	78	74	72	68	66	64
140	84	82	78	74	72	68	66	64	62
160	82	80	76	72	68	66	64	62	58
180	78	76	72	70	66	64	62	58	56
200	76	74	70	68	64	62	58	56	54

to very few parking stalls. For cloverleafs, the situation is not so clear, since sharp ramps (e.g., 50 m) allow the interchange to host 30 parking stalls per direction. The decision to install a safe harbor would, therefore, depend on the overall capacity for MRCs of the facility.

For longer distances between noses (e.g., 200 or 250 m), safe harbors benefit almost any ramp combination and for any interchange type –cloverleaves, trumpets, or diamonds–.

There are some limitations to using this expression: ramps should not be tapered and compound curves should not be present. The interchange should be located at a tangent of the main road (the results may vary minimally at smooth-curved sections). In addition, as expressed at diamond interchanges, single solutions with sharp curves should be proposed when re-entering secondary roads instead of the main one.

The practical implementation of Safe Harbors within interchange areas is also subject to regulatory and geometric design constraints. In many existing design standards, intermediate access points along interchange ramps are generally not permitted, in order to preserve traffic continuity, operational consistency, safety, and sight-distance requirements. This limitation directly affects the feasibility of locating Safe Harbors between ramps of interchanges. Consequently, the geometric solutions proposed in this study should be interpreted as design-oriented concepts that must be adapted to the different regulatory frameworks. Although Minimal Risk Conditions are expected to occur infrequently, they must be considered in design. Hence, geometric design standards should include guidance on providing controlled and safe connections to protected stopping areas (SH), avoiding situations in which vehicles would otherwise stop on the carriageway or even on the shoulder.

In contrast, the configuration of Safe Harbors would likely require specific geometric adaptation to accommodate heavy vehicles or truck-platooning scenarios, as the internal parking layout and maneuvering space are directly constrained by vehicle dimensions. This difference highlights a structural distinction between ERLs and SHs in terms of scalability to heterogeneous vehicle fleets.

Hard shoulders, ERLs, and Safe Harbors offer different levels of safety, spatial availability, and interaction with traffic flow. They should therefore be regarded not as competing solutions, but as complementary components of an MRC-ready infrastructure. Hard shoulders provide the highest availability but also the greatest exposure to moving traffic, whereas ERLs offer an intermediate balance between protection and accessibility. Safe Harbors represent the safest configuration by locating stopped vehicles outside the clear zone, although their spatial scarcity may limit reachability under certain conditions. Additional mitigation measures—such as physical separation, controlled access geometry, advance information through connectivity, and coordinated traffic management—may further reduce interference with the main traffic stream and enhance operational safety during MRM execution.

This system-level interpretation is consistent with the MRX risk-based framework introduced by BSI (2024), which emphasizes selecting the maneuver–location combination that minimizes overall risk under the specific triggering conditions.

5.3. Scope and limitations of the proposed framework

The definition of geometric criteria for Minimal Risk Conditions (MRC) in highly automated vehicles involves complex interactions among vehicle automation capabilities, traffic dynamics, infrastructure design, and regulatory constraints. The framework presented in this study should therefore be interpreted as a structured design-oriented contribution rather than as a comprehensive operational model.

Several limitations must be acknowledged. First, the experimental component focuses exclusively on passenger vehicles, which represent the most immediate deployment scenario for SAE Level 4. Heavy vehicles and platooning configurations were not considered, as their kinematic and spatial requirements would require dedicated investigation. Second, the proposed geometric configurations are conceptual and infrastructure-based, and no large-scale operational validation with real automated traffic has yet been conducted. Third, the analysis focuses primarily on stopping and parking maneuvers required to achieve MRC, while broader dynamic interactions in highly congested or complex environments remain open research topics.

Despite these limitations, the study provides structured geometric criteria that may support future standardization processes, simulation studies, and pilot implementations.

6. Conclusions

This paper proposes detailed solutions for MRC zones for SAE Level 4 + vehicles: hard shoulders, Emergency Refuge Lanes (ERL), and Safe Harbors (SH). These zones are classified among the safest infrastructure-based MRC solutions according to BSI (2024), and they should not be considered as alternatives but as complementary components within a CAV-ready road facility. Accordingly, the results should be interpreted as a foundational contribution toward MRC-oriented infrastructure design rather than as a definitive operational framework.

The hard shoulder is the riskiest of the three, but the most available solution. In fact, it would be a permanent solution for out-of-ODD vehicles due to severe weather conditions, as well as the best solution for vehicles with the most limited DDT. ERL is an intermediate solution, further from the traffic stream, with greater availability, but still with some risk to carriageway traffic. Finally, Safe Harbor provides a protected solution (barrier/guardrail), placing the SH outside the clear zone. However, with limited availability, mostly at interchanges, some vehicles may not be able to reach these locations.

Geometric design criteria have been proposed, based on the dimensions and maneuverability of existing vehicles, and the capacity of ERLs and SHs has been estimated. The findings provide some guidance on safely and efficiently implementing a CAV-ready infrastructure.

Furthermore, when ERLs are located upstream of interchange areas, sufficient longitudinal distance should be provided to allow vehicles departing from an ERL to accelerate from standstill to the prevailing highway speed before the beginning of deceleration lanes.

The results show that the existing road network presents a remarkable opportunity to place MRC zones, although the actual need remains unknown. This capacity will be determined only with the CAV Level 4 penetration in the market. Moreover, it is expected to vary as the percentage of CAVs increase and their ODDs vary. MRC zones should also be adequate for peak traffic hours or severe weather conditions. Future research should focus on developing a comprehensive demand model for Minimal Risk Condition (MRC) zones, considering factors such as vehicle penetration rates and operational design domain (ODD) limitations, while also aligning with criteria for the spatial distribution of MRCs.

In addition to a demand model for distributing MRCs, it is essential to identify the factors causing a vehicle to fall outside its operational design domain (ODD) or have a failure in some of the parts of the automated driving system. If these factors were known, road operators and vehicle manufacturers could collaborate to overcome these challenges. Until these issues are resolved, such locations would be necessary for MRCs.

There are other existing facilities where MRCs could be accommodated too, such as other interchange types –for SHs–, entrance or exit ramps –for ERLs– or other road types. Horizontal and vertical signing should also be discussed, as well as the accommodation of larger vehicles such as trucks.

Moreover, connectivity should play an essential role for MRCs. A vehicle performing a limited DDT should know in advance which of the nearby MRC zones are available, in order to calculate the MRM + MRC maneuver as accurately as possible.

Finally, other services could be incorporated alongside SHs: user waiting areas, vertiports, electric vehicle recharging points, etc. Additional research related to occupants exiting vehicles may need further study.

In future research related to ERLs, the same size of vehicles could be analyzed, even with some longer ones, but with a diverse sample of drivers, to verify the possible variability of behaviors. These are just some of the forthcoming challenges to explore, as the presence of CAVs increases in the coming years.

As CAV technology evolves, future studies should assess the long-term impacts of implementing MRC zones on traffic flow, safety outcomes, and infrastructure adaptation to accommodate higher levels of vehicle automation. Future research should extend the proposed geometric framework to heavy vehicles and truck-platooning configurations, whose spatial requirements and operational characteristics may significantly influence the design of MRC-related infrastructure.

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CRediT authorship contribution statement

Alfredo García: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **F. Javier Camacho-Torregrosa:** Writing – review & editing, Writing – original draft, Formal analysis. **David Llopis-Castelló:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Vicente Ferrer-Pérez:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **David McDonald:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2026.101981.

Data availability

The data supporting this study's findings are available from the corresponding author, A. García, upon reasonable request.

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