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Analysis of the influence of traffic variables on lane change manoeuvres decision-making in real-world traffic scenarios

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ABSTRACT

This paper presents an analysis of lane changing manoeuvres under real traffic conditions, focusing on how drivers adapt their behaviour across different driving regimes. Using naturalistic driving data collected on a high-capacity road in Madrid (Spain), the research explores the role of traffic context in decision-making focusing on gap acceptance, vehicle dynamics, safety metrics and motivational factors.

To analyse these dynamics, drivers were exposed to six controlled traffic configurations designed to reproduce representative real-world highway scenarios with different surrounding vehicle distributions, inter-vehicle distances, and relative speeds. Driver behaviour was analysed across three distinct manoeuvre phases, corresponding to car-following, anticipation, and lane change execution.

The results show that traffic density and the surrounding environment significantly shape driver strategies. Higher traffic complexity leads to longer anticipation phases, greater dispersion in timing, and reduced safety margins. While Time-to-Collision (TTC) offers general insights into risk, gap-based metrics proved more stable and informative for predicting the actual execution of the manoeuvre.

This study contributes to the understanding of context-dependent lane-change behaviour using controlled naturalistic driving scenarios. The findings support the development of predictive models and the design of advanced driver assistance systems (ADAS) and automated vehicles, enabling safer and more adaptive lane-change algorithms that better account for driver intent and traffic dynamics.

1. Introduction

The development of automated vehicles has experienced a notable increase in recent decades, driven by advancements in artificial intelligence, robotics, and sensor engineering (Cunneen et al., 2023). The objective of automated driving is not only to replicate human driving skills but to surpass them, thereby ensuring a safer and more efficient traffic environment. Achieving this goal requires a comprehensive understanding of human driving behaviour and its effective modelling in automated vehicles, which is essential for safe integration into mixed traffic scenarios (Li et al., 2023; Ma and Zhang, 2024; Crosato et al., 2024).

One of the most important processes in the development of automated vehicles is decision-making, which relies on data collected by sensors to evaluate the surrounding environment, identify potential obstacles, and assess critical situations on the road. To achieve this,

vehicles use decision-making systems designed to both emulate human responses in similar driving scenarios and predict the behaviour of other road users, such as drivers and pedestrians. These dual objectives are crucial for ensuring seamless interaction between automated vehicles and their environment while effectively anticipating potential risks. Designing such automated vehicle control strategies, can benefit from understanding human driver behaviour, which can serve as an apparently common example behaviour and to predict the behaviour of other road users.

Lane changing represents a particularly complex task for automated vehicles, as it requires real-time negotiation with dynamic traffic elements and adaptation to diverse human behaviours. Some driving variables capture key aspects of lane changes, making them a valuable case for studying driver intent and improving automated decision-making. Among these variables, the acceptable gap plays a fundamental role in determining when a lane change can be safely executed. This parameter

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defines the minimum space required to transition between lanes without compromising safety, which is influenced by factors such as traffic density, vehicle speed, and individual driver behaviour. Psychological elements, including impatience in heavy traffic, perceived risk, and confidence in one's driving abilities, further contribute to the variability of acceptable gap thresholds. Similar behavioural influences have been previously discussed in gap acceptance theory, particularly in intersection-related studies analysing driver decision-making in conflicting traffic (Guerrieri and Mauro, 2021; Brilon et al., 1999). In the context of lane-changing manoeuvres, recent research has also highlighted the role of driver uncertainty and subjective perception in lane-change decisions (Yan et al., 2023). These considerations are critical in automated driving, as they directly affect the accuracy of prediction models and the adaptability of lane-change algorithms in mixed traffic environments.

Similarly, Time-to-Collision (TTC) is a key variable assessing safety, which is also relevant in lane change conditions. This metric helps determine the time available before a potential collision occurs, allowing for proactive adjustments in driving behaviour (Lu et al., 2021). TTC values fluctuate based on the driving regime: in car-following scenarios, TTC tends to be high or even infinite, indicating a stable and low-risk situation. In contrast, during lane changes and overtaking, TTC decreases due to the reduced distance between vehicles, highlighting the increased risk associated with these manoeuvres (Nadimi et al., 2022; Vass et al., 2024).

The transition from car-following to a lane-change manoeuvre is marked by a shift in driver behaviour, often initiated by the first glance at the rear-view mirror, which signals an intention to change lanes (Löcken et al., 2019; Doshi and Trivedi, 2009; Antin et al., 2020). This moment is crucial, as it represents the shift from a conservative to a more dynamic driving style, accompanied by a reduction in TTC. Moreover, the decision to change lanes is motivated by a particular driver necessity, frequently triggered by the speed of surrounding vehicles (Ma and Li, 2023; Wang et al., 2024). This necessity may be associated with maintaining a desired speed or avoiding an undesired reduction in speed. The final decision to execute the lane change is often dictated by the relationship between vehicle speeds and the availability of an acceptable gap. Automated systems must account for these dynamics to optimize decision-making processes and improve the interaction between human-driven and autonomous vehicles.

Considering the findings mentioned above, this study analyses lane-change decision-making under six controlled traffic configurations designed to reproduce representative real-world highway scenarios. The experiment comprised of one vehicle driven by 22 human drivers under study, and four surrounding vehicles controlled by the experimenters to generate different traffic interactions, inter-vehicle distances, and relative speed conditions on a high-capacity road with a maximum speed limit of 120 km/h. GPS and driver visual behaviour data were collected to analyse the anticipation phase and the onset of lane-change intention.

The objective of this study is to analyse how the main variables in naturalistic driving contribute to lane change decision-making, addressing both objective indicators (e.g., vehicle dynamics) and subjective aspects (e.g., drivers' motivation). Unlike previous studies focused on isolated variables or simulation-based analyses, this work examines controlled yet realistic traffic interactions to identify context-dependent driver strategies during lane-change manoeuvres.

2. State of the art

This section presents a review of previous studies on driver behaviour in lane-change scenarios and on the main variables influencing lane-change decision-making, including behavioural models, lane-change motivations, acceptable gap determination, and safety metrics such as Time-to-Collision (TTC).

2.1. Driver behaviour models

The driving task can be primarily divided into two movement directions: longitudinal and lateral. In the early literature on the topic, these actions were referred to as car-following (Reuschel, 1950; Pipes, 1953) or lane changing (Sparmann, 1978; Gipps, 1986). Classical car-following theories initially focused on traffic flow dynamics and stability analysis (Chandler et al., 1958; Herman et al., 1959; Newell, 1961; Gazis et al., 1959), while later extensions introduced more flexible representations of driver interaction and behavioural adaptation (Bexelius, 1968). Subsequent approaches incorporated lane-changing behaviour, gap acceptance, and integrated driving behaviour modelling frameworks (Ahmed et al., 1996; Halati et al., 1997; Toledo, 2003). Several review studies also summarized the evolution of these modelling approaches (Brackstone and McDonald, 1999; Olstam and Tapani, 2004; Díaz-Álvarez, 2018).

Although longitudinal and lateral movements are conceptually distinct, they are often closely linked in real driving behaviour. Lane-change manoeuvres typically begin with a longitudinal adjustment – such as deceleration or acceleration – followed by lateral displacement. In this context, gap acceptance theory has become a key framework for modelling lateral decision-making. This describes how drivers evaluate spatio-temporal gaps in surrounding traffic to determine whether a lane change can be performed safely, as explored in the pioneering work of Herman and Weiss (1961), Drew et al. (1967), and Miller (1972).

The emergence of psychophysical models (Michaels, 1965; Wiedemann, 1974) marked a pivotal point in the development of driver behaviour models, facilitating the integration of cognitive variables and paving the way for more sophisticated and predictive frameworks. Subsequently, Michon et al. (1985) incorporated cognitive processes into driving task analysis, delineating the task into three hierarchical levels: strategic, tactical, and control, with decision-making situated at the second level.

Given the direct influence of the environment and the driver's state on the actions performed, subdivisions within the primary driving movements were established, known as regimes. The research conducted by Wiedemann and Reiter (1992) provides an illustrative example of this approach. Their psychophysical car-following model was defined by four distinct acceleration regimes: free-flow, vehicle following, closing, and emergency. Sharma et al. (2019) identified up to six distinct regimes that may be employed to complete a given trajectory. These are defined as follows: acceleration, free-flow, following, cruising, deceleration and stopping.

2.2. Motivations in lane-change decision-making

The motivations behind a lane change can be understood as behavioural triggers that initiate the decision-making process. Identifying and analysing these triggers is essential for anticipating lane-change intentions and improving predictive models of naturalistic driving behaviour. Numerous studies have investigated lane-change execution from different perspectives. Some works focused on manoeuvre structure and gap acceptance processes (Gipps, 1986; Ahmed et al., 1996; Mahmassani and Sheffi, 1981), while others analysed lane-changing behaviour within microscopic traffic simulation and vehicle interaction frameworks (Ahmed et al., 1996; Yang and Koutsopoulos, 1996; Hidas, 2002). Additional research examined the temporal dynamics and behavioural adaptation associated with lane-change execution (Mullakkal-Babu et al., 2020; Toledo and Zohar, 2007). Research on traffic interactions and queuing processes has also contributed to understanding decision-making under constrained traffic conditions (Madanat et al., 1993; Cassidy et al., 1995). Together, these studies highlight the relevance of traffic conditions, vehicle interactions, and behavioural adaptation in lane-change decision-making.

Among the different perspectives used to analyse lane-change behaviour, one of the most common distinctions is based on the

motivation underlying the manoeuvre. Lane-changing manoeuvres on highways are generally categorized as Mandatory Lane Changing (MLC) or Discretionary Lane Changing (DLC). MLC occurs when a driver must switch lanes due to external constraints, such as merging onto a highway or approaching an exit. In contrast, DLC happens when the driver voluntarily changes lanes to improve driving conditions, typically to achieve a higher speed or avoid congestion. The motivations and decision-making processes differ between these two types of manoeuvres. While MLC is driven by necessity, forcing drivers to adjust their positioning regardless of traffic conditions, DLC is more strongly influenced by driver preferences and context-dependent situational assessments.

Since DLC is more flexible and influenced by multiple dynamic factors, various studies have approached the manoeuvre from a segmented perspective, highlighting the importance of the anticipation phase, in which the driver evaluates the environment based on specific motivations. Moridpour et al. (2010) analysed lane changing in three stages, with a particular focus on the behaviour of heavy vehicles. Their study emphasized the influence of parameters such as gaps between vehicles, speed in the current and target lanes, and relative speed between vehicles. They also identified traffic density as a key factor in defining the anticipation phase of the manoeuvre, consistent with Li et al. (2019). Similarly, Balal et al. (2014) subdivided DLC into two phases: decision and execution.

On the other hand, Ali et al., (2020) identified metrics that trigger lane changes, such as TTC, relative speeds between adjacent vehicles, available gaps, and Delta-V. These findings emphasize the relevance of dynamic factors in modelling lane change behaviour, yet also suggest that the specific role of MLC as a measurable variable remains underexplored.

Similarly, Guo et al. (2018) demonstrated how the speed of the ego vehicle and surrounding vehicles influence the motivation to change lanes. Various studies have identified two main triggers for this manoeuvre: pressure from behind (when a vehicle is rapidly approaching) and the intention to gain speed (McDonald et al., 1997; Brackstone et al., 1998; Wu et al., 2000). In this sense, DLC involves a constant analysis of surrounding traffic, as drivers seek to optimize their trajectory without being constrained by road infrastructure.

Finally, based on the literature review, the most relevant parameters influencing DLC include the speed relationships between the Ego vehicle and the surrounding vehicles, as well as the available gaps and the overall traffic disposition. These parameters play a crucial role in the driver's ability to safely and effectively change lanes.

2.3. Determining acceptable gaps

In modelling lateral manoeuvres, such as merges or lane changes, gap acceptance is a key parameter for decision-making. A key model in this area is the Gipps model (Gipps, 1986), which states that drivers adjust their speed and distance relative to the vehicle in front to maintain an acceptable gap that allows them to react to unexpected situations. Various simulation studies have analysed acceptable gaps under different merging and lane-change conditions. Some approaches focused on interaction-based and game-theoretical representations of driver behaviour (Kang and Rakha, 2018), while others examined trajectory-based merging strategies in specific traffic contexts, such as heavy vehicles and weaving sections (Sharma et al., 2020). More recent research has also investigated acceptable gap dynamics in mixed traffic environments involving connected and automated vehicles (Pakzadnia and Hassan, 2023).

The determination of an acceptable gap between vehicles can be influenced by the complexity of the scenario and the driver's state. Studies like Paschalidis et al. (2018), where physiological sensors and driver models were used, showed that high stress levels can significantly impact decision-making. The acceptable gap is the most general concept in literature; however, some studies specify this parameter based on the

context (Bonsall et al., 2005; Sanik et al., 2016; Virdi et al., 2019; Yang et al., 2019), creating more specific models. In addition to the acceptable gap, other concepts such as the minimum safety gap, related to the minimum distance to the vehicle in front, and the critical and intermediate gaps, related to lane changes, have been defined. These refer to situations where the rear vehicle could collide if adequate measures are not taken.

Gaps between vehicles can be analysed in various ways. Generally, the distance between them is simply defined in meters or seconds, whereas the TTC metric also considers relative velocity to express distance in seconds in risk situations. The choice of the appropriate metric depends on the speed difference between vehicles. In situations with small speed differences, using distance in meters or seconds is more appropriate, while when speed differences are larger, TTC becomes the most suitable metric, as it reflects the remaining time before a potential collision. This distinction will be explored in greater detail in the following section.

2.4. Time-to-collision

One of the key metrics for assessing the risk of a critical situation is the TTC, first introduced by Hayward (1972). TTC represents the remaining time before a potential collision occurs between two vehicles travelling on the same trajectory and has been widely used as a surrogate safety metric in car-following and lane-change scenarios (Nadimi et al., 2022; Zhao and Lee, 2017; Das and Maurya, 2020; Li et al., 2020; Guo et al., 2023).

TTC is mainly used to determine the criticality of a situation when it falls below a certain threshold. This threshold acts as a risk boundary, below which an event is considered critical and requires attention. TTC values above this threshold are not typically analysed in risk assessments since they do not represent a danger. This is motivated by Vogel (2003), where in his study in real traffic conditions, he excluded non-critical safety cases where the leader was travelling faster than the following vehicle and set a threshold of 6 s.

A TTC threshold close to 1.5 s has been widely adopted in traffic safety research, particularly in early traffic conflict and collision-risk studies (Svensson, 1998; Sayed et al., 1994; Van Der Horst and Hogema, 1994). More recent works have also applied similar thresholds in simulation-based safety assessments, connected and automated vehicle research, and freeway merging analyses (Gallelli et al., 2019; Papadoulis et al., 2019; Xu et al., 2021).

Several studies utilize a 1.5-second threshold to classify risk levels, not only as a binary critical/non-critical boundary but also by subdividing critical situations into different severity levels. For instance, Sayed and Zein (1999) categorized TTC values into three distinct risk levels, identifying 1.0 s as high risk, 1.5 s as medium risk, and 2.0 s as low risk. In Yang et al. (2020), different times were proposed depending on road characteristics and traffic demand, categorising high risk (TTC = 1.5 s), medium risk (TTC = 3.5 s), and low risk (TTC = 9 s). Minderhoud and Bovy (2001) argued that the critical threshold for the car-following regime is approximately 3.5 to 5 s, while Bevrani and Chung (2012) proposed a TTC range of 4 to 10 s under varying leader vehicle speed conditions. Similarly, Li et al. (2020) established a TTC threshold ranging from 1 to 4 s to define event criticality, applying an upper limit of 10 s for further risk analysis within this range. Likewise, Huang et al. (2013) used video-based real-world intersection data and determined that TTC values ranged between 0.4 and 3 s, though conflicts arose during model calibration when the minimum TTC exceeded the determined threshold, ultimately reinforcing the 1.5-second threshold.

Despite its popularity, TTC has several drawbacks and limitations as a safety indicator. Gallelli et al. (2019) pointed out that TTC does not consider impact speed or interaction duration, limiting its ability to accurately assess collision risk. Chin and Quek (1997) also noted that while collision frequency increases with lower TTC values, this indicator

alone is not sufficient to accurately measure collision risk, as driver reaction times can sometimes exceed TTC.

Furthermore, some authors have questioned the applicability of TTC thresholds in different driving environments. Zhao and Lee (2017) noted that the minimum TTC values recommended in the literature may not be representative of real-world scenarios, particularly in environments without strictly defined lanes, as thresholds vary depending on the lateral vehicle positioning and the type of vehicle pair interacting.

In response to these limitations, other authors have also considered the use of dynamic TTC, given its variability depending on the perceived risk or the manoeuvre being executed. These studies also include factors such as gap acceptance during a lane change or traffic density (Nadimi et al., 2022; Janssen and Nilsson, 1992; Hirst et al., 1997; Ozbay et al., 2008; Rahman et al., 2019). Most existing studies apply TTC mainly to scenarios involving collisions, braking or evasive manoeuvres, while its role in initiating lane changes remains largely unexplored (Ali et al., 2020).

For this reason, one of the objectives of this study is to analyse, among other metrics, TTC during lane change manoeuvres in naturalistic driving environments that reflect real-world situations (Olsen et al., 2002; Chen et al., 2015).

3. Methods

3.1. Participants

A total of 22 driving experiments were conducted, involving 12 men and 10 women with an average age of 33.81 years (SD = 6.98). The average years of driving experience was 14.09 (SD = 5.78), with the most used vehicle being cars (68.18%), followed by motorcycles (22.73%) and SUVs (9.09%). Most drivers reported driving between 10,000 and 20,000 km annually.

3.2. Instrument and procedure

The real driving experiments were conducted with 5 vehicles, one of which performed the manoeuvres where the participant was located and the other 4 driven by skilled staff members which created the different scenarios according to their position. The vehicles were different, but all had manual gearboxes, no ADAS, and were equipped with a GPS system, based on Global Navigation Satellite System NV08C-CSM chipset working at 10 Hz and collecting data in real-time. The GPS recorded positioning and velocity data for each of the five vehicles using NMEA protocol messages. Specifically, GPGLGA messages provided latitude and longitude coordinates, while VTG (Velocity and Track over Ground) messages delivered both trajectory and precise ground speed data. The inclusion of VTG was crucial, as it provides speed based on satellite data, minimising errors due to signal noise or interpolation when calculating it from coordinates. Its stability makes it more reliable for recording vehicle dynamics in real time. Additionally, drivers were equipped with Tobii Pro Glasses 2 mobile eye-tracking, which recorded data on the driver's gaze and the observed scene.

The experiments were conducted along a 7.5 km stretch, round trip, of the M-45 public highway in Madrid (Spain), a high-capacity road located in the south-east of the city at 120 km/h speed limit (Fig. 1). Driving tests were always carried out in the morning, at hours of low traffic density to facilitate the performance of the proposed manoeuvres.

The manoeuvre analysed was a lane change conducted under six different configurations, based on the number of vehicles in the left lane. As can be seen in figure 2, vehicles Ego (the vehicle executing the manoeuvre) and F (the vehicle in front of vehicle Ego) were in the right lane. Vehicle F initially maintained a constant speed and remained in the same lane. In the left lane, vehicles L1, L2, and L3 were positioned in a row, and their presence and location defined each proposed condition. To execute the scenarios and undertake the real driving manoeuvres, vehicles F, L1, L2 and L3 adjusted their speeds and distances to cause

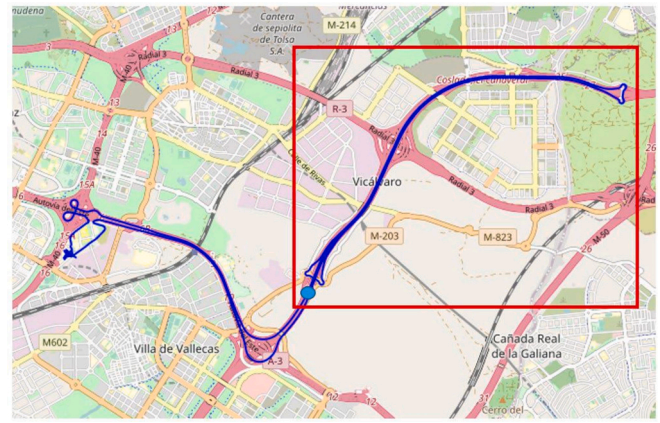


Fig. 1. Trajectory of the driving tests, located on the M-45 public road in Madrid (Spain).

several lane changes. The front vehicle was always present during the manoeuvres. The conditions are summarised as follows (Fig. 2):

- C_{free} (no vehicles in the left lane): the driver chooses the best moment to perform the manoeuvre
- C_{front} (lane change in front of vehicle L1): a vehicle in the left lane was sufficiently far away for the driver to perform the manoeuvre
- C_{back} (lane change behind vehicle L1): a vehicle in the left lane approached at high speed such that the driver would not feel safe performing the manoeuvre before L1 passed
- C_{mid1} (lane change between vehicles L1 and L2): a gap is generated between L1 and L2 large enough for the driver to perform the manoeuvre
- C_{mid2} (lane change between vehicles L2 and L3): a gap is generated between L2 and L3 large enough for the driver to perform the manoeuvre
- C_{last} (lane change behind vehicle L3): there is no gap between L1-L3, and the driver can only perform the manoeuvre after L3 passes

These configurations were selected to represent a simplified but representative range of lane-change situations commonly encountered on high-capacity highways. The proposed scenarios cover different levels of traffic density and gap availability in the target lane, ranging from free-flow conditions (C_{free}) to constrained insertion situations (C_{last}). C_{front} and C_{back} represent light traffic conditions in the adjacent lane, where the Ego vehicle can perform the overtaking manoeuvre either before or after an isolated vehicle. In contrast, C_{mid1} and C_{mid2} simulate denser traffic flows in which the driver must identify and adapt to the most suitable available gap within a moving vehicle platoon. Finally, C_{last} represents highly constrained situations in which the Ego

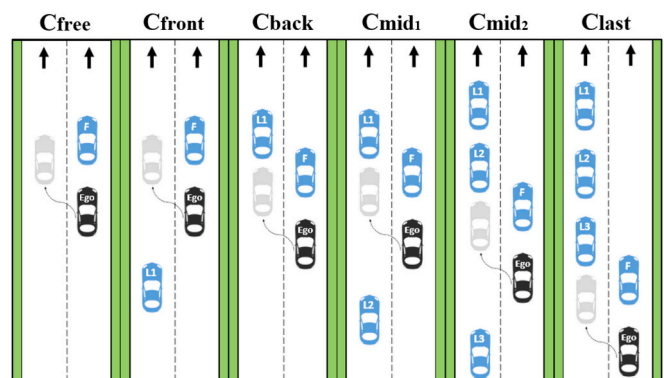


Fig. 2. Conditions of lane change manoeuvres.

vehicle must wait until all surrounding vehicles have passed before initiating the manoeuvre. Although simplified, the three-vehicle platoon was considered sufficiently representative to reproduce complex lane-change decision-making processes under real traffic conditions. The selected scenarios were intended to capture the most relevant variations in surrounding traffic disposition influencing discretionary lane-change behaviour, while maintaining a controlled and reproducible experimental setup.

The participants were instructed to drive in their usual manner, without any additional guidance, in order to avoid influencing their overtaking decisions. It was important to ensure that vehicle Ego was unaware of the experimental intentions, allowing participants to perform the manoeuvres naturally. The manoeuvres were performed in a randomised order, with each one adapted to the current traffic conditions. The study was designed as a within-subject experiment, ensuring that every participant completed all the proposed scenarios at least once. Participants generally adhered to the legal speed limit (120 km/h) where their maximum speed over the entire experiment was 118.72 km/h averaged over participants.

Each manoeuvre began with the Ego vehicle driving at a self-selected comfortable speed in a free-flow situation. At a certain point, vehicle F positioned itself in front of the Ego vehicle, initiating a car-following phase in which F maintained a constant speed. After a period of car-following, vehicle F gradually released the gas pedal—without braking—sometimes reaching speeds as low as 70 km/h. This reduction in speed was intended to naturally prompt the Ego vehicle driver to initiate an overtaking manoeuvre.

Throughout the experiment, participants experienced different driving regimes in an interurban environment, which were categorised as free-flow, car-following, lane-changing, and braking, based on the regimes of Sharma et al. (2019). The coordination among all vehicles was crucial to successfully execute the different conditions. To ensure smooth and controlled manoeuvres, all vehicles were hands-free audio connected, except for the Ego vehicle, allowing drivers to adjust in real time to the evolving traffic conditions. Given that the experiments were conducted in real traffic, external vehicles occasionally interfered with the planned formations, requiring adaptive responses from the test vehicles to maintain experimental consistency. In these situations, if the resulting traffic configuration matched one of the predefined experimental scenarios, the manoeuvre was reclassified accordingly and analysed under the condition performed rather than the originally intended one. Conversely, manoeuvres in which external traffic substantially altered the driver behaviour or prevented a consistent execution of the scenario were excluded from the final dataset.

A total of 247 manoeuvres were performed during the real driving tests, where drivers executed the lane change actions corresponding to each proposed formation. Due to issues with GPS data acquisition and the eye-tracking system in four participants, only 18 participants were considered for this study, reducing the total to 198 manoeuvres. Drivers executed the lane change actions corresponding to each proposed formation, obtaining approximately the same percentage for each one ($C_{\text{free}} = 16.16\%$, $C_{\text{front}} = 19.19\%$, $C_{\text{back}} = 15.15\%$, $C_{\text{mid1}} = 19.19\%$, $C_{\text{mid2}} = 14.65\%$, $C_{\text{last}} = 12.12\%$). In only eight cases (4.04%), the manoeuvre initially planned for the formation was modified due to real traffic interactions or spontaneous driver behaviour. In these situations, the manoeuvre was reclassified according to the traffic configuration executed. Most of these cases involved participants executing C_{mid1} instead of C_{mid2} or initiating an overtaking manoeuvre independently, typically corresponding to C_{free} conditions. Manoeuvres in which external interference prevented a consistent execution of the scenario were excluded from the analysis.

The scenarios were executed in a randomized order, with each proposed manoeuvre being repeated an average of 1.87 times per participant.

3.3. Data analysis

In order to analyse the data obtained from the experimental tests, specific criteria were established to identify the transitions between three driving regimes—car-following, anticipation, and lane change execution—, based on the speed data of the vehicle performing the manoeuvre and driver's visual behaviour. As in other studies (Toledo and Zohar, 2007; Moridpour et al., 2010; Li et al., 2019), this analysis incorporates an anticipation stage, defined as the approaching phase in which the driver intends to overtake the preceding vehicle. This stage, which occurs between the car-following and lane-changing regimes, is crucial for understanding how drivers perceive and react to lane change situations. By examining this pre-manoeuve phase, we aim to identify behavioural patterns that provide insight into how drivers plan and adjust their actions before executing the lane change, offering a more detailed view of their perception and decision-making mechanisms in complex traffic environments.

The classification of the three driving regimes was structured around key transition points, which mark the beginning of each phase or regime: from free-flowing to car-following (CF), from car-following to lane-change anticipation (AN), and from anticipation to lane-changing (LC). These transitions were manually identified from the recorded data for each participant and each manoeuvre by considering a combination of speed adjustments, visual attention shifts, and vehicle positioning, as described below:

- **From free-flow to car-following (CF point):** A change in speed, either from a constant to a decreasing speed or from increasing to decreasing, indicates that the driver is adjusting speed in accordance with the speed of the vehicle ahead.
- **From car-following to anticipation (AN point):** The first glance at the left rear-view mirror, observed through visual tracking glasses, is considered a signal for the start of the lane-change anticipation stage (Lethaus and Rataj, 2007; Sanchez-Mateo et al., 2023).
- **From anticipation to lane change (LC point):** The lane-change regime starts when the vehicle increases its speed, indicating an acceleration to execute the overtaking manoeuvre

Fig. 3 illustrates the transition points in the upper section and the driving regimes in the lower section. The AN point, typically included within the car-following regime, is analysed separately in this study to better capture the anticipation phase before the lane change.

Fig. 4 shows an example of these points in a C_{free} condition (without vehicles in the left lane) in relation to the speed of the Ego vehicle and the front vehicle in the right lane (Vehicle F). In 4a, the CF point indicates a change in speed where the driver stops accelerating due to the front vehicle being detected, in this case vehicle F, around second 15. The AN point, anticipation, is then determined by observing, using the eye-tracking system, an increase in the driver's gaze towards the left rear-view mirror, which corresponds to the second 20 in this example (Fig. 4b). Finally, the LC point indicates the start of the lane change manoeuvre, where the driver applies an acceleration to increase its speed in the execution of the manoeuvre.

Fig. 4c and 4d show a decreasing gap between vehicle Ego and F from second 20 onwards, reaching a minimum just before the lane change, suggesting the driver monitored the space before initiating the manoeuvre.

Fig. 5 shows one of the most challenging manoeuvres, C_{mid2} , where the Ego vehicle changes lane between vehicles L2 and L3. Due to GPS limitations, Fig. 5b and 5c display small but non-zero distances during overtaking. The largest gap appears between seconds 20–25, when both L2 and L3 move furthest from the zero axis (Ego vehicle position), while anticipation occurs just before second 20. As shown in Fig. 5a, the Ego vehicle starts accelerating around second 25 (LC point) and merges into the gap by second 30. At that moment, it has overtaken L2 and reached its maximum distance from L3.

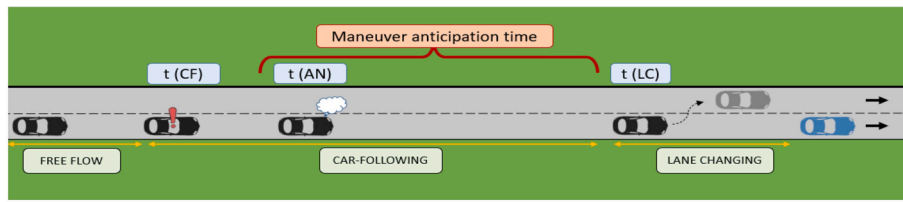
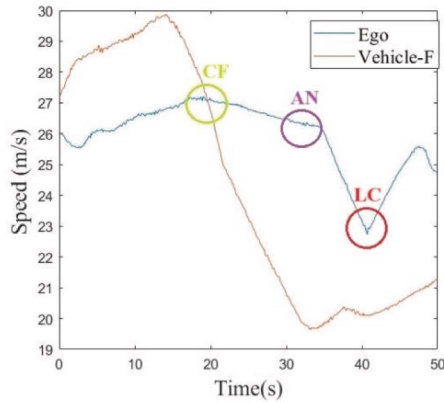
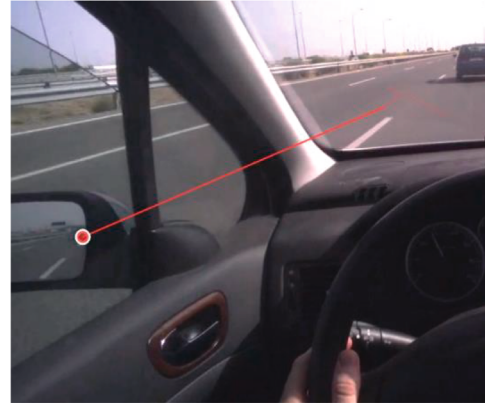


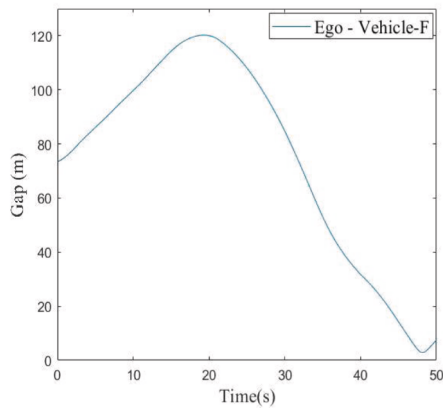
Fig. 3. Driving regimes during lane change manoeuvre.



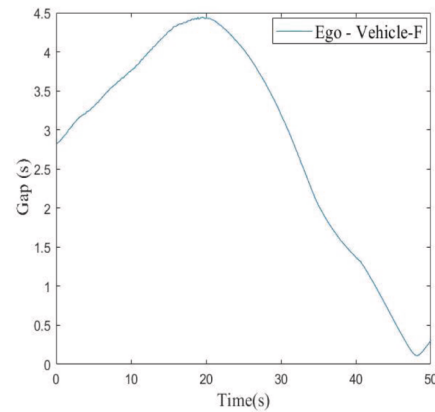
a)



b)



c)



d)

Fig. 4. C_{free} manoeuvre: a) Ego and vehicle F speeds in lane changing and points of interest, CF, AN and LC, b) First glance at the left rear-view mirror, corresponding to AN point, c) and d) Gap between Ego and vehicle F, C_{free} manoeuvre, in meters and seconds, respectively.

After identifying the transition points and driving regimes for each manoeuvre, additional traffic and safety metrics were computed to characterize driver behavior during lane-change execution and anticipation phases. One of the key metrics considered in this study is the TTC, originally introduced by Hayward (1972), calculated as shown in Eq. (1).

$$TTC(t) = \frac{X_F(t) - X_{Ego}(t) - l_F}{V_{Ego}(t) - V_F(t)} \quad \forall \quad V_{Ego}(t) > V_F(t) \quad (1)$$

where X represents the position, V denotes the speed, and l_F indicates the length of the front vehicle. The subscripts F and Ego refer to the front vehicle and the Ego vehicle, respectively, in the car-following process. As noted in the literature, TTC is valid only if the Ego vehicle is traveling faster than the front vehicle; otherwise, if the speed difference, $\Delta v = V_{Ego}$

$(t) - V_F(t)$, is not positive, TTC is considered infinite.

4. Results

This section presents the results of the real driving experiments, structured around three main sections: duration of driving regimes, lane change dynamics (including acceptable gap, speed, and safety metrics), and motivations for lane changes. The analysis follows a progressive approach, starting with objective variables related to traffic configurations and driver decisions, and moving towards more subjective factors influencing decision-making. High standard deviation values result from outliers which were kept in the dataset to preserve the natural variability of the driving behaviour.

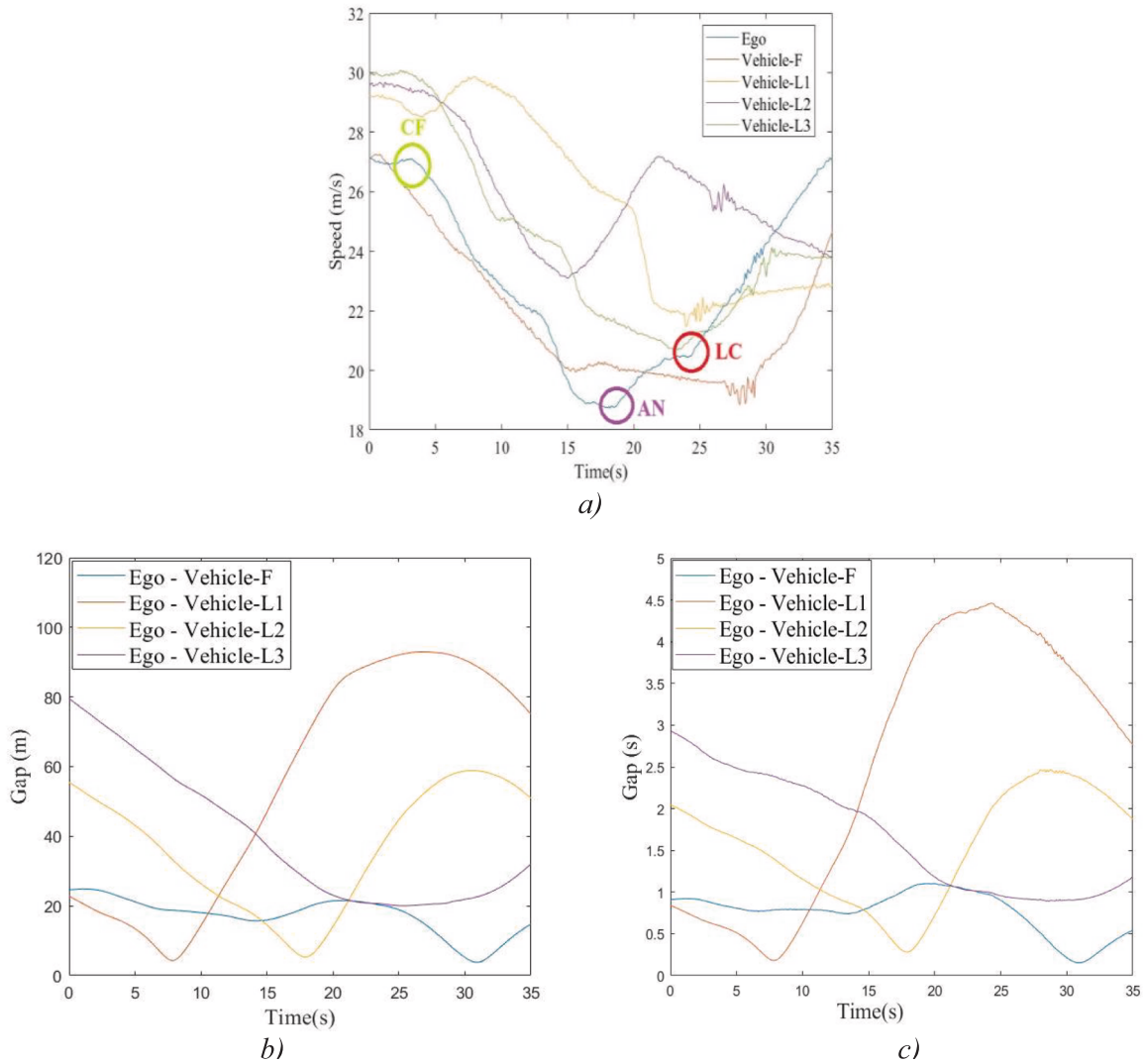


Fig. 5. a) C_{mid2} manoeuvre: all vehicles' speeds in lane changing between L2 and L3 vehicles, and points of interest, CF, AN and LC on Ego vehicle, b) and c) gap between ego and other vehicles in meters and seconds, respectively.

4.1. Duration of driving regimes

The lane change manoeuvre was analysed by segmenting it into three different driving regimes: car-following (CF), anticipation (AN), and lane change execution (LC). Table 1 presents the duration of each phase and their transitions across the six traffic configurations. Given the high SD observed in Table 1, Fig. 6 shows the dispersion of the data for a

Table 1

Durations between driving regime points (*high values for SD result from outliers).

Driving regimes	C_{free} (n = 32)		C_{front} (n = 38)		C_{back} (n = 30)	
	Mean	SD	Mean	SD	Mean	SD
CF – AN (s)	0.826	1.706*	1.485	2.791*	3.620	8.026*
AN – LC (s)	8.853	7.037	6.961	2.911	10.557	8.128
Total CF – LC (s)	9.679	6.523	8.446	3.113	14.177	4.567
Driving regimes	C_{mid1} (n = 38)		C_{mid2} (n = 29)		C_{last} (n = 24)	
	Mean	SD	Mean	SD	Mean	SD
CF – AN (s)	2.787	5.120*	1.187	3.494*	0.632	2.030*
AN – LC (s)	11.842	6.470	19.187	8.392	23.712	7.980
Total CF – LC (s)	14.629	4.779	20.375	8.895	23.08	8.717

better understanding.

Results show that the time elapsing between points CF and AN is generally short. This is consistent with behavioural observations, as drivers often start checking the left lane shortly after switching from free-flowing to car-following. As a result, these two points are sometimes difficult to distinguish. In contrast, the duration between AN and LC is typically longer and more variable.

Anticipation time varies significantly across traffic configurations (varying from less to more complexity). When the left lane is free, drivers tend to anticipate and execute the manoeuvre quickly, with little variation. However, as the presence of vehicles increases, there is greater variability in anticipation times, reflecting different decision-making strategies. In configurations where the driver must merge between vehicles, the anticipation time becomes increasingly dispersed, identifying two different patterns: some drivers decide quickly due to the lack of alternatives, while others prolong the anticipation phase evaluating possible opportunities.

These findings underscore the influence of environmental complexity on strategic decision-making during lane changes, providing valuable information for models of driver behaviour and the development of advanced driver assistance systems.

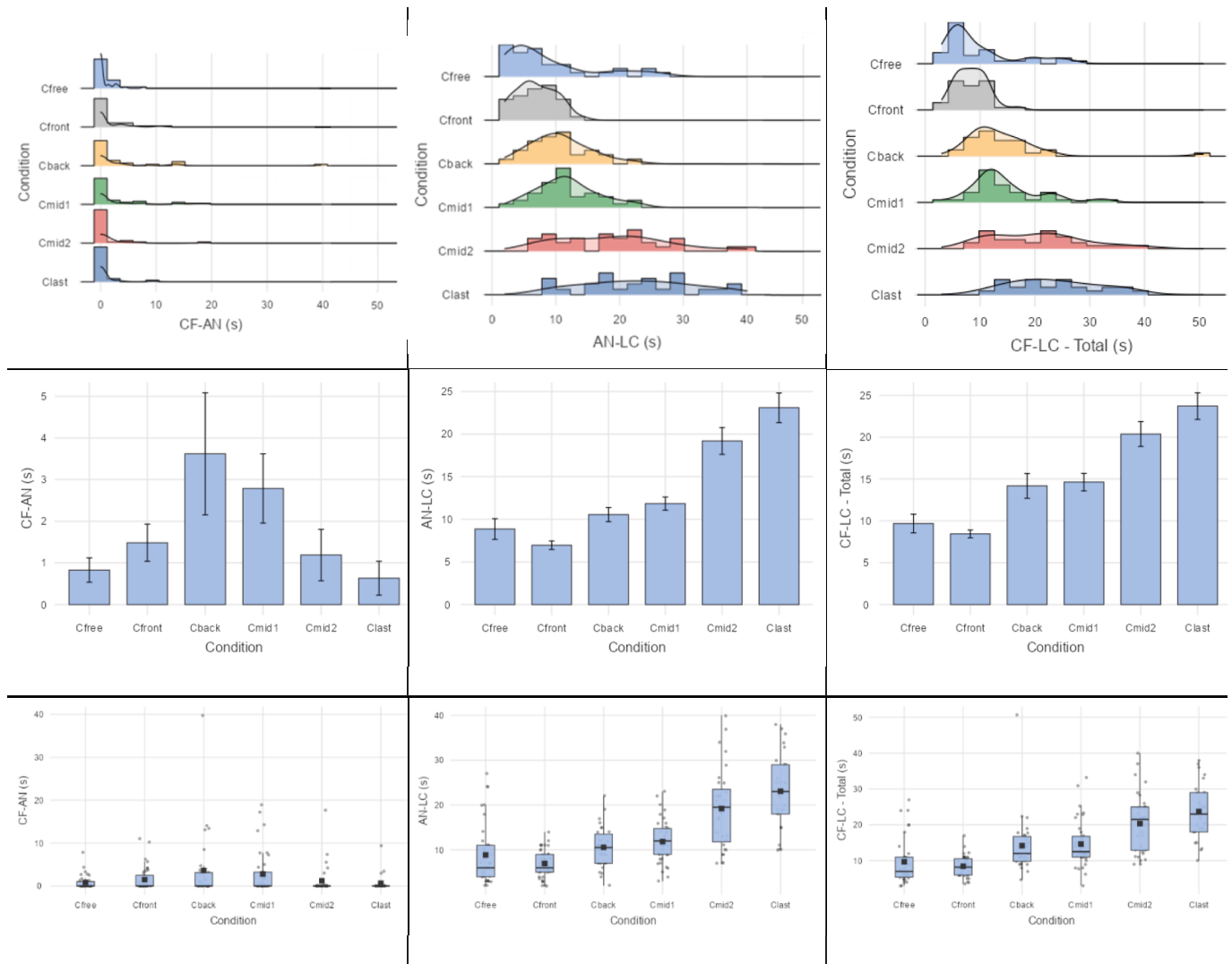


Fig. 6. Durations between CF-AN, AN-LC and the total time of the manoeuvre. From top to bottom: histogram, mean and SD and, mean and SD with outliers.

4.2. Dynamics of lane change manoeuvres

This section investigates how drivers adapt their gap acceptance behaviour during lane changes across different traffic configurations. The analysis focuses on the available inter-vehicle gap—particularly the acceptable gap at the moment of lane change execution—the Ego vehicle's speed and relative speed differences (Delta-V), and safety-related metrics such as safety margin and TTC. All results are structured according to the three defined driving regimes.

4.2.1. Gap analysis

To contextualise the gap-related findings, Table 2 and 3 provide an overview of the gap between the Ego vehicle and surrounding traffic, expressed in meters and seconds, respectively. Values are reported for each of the three driving regimes—car-following (CF), anticipation (AN), and lane-change (LC)—and include the distance to the front and back vehicles in the left lane, as well as the front vehicle in the right lane.

To understand the results, it is necessary to consider the vehicle configurations shown in Fig. 2, where in the case of C_{free} there are no vehicles in the left lane, and the corresponding gaps are not defined. An important aspect is the evolution of the dynamics of the vehicles in the different driving regimes. In terms of distance in metres at the LC point (Table 2), it can be seen that Ego vehicle always occupied a position between the vehicles in front (distance in positive) and behind (distance

in negative) in the left lane.

However, in the previous phases, CF and AN, when the driver switches from free-flow to car-following, and subsequently to anticipation, distance values can be less intuitive. In C_{mid2} , for instance, although the lane change occurs between vehicles L2 (Front Left veh.) and L3 (Back Left veh.), their relative distances in the CF and AN point were negative (Table 2, -35.3 m to L2, and -62.9 m to L3), indicating that the Ego vehicle had not yet overtaken them. While an earlier manoeuvre might appear feasible, it was constrained by vehicle L1 ahead of the convoy in the left lane, and by the lack of driving demand to initiate a lane change at that time.

In some configurations, a high SD is observed at the AN point, suggesting an unsafe moment to initiate a lane change, as the available gap may vary greatly—ranging from too narrow to excessively large. This reflects the driver's behaviour when checking the rear-view mirror and evaluating the situation, especially in complex traffic environments. The gap in terms of seconds shows similar trends, observing that time gaps are between 0.559 and 2.475 s (Table 3), which aligns with safety margin values in the literature. A detailed analysis of these values at LC point is provided in the next subsections.

4.2.1.1. Acceptable gap. The concept of gap acceptance in driving models is crucial for lane-change decisions, particularly for lateral manoeuvres. Some authors distinguish between front and back gaps

Table 2

Gap in meters between vehicles in different driving regimes (CF, AN, LC point) and lane change conditions (*high values for SD result from outliers).

Gap (m)		C _{free} (n = 32)		C _{front} (n = 38)		C _{back} (n = 30)	
		Mean	SD	Mean	SD	Mean	SD
CF point	Ego – Front Right veh.	30.6	11.0	26.3	10.8	28.6	14.8
	Ego – Front Left veh.					–17.0	13.1
	Ego – Back Left veh.			–26.0	12.6		
AN point	Ego – Front Right veh.	29.5	10.7	25.7	10.3	28.5	13.6
	Ego – Front Left veh.					–8.7	17.4*
	Ego – Back Left veh.			–24.5	12.3		
LC point	Ego – Front Right veh.	18.2	11.5	16.7	8.7	16.4	9.1
	Ego – Front Left veh.					28.4	15.8
	Ego – Back Left veh.			–20.7	12.1		
Gap (m)		C _{mid₁} (n = 38)		C _{mid₂} (n = 29)		C _{last} (n = 24)	
		Mean	SD	Mean	SD	Mean	SD
CF point	Ego – Front Right veh.	36.0	22.4	32.4	14.8	29.0	10.0
	Ego – Front Left veh.	–12.2	15.4*	–37.3	17.8	–59.4	22.0
	Ego – Back Left veh.	–57.8	23.9	–69.0	18.4		
AN point	Ego – Front Right veh.	33.1	18.4	30.9	11.3	28.3	9.6
	Ego – Front Left veh.	–6.7	20.5*	–35.3	17.9	–56.9	21.6
	Ego – Back Left veh.	–52.9	25.3	–62.9	17.9		
LC point	Ego – Front Right veh.	20.6	12.0	16.1	9.6	14.8	9.2
	Ego – Front Left veh.	26.9	19.6	23.3	17.9	31.5	22.9
	Ego – Back Left veh.	–34.9	15.5	–26.9	12.2		

(Sharma et al., 2020; Pakzadnia and Hassan, 2023), both of which

Table 3

Gap in seconds between vehicles in different driving regimes (CF, AN, LC point) and lane change conditions.

Gap (s)		C _{free} (n = 32)		C _{front} (n = 38)		C _{back} (n = 30)	
		Mean	SD	Mean	SD	Mean	SD
CF point	Ego – Front Right veh.	1.229	0.474	1.002	0.433	1.109	0.635
	Ego – Front Left veh.					0.623	0.3778
	Ego – Back Left veh.			0.957	0.426		
AN point	Ego – Front Right veh.	1.197	0.462	1.006	0.423	1.128	0.587
	Ego – Front Left veh.					0.559	0.332
	Ego – Back Left veh.			0.909	0.427		
LC point	Ego – Front Right veh.	0.751	0.483	0.701	0.379	0.720	0.388
	Ego – Front Left veh.			–	–	1.059	0.670
	Ego – Back Left veh.			0.805	0.430	–	–
Gap (s)		C _{mid₁} (n = 38)		C _{mid₂} (n = 29)		C _{last} (n = 24)	
		Mean	SD	Mean	SD	Mean	SD
CF point	Ego – Front Right veh.	1.384	0.810	1.269	0.611	1.138	0.418
	Ego – Front Left veh.	0.585	0.376	1.363	0.504	2.053	0.751
	Ego – Back Left veh.	2.070	0.745	2.475	0.623		
AN point	Ego – Front Right veh.	1.371	0.896	1.228	0.493	1.125	0.405
	Ego – Front Left veh.	0.613	0.512	1.295	0.522	1.949	0.742
	Ego – Back Left veh.	1.908	0.812	2.411	0.645		
LC point	Ego – Front Right veh.	0.911	0.549	0.713	0.426	0.643	0.384
	Ego – Front Left veh.	1.027	0.816	0.917	0.749	1.221	0.939
	Ego – Back Left veh.	1.343	0.597	1.057	0.474		

influence the decision to accept or reject a manoeuvre.

In this study, the acceptable gap is assessed at the lane change execution point (LC), as shown in Fig. 7. The analysis includes distances to the front vehicle in the right lane and to the front and rear vehicles in the left lane, excluding the C_{free} condition. Negative gaps indicate the presence of vehicles behind the Ego vehicle.

In C_{mid1} and C_{mid2}, where the lane change occurs between two vehicles, the gap in the left lane is generally symmetrical, although slightly larger with respect to the back left vehicle (23% and 13% respectively). Furthermore, under these conditions, the gap to the front left vehicle is consistently greater than that to the front right vehicle, with the largest difference observed in C_{last}.

4.2.2. Ego speed and Delta-V analysis

This section analyses the speed profile of the Ego vehicle (Table 4) and its relative velocity with surrounding traffic (Delta-V) (Table 5) to understand how drivers adapt their behaviour under different traffic configurations across the three driving regimes.

In configurations where one or more vehicles are present in the left lane (all except C_{free}), the Ego vehicle's speed decreases gradually across the manoeuvre phases (–1.29% CF-AN and –4.36% AN-LC) due to braking and reduced acceleration of the front vehicle. In contrast, this pattern is not observed in the C_{free} manoeuvre, where the Ego vehicle reaches significantly higher speeds in the LC point with a sharper transition between phases (–0.45% CF-AN, 3.41% AN-LC).

Overall, Delta-V with the front vehicle in the right lane increases progressively from CF to AN and LC across all configurations. This reflects how the Ego vehicle increases its speed in preparation for overtaking.

Regarding the vehicles in the left lane, Delta-V values are consistently negative with respect to the front left vehicle, indicating that it always travels faster than the Ego vehicle—regardless of the configuration. For the back left vehicle, this expected pattern reverses only in C_{mid2}, where Delta-V becomes positive—suggesting that the following vehicle slows down to facilitate the manoeuvre. This may indicate either a more aggressive manoeuvre or implicit cooperation by the following driver, who adjusts speed to facilitate the gap.

High standard deviations observed in several Delta-V measurements, particularly to the front right and back left vehicle, point to considerable variability in driver behaviour. This may reflect differing risk tolerances, levels of assertiveness, or reactions from surrounding vehicles during the

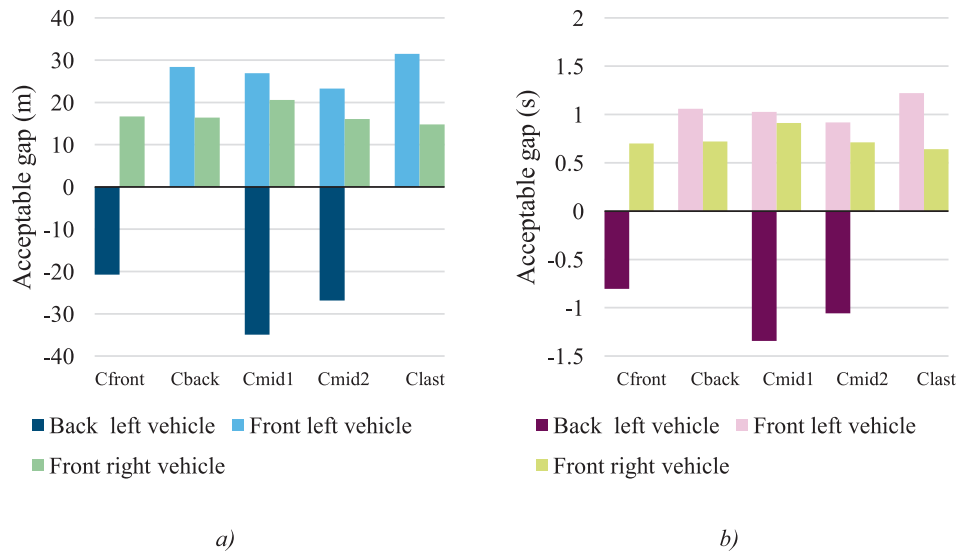


Fig. 7. Acceptable gap in meters (a), and in seconds (b), according to lane change condition at LC point.

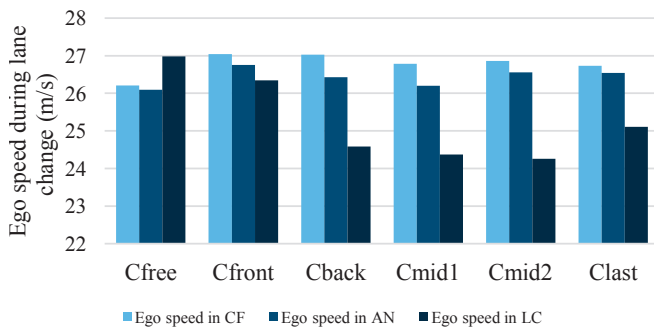


Fig. 8. Ego speed during lane change manoeuvre according to driving regimes.

Table 4

Ego vehicle speed during lane change manoeuvre according to driving regimes.

Speed (m/s)	C _{free} (n = 32)		C _{front} (n = 38)		C _{back} (n = 30)	
	Mean	SD	Mean	SD	Mean	SD
Ego speed in CF	26.211	2.111	27.045	1.484	27.027	1.459
Ego speed in AN	26.092	2.030	26.758	1.659	26.431	1.977
Ego speed in LC	26.982	2.615	26.347	1.989	24.584	2.209

Speed (m/s)	C _{mid1} (n = 38)		C _{mid2} (n = 29)		C _{last} (n = 24)	
	Mean	SD	Mean	SD	Mean	SD
Ego speed in CF	26.782	2.074	26.859	1.107	26.732	1.219
Ego speed in AN	26.198	2.033	26.557	1.133	26.539	1.400
Ego speed in LC	24.373	2.019	24.255	2.284	25.105	1.784

execution of the lane change.

4.2.3. Safety metrics

The safety metrics analysed in this study are based on dynamic measures of the vehicles during each manoeuvre. This section analyses two safety indicators—safety margin and Time-to-Collision (TTC)—evaluated across the three driving regimes: car-following (CF), anticipation (AN), and lane change (LC). Their variation is examined across different driving regimes to better understand how drivers adjust their behaviour in response to surrounding conditions.

4.2.3.1. Safety margin. The safety margin, often represented by the distance or time to the front vehicle, is a critical measure in

understanding the safety of lane change manoeuvres. The final phase of the manoeuvre, just before overtaking, typically involves the smallest margin and is therefore key to understanding the manoeuvre's risk level. This phase is sometimes used in driving models as a trigger to initiate the lane change manoeuvre if the TTC falls below a certain threshold, and also to define the urgency of it, as suggested in existing literature (Ali et al., 2020; Yang et al., 2019; Wang et al., 2019).

Fig. 9a and 9b represent the distance between the Ego vehicle and the front vehicle in meters and seconds, until the end of the lane change manoeuvre. It should be noted that, in Fig. 9, the zero point corresponds to the moment when the Ego vehicle crosses the lane centreline, which is used as the reference point for the gap measurements.

Although the overall differences between regimes are limited, specific cases present notable insights. For instance, in case C_{back}, where the driver passes behind an unexpected vehicle in the left lane, the time gap in AN is longer than in CF (Fig. 9b) which could be due to the sudden appearance of a vehicle at high speed in the left lane, preventing the driver from initiating the overtaking manoeuvre. On the other hand, a stepwise decrease is observed in the conditions with multiple vehicles in the left lane, being the gap smaller as more vehicles are in the left lane.

On average, the gap in meters between the Ego vehicle and the front vehicle is larger during CF in all conditions, with an average of −3.55% for distance and −1.69% for time. This indicates that drivers tend to maintain a safe distance before initiating the manoeuvre. On the other hand, between AN and LC, a much more pronounced reduction is observed, with an average of −44.69% for distance and −37.02% for time. This suggests that, after analysing the surroundings in AN, the driver significantly reduces the distance to execute the manoeuvre.

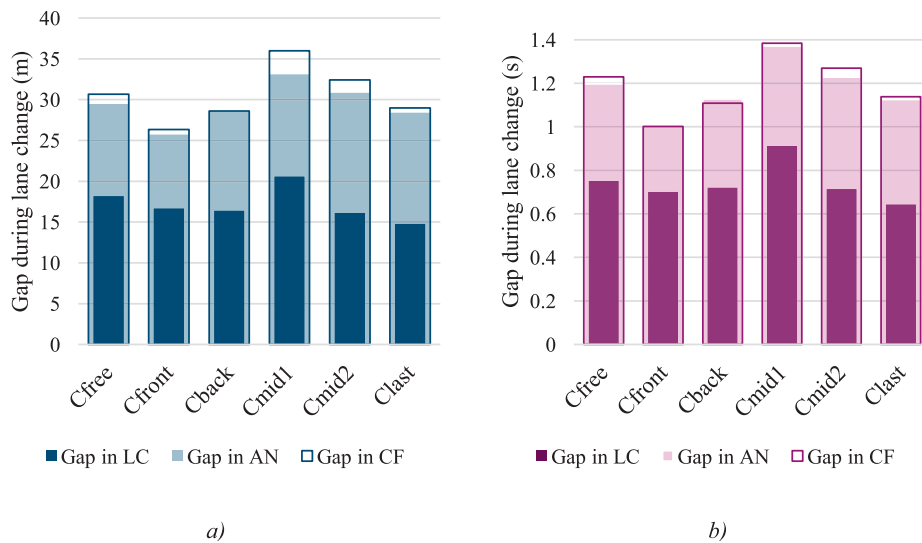
4.2.3.2. TTC. The TTC metric, calculated following Eq. (1) mentioned earlier, is specifically evaluated for the LC point in table 6. TTC values for left-lane vehicles are shown for reference and are notably higher than those for the front vehicle. Of the 198 manoeuvres analysed, 167 met the condition of a positive velocity difference ($\Delta v > 0$), representing 84.34% of the total sample. Despite the typical limitations of TTC in risk situations, this metric remains an interesting variable to study, as it helps to understand driver behaviour beyond critical boundaries, providing a more comprehensive view of the risk level and manoeuvre dynamics.

Due to the high variability observed in Table 6 (large SD values), the median is considered a more reliable measure of central tendency, being less sensitive to extreme values (Chen et al., 2015). The median TTC remains consistent across all conditions (Fig. 10), averaging 6.6 s for TTC to the front vehicle, which aligns with the experimental design and

Table 5

Delta-V between Ego and front vehicle during lane change manoeuvre according to driving regimes (*high values for SD result from outliers).

Delta-V (m/s)		C _{free} (n = 32)		C _{front} (n = 38)		C _{back} (n = 30)	
		Mean	SD	Mean	SD	Mean	SD
CF point	Ego – Front Right veh.	1.065	1.257*	0.394	1.580*	0.353	2.112*
	Ego – Front Left veh.					–1.960	1.482
	Ego – Back Left veh.			–0.478	0.854*		
AN point	Ego – Front Right veh.	1.274	1.279	0.841	1.472*	0.693	1.761*
	Ego – Front Left veh.					–2.620	1.544
	Ego – Back Left veh.			–0.585	0.985*		
LC point	Ego – Front Right veh.	2.506	1.564	2.346	1.246	1.850	1.484
	Ego – Front Left veh.					–3.225	2.670
	Ego – Back Left veh.			–0.242	1.627*		
Delta-V (m/s)		C _{mid1} (n = 38)		C _{mid2} (n = 29)		C _{last} (n = 24)	
		Mean	SD	Mean	SD	Mean	SD
CF point	Ego – Front Right veh.	0.828	1.711*	1.088	1.292*	1.022	0.949
	Ego – Front Left veh.	–1.523	1.352	–1.579	1.598*	–2.143	1.323
	Ego – Back Left veh.	–0.889	1.711*	0.696	1.292*		
AN point	Ego – Front Right veh.	1.192	1.628*	1.135	1.276*	1.032	0.917
	Ego – Front Left veh.	–1.820	1.568	–1.880	1.458	–2.635	2.046
	Ego – Back Left veh.	–1.222	1.992*	0.420	7.091*		
LC point	Ego – Front Right veh.	1.543	1.388	1.525	1.384	2.195	1.528
	Ego – Front Left veh.	–2.601	2.347	–2.078	3.315*	–1.468	2.984*
	Ego – Back Left veh.	–1.754	2.324*	0.457	6.728*		

**Fig. 9.** a) Gap in meters and b) gap in seconds between ego and vehicle F during lane change manoeuvre according to driving regimes.**Table 6**

TTC at LC point regarding lane change condition.

TTC (s)	C _{free} (n = 32)			C _{front} (n = 38)			C _{back} (n = 30)		
	Median	Mean	SD	Median	Mean	SD	Median	Mean	SD
Ego – Front Right veh.	5.378	6.948	6.313	5.180	7.559	7.214	8.283	28.415	54.401
Ego – Front Left veh.							20.907	22.055	10.367
Ego – Back Left veh.				15.224	28.119	49.057			
TTC (s)	C _{mid1} (n = 38)			C _{mid2} (n = 29)			C _{last} (n = 24)		
	Median	Mean	SD	Median	Mean	SD	Median	Mean	SD
Ego – Front Right veh.	9.714	21.147	37.317	6.969	17.255	23.871	4.043	29.207	72.265
Ego – Front Left veh.	9.987	16.251	15.576	15.427	28.852	31.769	27.017	47.275	46.227
Ego – Back Left veh.	43.507	56.235	70.048	16.951	48.588	106.533			

literature for low-risk situations (Li et al., 2020; Vogel, 2003). These results suggest that, from a TTC perspective, the manoeuvres occur under non-critical conditions. However, empirical observations indicate

that drivers still initiate the manoeuvre, suggesting that TTC alone may not be a sufficiently robust predictor of lane-change decisions. TTC respect to vehicles in the left lane are shown for information purposes

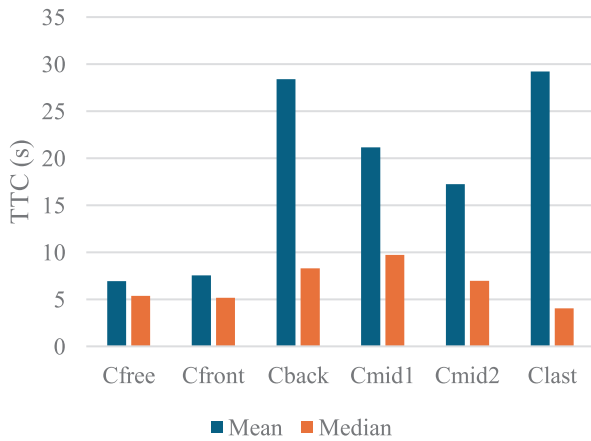


Fig. 10. Difference between mean and median values of TTC for each lane change condition at LC point.

only.

Comparing TTC to the front vehicle with available gap distance in temporal terms (Fig. 11), reveals that safety gap margins offer a more reliable measure for predicting lane-change behaviour. Even without outliers, TTC values remain notably high, suggesting this measure may not fully reflect the decision-making processes behind lane-change execution. These findings support the idea that gap-based indicators better capture the actual conditions under which drivers decide to change lanes.

4.2.4. Relation between metrics

This section integrates the results from previous analyses to highlight key relationships between driving regimes, traffic configurations, and the behaviour of surrounding vehicles. These interactions help explain the variability in lane changing and provide a broader understanding of the underlying strategies adopted by drivers.

Regarding defined driving regimes and their influence on manoeuvre

dynamics, a consistent pattern is observed in the transition from CF to AN, which tends to be brief in all conditions, while the transition from AN to LC is longer and more dispersed (Fig. 6). This suggests that drivers begin to evaluate the manoeuvre immediately after leaving the free-flow regime. The safety margin follows a similar trend, with minimal differences between CF and AN, and a more pronounced decrease from AN to LC (Fig. 9). These observations indicate that drivers assess their environment quickly and initiate the manoeuvre when conditions align.

Each variable evolves differently across phases. Ego vehicle speed decreases progressively from CF to LC due to the presence of a slower front vehicle, except in C_{free} , where no vehicles are present in the left lane and higher speeds are maintained (Fig. 8). In contrast, Delta-V with the front right vehicle increases consistently across phases, reflecting acceleration in preparation for overtaking (Table 5). Safety margins also decline from CF to LC, indicating a gradual reduction in gap as the driver prepares for the manoeuvre (Fig. 9). Uncertainty is particularly noticeable at specific moments in the manoeuvre. The gap in AN shows high variability (Table 2), reinforcing the idea of this phase as one of evaluation. Likewise, Delta-V relative to the front right and back left vehicles also shows wide dispersion (Table 5), reflecting diverse negotiation strategies and differences in driver assertiveness.

Data confirm that the actual gap enabling the manoeuvre appears only in the LC phase, when the surrounding traffic has already adjusted (Table 2). Earlier phases involve positioning and observation rather than viable opportunities, reinforcing the view of LC as the decisive stage where spatial and dynamic constraints converge. At the moment of the lane change, the safety margin ranges from 0.559 to 2.475 s (Table 3), consistent with values reported in the literature for safe lane changes. Additionally, the acceptable gap shows a slight asymmetry in C_{mid1} and C_{mid2} , being 23% and 13% larger with respect to the back vehicle, suggesting a tendency to rely more on forward visibility than rear estimations.

In contrast, Time-to-Collision (TTC) appears less reliable in this context. As shown in Fig. 11, gap-based measures display more stable behaviour with fewer outliers. Median TTC value at the LC point remains around 6.6 s across scenarios (Fig. 10), aligning with previous

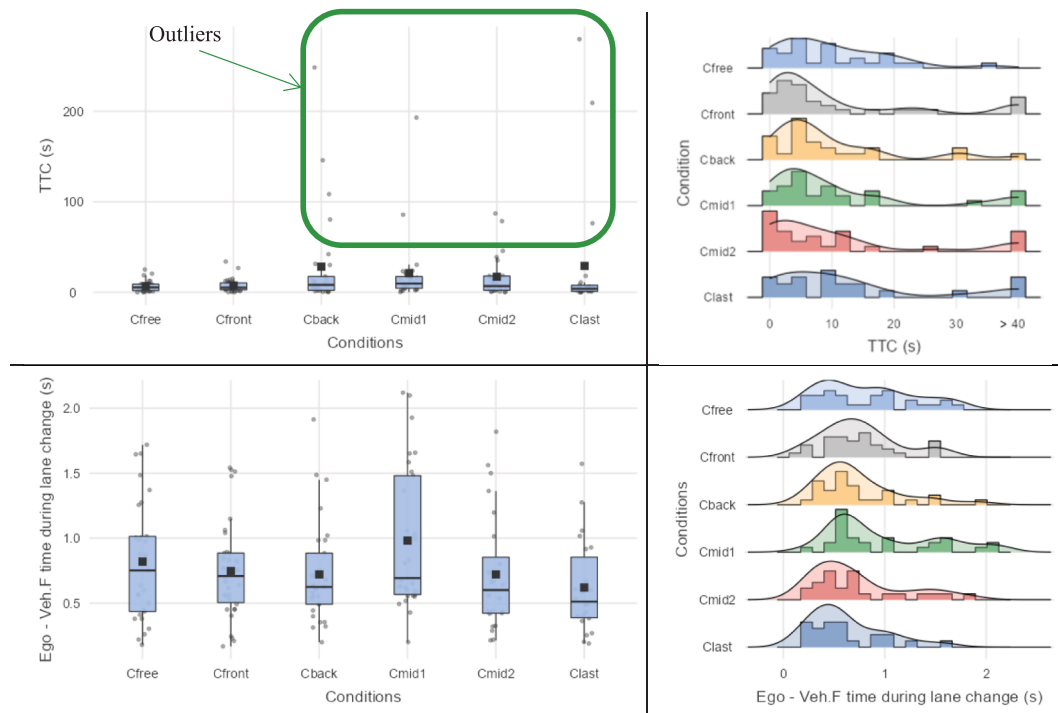


Fig. 11. Comparison between TTC values (top) and gap in seconds between Ego and Veh. F (bottom) in terms of mean and SD with outlier (left) and histogram (right), at LC point according to lane change condition.

research associated with medium–low risk conditions (Yang et al., 2019; Olsen et al., 2002; Wang et al., 2019).

These findings suggest that, while TTC may offer general insights into risk, gap-related metrics provide more precise and actionable indicators for predicting lane change. These results reflect the non-critical nature of the manoeuvres, consistent with real-world conditions where lane changes are often not perceived as dangerous.

Driver responses are also shaped by traffic conditions. As left-lane density increases, anticipation times become longer (Fig. 6), suggesting different strategies. Some drivers opt for quick manoeuvres when options are limited, while others extend the evaluation phase, waiting for a safer or more convenient opportunity. This pattern also appears in the safety margin data, where the available gap shows a stepwise decrease as the number of surrounding vehicles increases (Fig. 9). This indicates that, in denser scenarios, drivers maintain closer distances to avoid missing brief openings, adopting a more opportunistic or competitive behaviour.

These findings underscore how driver responses adapt to traffic complexity across different regimes, highlighting the layered nature of lane-change decision-making (Moridpour et al., 2010; Li et al., 2019). Moreover, they offer valuable insights for future research aimed at refining naturalistic driving models and improving our understanding of the strategies that guide lane-change execution.

Finally, the position and behaviour of surrounding vehicles significantly influence the manoeuvre. Delta-V values between the Ego vehicle and the left lane vehicles are generally negative for both front and back positions, indicating that these vehicles travel faster than Ego. However, in the C_{mid2} , a positive Delta-V with back left vehicle suggests that the driver either forces the lane change or that there is implicit cooperative behaviour between them (Table 5). Similarly, the high standard deviations observed in several measurements of this parameter, especially with regards to the front right and back left vehicles, point to considerable variability in driver behaviour. This may reflect differing risk tolerances, levels of assertiveness, or adaptive responses to the behaviour of surrounding traffic during the execution of the manoeuvre.

These interactions demonstrate how the surrounding traffic is not merely an obstacle, but an active component of the decision-making process, capable of influencing both the timing and manner of lane-change execution.

4.3. Motivations behind the need for lane changing

Understanding the motivations behind lane-change decisions is essential for improving naturalistic driving models. While multiple factors influence these decisions, speed differentials between the Ego vehicle and surrounding traffic provide key insights into the underlying dynamics of lane-change initiation.

As observed in Section 3.2.2, Delta-V with the front vehicle increases progressively from car-following (CF) to lane-change (LC), reflecting that the Ego vehicle is preparing to execute the manoeuvre (Hetrick, 1997). In some cases, the manoeuvre appears to be facilitated by surrounding vehicles, while in others it is more assertively executed by the Ego driver. These patterns suggest that speed relationships may play an important role in the decision-making process.

Building on these findings, this section examines three speed relationships that may influence lane-change decisions at the AN point (Table 7). It is important to note that lane changes motivated by route changes, such as exits, were not considered in this experiment. First, the speed difference between the Ego vehicle and the front vehicle (v_F) is analysed, as a significant Delta-V could indicate an urgent need to change lanes to avoid abrupt deceleration. Second, the average speed in the left lane (v_m) is compared to the Ego vehicle's speed, since a higher adjacent lane speed may encourage the manoeuvre, while a lower speed may discourage it. Lastly, the relationship between the Ego vehicle's speed and the road's maximum speed limit – 120 km/h in this experiment (v_{max}) – is considered to assess how proximity to this limit

Table 7

Speed ratios according to lane change condition at the AN point.

	Speed ratios	C_{free} (n = 32)		C_{front} (n = 38)		C_{back} (n = 30)	
		Mean	SD	Mean	SD	Mean	SD
AN point	v_{Ego} / v_F	1.08	0.45	1.07	0.43	1.08	0.38
	v_{Ego} / v_m	1.18	0.50	1.04	0.43	0.94	0.33
	v_{Ego} / v_{max}	0.84	0.35	0.77	0.31	0.74	0.26
	Speed ratios	C_{mid1} (n = 38)		C_{mid2} (n = 29)		C_{last} (n = 24)	
		Mean	SD	Mean	SD	Mean	SD
AN point	v_{Ego} / v_F	1.03	0.39	1.02	0.40	1.08	0.34
	v_{Ego} / v_m	0.97	0.37	1.01	0.40	0.92	0.29
	v_{Ego} / v_{max}	0.70	0.27	0.69	0.27	0.74	0.23

influences lane-change decisions.

At the anticipation point (AN), the Ego vehicle was travelling at a higher speed than the front vehicle, as were the vehicles in the left lane, with an average of 1.06 and 1.01 respectively, which indicates that Ego vehicle was approximately 8% faster than the front vehicle, and 6% faster than vehicles in the left lane (Table 7). However, despite this relative increase, the Ego vehicle's speed remains, on average, 25% below the road's maximum speed limit, suggesting that drivers still have margin to increase their speed when executing the manoeuvre (Moridpour et al., 2010). This behaviour suggests that drivers aim not only to maintain their own speed but also to adapt to the overall traffic dynamics, minimizing the need for sudden braking or abrupt adjustments.

Additionally, lane changes are not always made to increase speed but can also be guided by a positioning strategy or the anticipation of future manoeuvres, which highlights the complexity of the process and the constant evaluation of the environment by the driver.

4.4. Limitations

This study presents several limitations that should be considered when interpreting the results. Although the number of participants was limited, each driver performed between 10 and 12 lane-change manoeuvres, resulting in a total of 198 valid manoeuvres analysed under controlled real-traffic conditions. Since the objective was to identify general behavioural trends rather than differences between driver typologies, the resulting dataset was considered sufficiently representative for the scope of the study. Nevertheless, future research could investigate how these findings vary across different driver profiles and driving styles using larger and more categorised samples.

Another limitation concerns the controlled nature of the experimental scenarios. Although the configurations were designed to reproduce representative highway lane-change situations, they remain simplified and may not fully capture the complexity and spontaneity of real traffic interactions. Furthermore, the experiments were conducted on a two-lane highway section without considering infrastructure elements such as merging areas, exits, or pronounced curvature, and without analysing the influence of weather or visibility conditions. Finally, the study focused primarily on observable behavioural and traffic-related variables, without explicitly considering motivational or psychological factors that may also influence lane-change decision-making.

5. Conclusions

This article examined how real traffic conditions influence driver behaviour during lane change manoeuvres, focusing on the temporal structure of driving regimes across the phases of car-following, anticipation, and lane change, and the dynamics of driver decision-making. The results highlight that the transition from free-flow to anticipation and then to lane change execution is not merely sequential, but is

marked by specific shifts in vehicle dynamics, such as increasing Ego speed, decreasing relative speed, and evolving safety margins.

The findings show that the critical gap needed to execute a safe lane change only becomes available—and reliably utilised by drivers—during the final lane change phase, once spatial and temporal alignment with surrounding traffic is achieved. In higher-density scenarios, anticipation phases tend to be longer and more dispersed, suggesting that drivers adopt more opportunistic strategies when the environment becomes less predictable.

Another relevant insight is the role of relative speed as a potential trigger for manoeuvre initiation. Drivers often accelerate to exceed the speed of both the front vehicle and the traffic in the adjacent lane, yet remain within speed limits. This suggests that their decisions are not driven by urgency alone but by strategic considerations—anticipating future traffic demands or improving position in flow.

From a methodological standpoint, the comparison of traditional indicators such TTC, while commonly used, may lack the sensitivity required to account for environmental variability in overtaking scenarios. In contrast, gap-based measures and relative dynamics (e.g., Delta-V) produced more consistent trends with fewer outliers, making them more suitable for identifying the conditions under which lane changes are executed.

In conclusion, this study advances the understanding of lane-change decision-making by integrating behavioural indicators with contextual traffic dynamics. The findings support the refinement of naturalistic driving models and ADAS functionalities through the use of phase-sensitive metrics that reflect how drivers respond to complexity, manage safety margins, and adapt their behaviour to surrounding vehicles. Recognising these interactions is essential for designing safer, more context-aware, and behaviourally grounded mobility systems.

CRediT authorship contribution statement

Sofia Sanchez-Mateo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Riender Happee:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Felipe Jiménez:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

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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.

Data availability

The authors do not have permission to share data.

References

- Cunneen, M., 2023. Autonomous vehicles, artificial intelligence, risk and colliding narratives, in: Fossa, F., Cheli, F. (Eds) *Connected and Automated Vehicles: Integrating Engineering and Ethics. Studies in Applied Philosophy, Epistemology and Rational Ethics*, Springer, Cham, pp. 175–195. [Doi:10.1007/978-3-031-39991-6_10](https://doi.org/10.1007/978-3-031-39991-6_10).
- Li, X., Xiao, Y., Zhao, X., Ma, X., Wang, X., 2023. Modeling mixed traffic flows of human-driving vehicles and connected and autonomous vehicles considering human drivers' cognitive characteristics and driving behavior interaction. *Physica A* 609, 128368. <https://doi.org/10.1016/j.physa.2022.128368>.

- Ma, Z., Zhang, Y., 2024. Driver-automated vehicle interaction in mixed traffic: types of interaction and drivers' driving styles. *Hum. Factors* 66, 544–561. <https://doi.org/10.1177/00187208221088358>.
- Crosato, L., Tian, K., Shum, H.P.H., Ho, E.S.L., Wang, Y., Wei, C., 2024. Social interaction-aware dynamical models and decision-making for autonomous vehicles. *Adv. Intell. Syst.* 6, 2300575. <https://doi.org/10.1002/aisy.202300575>.
- Guerrieri, M., Mauro, R., 2021. Interference between traffic flows: the gap acceptance theory, in: *A Concise Introduction to Traffic Engineering*. Springer Tracts in Civil Engineering, Springer, Cham, pp. 131–139. [Doi:10.1007/978-3-030-60723-4_7](https://doi.org/10.1007/978-3-030-60723-4_7).
- Brilon, W., Koenig, R., Troutbeck, R.J., 1999. Useful estimation procedures for critical gaps. *Transp. Res. A Policy Pract.* 33, 161–186. [https://doi.org/10.1016/S0965-8564\(98\)00048-2](https://doi.org/10.1016/S0965-8564(98)00048-2).
- Yan, F., Eilers, M., Baumann, M., 2023. Investigating driver uncertainty about lane change decisions. *Transport. Res. F: Traffic Psychol. Behav.* 95, 369–379. <https://doi.org/10.1016/j.trf.2023.04.013>.
- Lu, C., He, X., van Lint, H., Tu, H., Happee, R., Wang, M., 2021. Performance evaluation of surrogate measures of safety with naturalistic driving data. *Accid. Anal. Prev.* 162, 106403. <https://doi.org/10.1016/j.aap.2021.106403>.
- Nadimi, N., Naseralavi, S.S., Asadamraji, M., 2022. Calculating dynamic thresholds for critical time to collision as a safety measure. In: *Proceedings of the Institution of Civil Engineers: Transport* 175, pp. 403–412. <https://doi.org/10.1680/jtran.19.00066>.
- Vass, S., Donà, R., Mattas, K., Morandin, G., Toth, B., Heé, M.Á., Galassi, M.C., Ciuffo, B., 2024. Are low-speed automated vehicles ready for deployment? Implications on Safety and Urban Traffic. <https://doi.org/10.2139/ssrn.4760713> (preprint).
- Löcken, A., Yan, F., Heuten, W., Boll, S., 2019. Investigating driver gaze behavior during lane changes using two visual cues: ambient light and focal icons. *J. Multimodal User Interf.* 13, 119–136. <https://doi.org/10.1007/s12193-019-00299-7>.
- Doshi, A., Trivedi, M.M., 2009. On the roles of eye gaze and head dynamics in predicting driver's intent to change lanes. *IEEE Trans. Intell. Transp. Syst.* 10, 453–462. <https://doi.org/10.1109/TITS.2009.2026675>.
- Antin, J.F., Wotring, B., Perez, M.A., Glaser, D., 2020. Investigating lane change behaviors and difficulties for senior drivers using naturalistic driving data. *J. Saf. Res.* 74, 81–87. <https://doi.org/10.1016/j.jsr.2020.04.008>.
- Ma, C., Li, D., 2023. A review of vehicle lane change research. *Physica A* 626, 129060. <https://doi.org/10.1016/j.physa.2023.129060>.
- Wang, X., Xu, L., Li, A., 2024. Analysis of drivers' lane-changing behavior on approaching signalized intersections. *Adv. Transp. Stud.* 62, 37–54. <https://doi.org/10.53136/9791221811173>.
- Reuschel, A., 1950. Fahrzeugbewegungen in der Kolonne bei gleich- förmig beschleunigtem oder verzögertem leitfahrzeug, österreichischen. *Ingenieur-Archiv* 4, 193–215.
- Pipes, L.A., 1953. An operational analysis of traffic dynamics. *J. Appl. Phys.* 24, 274–281. <https://doi.org/10.1063/1.1721265>.
- Sparmann, U., 1978. Spurwechselvorgänge auf zweispurigen BAB-Richtungsfahrbahnen. *Forsch Strassenbau Und Strassenverkehrstechnik*.
- Gipps, P.G., 1986. A model for the structure of lane-changing decisions. *Transp. Res. B Methodol.* 20, 403–414. [https://doi.org/10.1016/0191-2615\(86\)90012-3](https://doi.org/10.1016/0191-2615(86)90012-3).
- Chandler, R.E., Herman, R., Montroll, E.W., 1958. Traffic dynamics: studies in car following. *Oper. Res.* 6, 165–184. <https://doi.org/10.1287/opre.6.2.165>.
- Herman, R., Montroll, E.W., Potts, R.B., Rothery, R.W., 1959. Traffic dynamics: analysis of stability in car following. *Oper. Res.* 7, 86–106. <https://doi.org/10.1287/opre.7.1.86>.
- Newell, G.F., 1961. Nonlinear effects in the dynamics of car following. *Oper. Res.* 9, 209–229. <https://doi.org/10.1287/opre.9.2.209>.
- Gazis, D.C., Herman, R., Potts, R.B., 1959. Car-following theory of steady-state traffic flow. *Oper. Res.* 7, 499–505. <https://doi.org/10.1287/opre.7.4.499>.
- Bexelius, S., 1968. An extended model for car-following. *Transp. Res.* 2, 13–21. [https://doi.org/10.1016/0041-1647\(68\)90004-X](https://doi.org/10.1016/0041-1647(68)90004-X).
- Ahmed, K., Ben-Akiva, M.E., Koutsopoulos, H.N., Mishalani, R.G., 1996. Models of freeway lane changing and gap acceptance behavior. In: *Proceedings of the 13th International Symposium on the Theory of Traffic Flow and Transportation*, pp. 501–515.
- Halati, A., Lieu, H., Walker, S., 1997. CORSIM- corridor traffic simulation model, in: *Proceedings of the Conference on Traffic Congestion and Traffic Safety in the 21st Century*, American Society of Civil Engineers, pp. 570–576.
- Toledo, T., 2003. Integrated driving behavior modeling, PhD Dissertation, Department of Civil and Environmental Engineering, MIT.
- Brackstone, M., McDonald, M., 1999. Car-following: a historical review. *Transport. Res. F: Traffic Psychol. Behav.* 2, 181–196. [https://doi.org/10.1016/S1369-8478\(00\)00005-X](https://doi.org/10.1016/S1369-8478(00)00005-X).
- Olstam, J.J., Tapani, A., 2004. Comparison of car-following models. Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.
- Herman, R., Weiss, G., 1961. Comments on the highway-crossing problem. *Oper. Res.* 9, 828–840.
- Drew, D.R., LaMotte, L.R., Buhr, J.H., Wattleworth, J.A., 1967. Gap acceptance in the freeway merging process. *Highw. Res. Rec.* 208, 1–36.
- Miller, A., 1972. Nine estimators of gap-acceptance parameters. In: *5th International Symposium on the Theory of Traffic Flow and Transportation*, pp. 215–235.
- Michaels, R.M., 1963, 1965. Perceptual factors in car following. In: *Proceedings of the 2nd International Symposium on the Theory of Road Traffic Flow*, pp. 44–59.
- Wiedemann, R., 1974. *Simulation des strassenverkehrsflusses*. University of Karlsruhe.
- Michon, J.A., 1985. A critical view of driver behavior models: what do we know, what should we do? In: Evans, L., Schwing, R. (Eds.), *Human Behavior and Traffic Safety*. Springer, Boston, MA, pp. 485–524. https://doi.org/10.1007/978-1-4613-2173-6_19.

- Díaz-Álvarez, A., 2018. Modelado de comportamiento de conductores con técnicas de inteligencia computacional. Universidad Politécnica de Madrid PhD Dissertation. <https://doi.org/10.20868/UPM.thesis.52110>.
- Wiedemann, R., Reiter, U., 1992. Microscopic traffic simulation: the simulation system MISSION, background and actual state. Project ICARUS (V1052) Final Report, Brussels, CEC. 2: Appendix A. Brussels.
- Sharma, A., Zheng, Z., Bhaskar, A., 2019. Is more always better? The impact of vehicular trajectory completeness on car-following model calibration and validation. *Transp. Res. Part B: Methodol.* 120, 49–75. <https://doi.org/10.1016/j.trb.2018.12.016>.
- Mahmassani, H., Sheffi, Y., 1981. Using gap sequences to estimate gap acceptance functions. *Transp. Res. B Methodol.* 15, 143–148. [https://doi.org/10.1016/0191-2615\(81\)90001-1](https://doi.org/10.1016/0191-2615(81)90001-1).
- Yang, Q., Koutsopoulos, H.N., 1996. A microscopic traffic simulator for evaluation of dynamic traffic management systems. *Transp. Res. Part C Emerging Technol.* 4, 113–129. [https://doi.org/10.1016/S0968-090X\(96\)00006-X](https://doi.org/10.1016/S0968-090X(96)00006-X).
- Hidas, P., 2002. Modelling lane changing and merging in microscopic traffic simulation. *Transp. Res. Part C Emerging Technol.* 10, 351–371. [https://doi.org/10.1016/S0968-090X\(02\)00026-8](https://doi.org/10.1016/S0968-090X(02)00026-8).
- Mullakkal-Babu, F.A., Wang, M., Van Arem, B., Happee, R., 2020. Empirics and models of fragmented lane changes. *IEEE Open J. Intell. Transp. Syst.* 1, 187–200. <https://doi.org/10.1109/OJITS.2020.3029056>.
- Toledo, T., Zohar, D., 2007. Modeling duration of lane changes. *Transp. Res. Record: J. Transp. Res. Board* 71–78. <https://doi.org/10.3141/1999-08>.
- Madanat, S., Cassidy, M.J., Wang, M.H., 1993. A probabilistic model of queuing delay at stop controlled intersection approaches. *ASCE J. Transp. Eng.* 120, 21–36.
- Cassidy, M.J., Madanat, S.M., Wang, M.H., Yang, F., 1995. Unsignalized intersection capacity and level of service: Revisiting critical gap. *Transp. Res. Rec.* 16–23.
- Moridpour, S., Rose, G., Sarvi, M., 2010. Effect of surrounding traffic characteristics on lane changing behavior. *J. Transp. Eng.* 136, 973–985. [https://doi.org/10.1061/\(ASCE\)TE.1943-5436.0000165](https://doi.org/10.1061/(ASCE)TE.1943-5436.0000165).
- Li, X., Wang, W., Roetting, M., 2019. Estimating driver's lane-change intent considering driving style and contextual traffic. *IEEE Trans. Intell. Transp. Syst.* 20, 38–3271. <https://doi.org/10.1109/TITS.2018.2873595>.
- Balal, E., Cheu, R.L., Gyan-Sarkodie, T., Miramontes, J., 2014. Analysis of discretionary lane changing parameters on freeways. *Int. J. Transp. Sci. Technol.* 3, 277–296. <https://doi.org/10.1260/2046-0430.3.3.277>.
- Ali, Y., Zheng, Z., Mazharul Haque, M., Yildirimoglu, M., Washington, S., 2020. Understanding the discretionary lane-changing behaviour in the connected environment. *Accid. Anal. Prev.* 137. <https://doi.org/10.1016/j.aap.2020.105463>.
- Guo, M., Wu, Z., Zhu, H., 2018. Empirical study of lane-changing behavior on three Chinese freeways. *PLoS One* 13, e0191466. <https://doi.org/10.1371/journal.pone.0191466>.
- McDonald, M., Wu, J., Brackstone, M., 1997. Development of a fuzzy logic based microscopic motorway simulation model. In: *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*. IEEE, pp. 82–87. <https://doi.org/10.1109/itsc.1997.660454>.
- Brackstone, M., McDonald, M., Wu, J., 1998. Lane changing on the motorway: factors affecting its occurrence, and their implications. In: *Ninth International Conference on Road Transport Information and Control*, Pergamon, pp. 160–164. <https://doi.org/10.1049/cp:19980175>.
- Wu, J., Brackstone, M., McDonald, M., 2000. Fuzzy sets and systems for a motorway microscopic simulation model. *Fuzzy Set. Syst.* 116, 65–76. [https://doi.org/10.1016/S0165-0114\(99\)00038-X](https://doi.org/10.1016/S0165-0114(99)00038-X).
- Kang, K., Rakha, H.A., 2018. Modeling driver merging behavior: a repeated game theoretical approach. *Transp. Res. Rec.* 2672, 144–153. <https://doi.org/10.1177/0361198118792982>.
- Sharma, S., Snelder, M., Tavasszy, L., Van Lint, H., 2020. Categorizing merging and diverging strategies of truck drivers at motorway ramps and weaving sections using a trajectory dataset. *Transp. Res. Rec.* 2674, 855–866. <https://doi.org/10.1177/0361198120932568>.
- Pakzadnia, A., Hassan, Y., 2023. Expected safety performance of different freeway merging strategies in an environment of mixed vehicle technologies. *J. Transp. Eng., Part A: Syst.* 149, 04022143. <https://doi.org/10.1061/jtepbs.teeng-7280>.
- Paschalidis, E., Choudhury, C.F., Hess, S., 2018. Modelling the effects of stress on gap-acceptance decisions combining data from driving simulator and physiological sensors. *Transport. Res. F: Traffic Psychol. Behav.* 59, 418–435. <https://doi.org/10.1016/j.trf.2018.09.019>.
- Bonsall, P., Liu, R., Young, W., 2005. Modelling safety-related driving behaviour - impact of parameter values. *Transp. Res. A Policy Pract.* 39, 425–444. <https://doi.org/10.1016/j.tra.2005.02.002>.
- Sanik, M.E., Hamid, N.B., Nor, A.H.M., Prasertijo, J., Ani, M.S.C., Mustakim, F., 2016. Drivers lane changing behaviour at urban intersection by using gap acceptance approach. *ARPN J. Eng. Appl. Sci.* 11, 14070–14074.
- Virdi, N., Grzybowska, H., Waller, S.T., Dixit, V., 2019. A safety assessment of mixed fleets with connected and autonomous vehicles using the surrogate safety assessment module. *Accid. Anal. Prev.* 131, 95–111. <https://doi.org/10.1016/J.AAP.2019.06.001>.
- Yang, M., Wang, X., Quddus, M., 2019. Examining lane change gap acceptance, duration and impact using naturalistic driving data. *Transp. Res. Part C Emerging Technol.* 104, 317–331. <https://doi.org/10.1016/j.trc.2019.05.024>.
- Hayward, J.C., 1972. Near-miss determination through use of scale of danger. *Highway Research Board* 24–35.
- Zhao, P., Lee, C., 2017. Analysis and validation of surrogate safety measures by types of lead and following vehicles. *Transp. Res. Rec.* 2659, 137–147. <https://doi.org/10.3141/2659-15>.
- Das, S., Maurya, A.K., 2020. Defining time-to-collision thresholds by the type of lead vehicle in non-lane-based traffic environments. *IEEE Trans. Intell. Transp. Syst.* 21, 4972–4982. <https://doi.org/10.1109/TITS.2019.2946001>.
- Li, Y., Wu, D., Lee, J., Yang, M., Shi, Y., 2020. Analysis of the transition condition of rear-end collisions using time-to-collision index and vehicle trajectory data. *Accid. Anal. Prev.* 144, 105676. <https://doi.org/10.1016/j.aap.2020.105676>.
- Guo, H., Xie, K., Keyvan-Ekbatani, M., 2023. Modeling driver's evasive behavior during safety-critical lane changes: two-dimensional time-to-collision and deep reinforcement learning. *Accid. Anal. Prev.* 186, 107063. <https://doi.org/10.1016/j.aap.2023.107063>.
- Vogel, K., 2003. A comparison of headway and time to collision as safety indicators. *Accid. Anal. Prev.* 35, 427–433. [https://doi.org/10.1016/S0001-4575\(02\)00022-2](https://doi.org/10.1016/S0001-4575(02)00022-2).
- Svensson, Å., 1998. A method for analysing the traffic process in a safety perspective. University of Lund, Lund, Sweden. PhD Dissertation.
- Sayed, T., Brown, G., Navin, F., 1994. Simulation of traffic conflicts at unsignalized intersections with TSC-Sim. *Accid. Anal. Prev.* 26, 593–607. [https://doi.org/10.1016/0001-4575\(94\)90021-3](https://doi.org/10.1016/0001-4575(94)90021-3).
- Van Der Horst, R., Hogema, J., 1994. Time-to-collision and collision avoidance systems. *Proc. 6th ICTCT Workshop Salzburg*.
- Gallelli, V., Guido, G., Vitale, A., Vaiana, R., 2019. Effects of calibration process on the simulation of rear-end conflicts at roundabouts. *J. Traff. Transp. Eng. (Eng. Ed.)* 6, 175–184. <https://doi.org/10.1016/j.jtte.2018.03.006>.
- Papadoulis, A., Quddus, M., Imprialou, M., 2019. Evaluating the safety impact of connected and autonomous vehicles on motorways. *Accid. Anal. Prev.* 124, 12–22. <https://doi.org/10.1016/j.aap.2018.12.019>.
- Xu, Z., Zou, X., Oh, T., Vu, H.L., 2021. Studying freeway merging conflicts using virtual reality technology. *J. Saf. Res.* 76, 16–29. <https://doi.org/10.1016/j.jsr.2020.11.002>.
- Sayed, T., Zein, S., 1999. Traffic conflict standards for intersections. *Transp. Plan. Technol.* 22, 309–323. <https://doi.org/10.1080/03081069908717634>.
- Yang, G., Ahmed, M., Gaweesh, S., Adomah, E., 2020. Connected vehicle real-time traveler information messages for freeway speed harmonization under adverse weather conditions: trajectory level analysis using driving simulator. *Accid. Anal. Prev.* 146, 105707. <https://doi.org/10.1016/j.aap.2020.105707>.
- Minderhoud, M.M., Bovy, P.H.L., 2001. Extended time-to-collision measures for road traffic safety assessment. *Accid. Anal. Prev.* 33, 89–97. [https://doi.org/10.1016/S0001-4575\(00\)00019-1](https://doi.org/10.1016/S0001-4575(00)00019-1).
- Bevrani, K., Chung, E., 2012. Comparison and modification of car following models toward a more accurate microscopic simulation parameters reproduction, in: Chung, E and Stevens, A (Eds.). 19th Intelligent Transport Systems World Congress, ITS, AustriaTech.
- Huang, F., Liu, P., Yu, H., Wang, W., 2013. Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections. *Accid. Anal. Prev.* 50, 1014–1024. <https://doi.org/10.1016/j.aap.2012.08.018>.
- Chin, H.C., Quek, S.T., 1997. Measurement of traffic conflicts. *Saf. Sci.* 26, 169–185. [https://doi.org/10.1016/S0925-7535\(97\)00041-6](https://doi.org/10.1016/S0925-7535(97)00041-6).
- Janssen, W., Nilsson, L., 1992. An experimental evaluation of in-vehicle collision avoidance systems, VTI särtryck 181. Statens Väg-och Trafikinstitut.
- Hirst, S., Graham, R., 1997. Ergonomics and safety of intelligent driver interfaces, in: Y. Ian Noy (Ed.), *The Format and Perception of Collision Warnings*.
- Ozbay, K., Yang, H., Bartin, B., Mudigonda, S., 2008. Derivation and validation of new simulation-based surrogate safety measure. *Transp. Res. Rec.* 2083, 105–113. <https://doi.org/10.3141/2083-12>.
- Rahman, M.S., Abdel-Aty, M., Lee, J., Rahman, M.H., 2019. Safety benefits of arterials' crash risk under connected and automated vehicles. *Transp. Res. Part C Emerging Technol.* 100, 354–371. <https://doi.org/10.1016/j.trc.2019.01.029>.
- Olsen, E.C.B., Lee, S.E., Wierwille, W.W., Goodman, M.J., 2002. Analysis of distribution, frequency, and duration of naturalistic lane changes. In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 46, pp. 1789–1793. <https://doi.org/10.1177/154193120204602203>.
- Chen, R., Kusano, K.D., Gabler, H.C., 2015. Driver behavior during overtaking maneuvers from the 100-car naturalistic driving study. *Traffic Inj. Prev.* 16, S176–S181. <https://doi.org/10.1080/15389588.2015.1057281>.
- Lethaus, F., Rataj, J., 2007. Do eye movements reflect driving manoeuvres? *IET Intel. Transport Syst.* 1, 199–204. <https://doi.org/10.1049/iet-its:20060058>.
- Sanchez-Mateo, S., Valle-Barrio, A., Díaz-Álvarez, A., Jiménez, F., 2023. Assessing a deterministic model for autonomous driving through visual behavior, in: *Proceedings of the XV Ibero-American Congress of Mechanical Engineering*, Springer, Cham, pp. 154–160. https://doi.org/10.1007/978-3-031-38563-6_23.
- Wang, X., Yang, M., Hurwitz, D., 2019. Analysis of cut-in behavior based on naturalistic driving data. *Accid. Anal. Prev.* 124, 127–137. <https://doi.org/10.1016/j.aap.2019.01.006>.
- Hetrick, S., 1997. Examination of driver lane change behavior and the potential effectiveness of warning onset rules for lane change or "side" crash avoidance systems. Virginia Polytechnic Institute and State University. PhD Dissertation.