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How lane changing affects urban congestion

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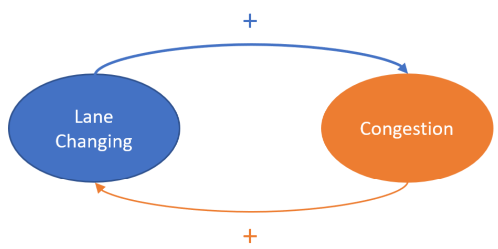
1. Introduction

As one of the two primary driving tasks in traffic flow, lane changing represents the lateral interaction of vehicles on the road and significantly impacts traffic flow characteristics (Zheng, 2014). Due to its prevalence and importance, lane changing has been extensively studied over the past few decades. Most research highlights its negative effects, mainly encompassing safety loss (Zheng et al., 2010) and capacity reduction (Mauch and Cassidy, 2002). Knoop et al. (2012) suggested that in a non-weaving freeway section, the lane changing rate would increase with vehicle density, stemming from drivers' desire to improve speed in congested conditions (Toledo and Katz, 2009). Conversely, at weaving sites, Ahmed et al. (2019) proposed that the lane changing rate would decrease as vehicle density increased. Although the data sets and measurement methods chosen by the two studies differ, they demonstrate that the likelihood of lane changes depends on both the purpose of the lane change and traffic density. Previous research has indicated that lane changing decreases discharge rate or output flow (Patire and Cassidy, 2011), as it disrupts the flow and accelerates queue expansion, particularly during peak travel periods. However, for lane changing, especially discretionary lane changing, speed disturbance also follows (Patire and Cassidy, 2011). As such, we hypothesize that there is a mutually reinforcing relationship between lane changing and congestion from a system perspective, as illustrated in Figure 1. This implies that congestion can prompt drivers to perform lane changing, which, in turn, further exacerbates the overall traffic congestion.

Figure 1: A mutually reinforcing relationship between lane changing and congestion



2. Study area and data

The analysis site is a section of the M1 motorway in Sydney, located south of the Central Business District (CBD) and north of the Sydney Airport. The M1 motorway is a major arterial road in Sydney, Australia, extending from the city's southern suburbs to the Central Coast region of New South Wales, and serves as a crucial route for commuters and freight traffic in the region (Faulkner et al., 2014). The selected northbound stretch, as depicted in Figure 2, spans a total length of 4.01 km and is one of the busiest sections in Sydney. The entire motorway stretch consists of three northbound lanes: the shoulder lane, center lane, and median lane, from left to right.

Figure 2: The selected motorway stretch of M1 motorway

Segments 1, 3, and 5 in Figure 2 are general areas, which means that these segments do not contain any facilities for influencing the driver to decide lane changing or not. For discretionary lane changes, drivers tend to change lanes to improve their driving environment, mainly reflected in speed gains, safety improvements, or both (Toledo and Katz, 2009). Therefore, lane changes in general areas are more likely to be discretionary (though some may be pre-positioning for a future mandatory change). Segments 2 and 4 represent the designated right lane restriction and merging areas, respectively, located at distances 0.8 km-1.0 km and 1.2 km-1.4 km from the beginning of the section.

In Australia, the ’keep left unless overtaking’ rule is a crucial component of road regulations designed to enhance safety and traffic flow on multi-lane freeways (Smart et al., 2009). This rule is not limited to highways, it also applies to roadways. Drivers in this area who remain in the right lane without a valid reason such as overtaking, turning right, or making a U-turn may face penalties, which require them to change lanes to avoid penalties or perform overtaking. In the merging area, all drivers must adjust their speed and position to prevent collisions or force other drivers into evasive maneuvers (Transportation Officials, 2011). Additionally, drivers in the left through lane tend to change lanes to the center or median lanes to alleviate merging pressure at the shoulder lane.

For mandatory lane changes, most cases are due to when drivers have to leave the current lane to follow their driving path, bypass lane blockages or obey traffic signs (Toledo and Katz, 2009), and the main motivation is to reach the planned destination (Zheng, 2014). Consequently, we differentiate the lane changing behavior in these two areas. However, we cannot assume that every lane change in the respective area is strictly for the labeled purpose.

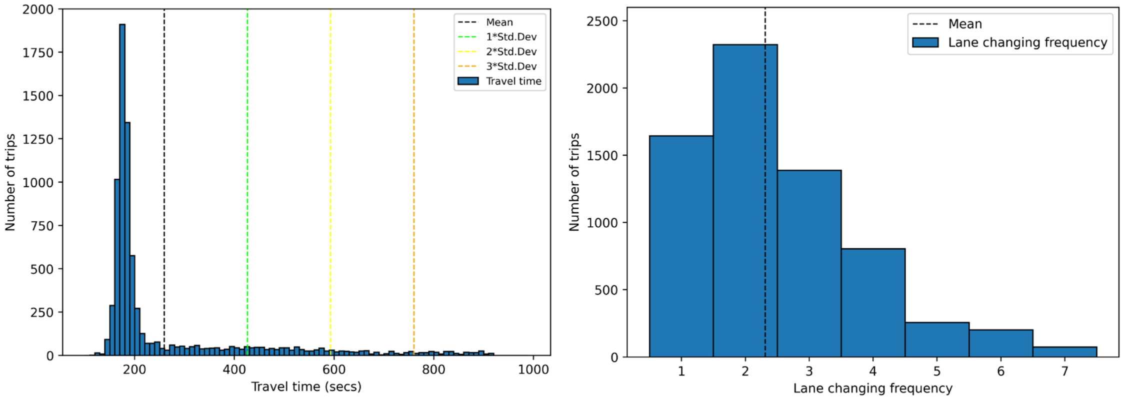
CompassIOT is an Australian road intelligence company that collects blackbox and satnav (GPS) location data from over 700,000 connected vehicles across the country, amassing more than one billion high-precision data points. We obtained an extract of the vehicle trajectory data for the M1 motorway from January to August 2022 and selected 9,345 trips that completed the chosen stretch. There is an off-ramp at 175 m and 650 m downstream of the selected stretch respectively. We assume that the lane changing performed when the vehicle approaches the end of the stretch is discretionary if it did not exit the mainline from these two off-ramps. Therefore, 8,371 trips satisfy this condition among the extracted 9,345 trips. The data provides information on vehicle type, latitude and longitude coordinates, lateral and longitudinal acceleration, and corresponding time-of-day data with a 2-second resolution. We extract the departure time and travel time for each trip, as well as the number and location of lane changes. We divide the 24 hours of the day into 288 5 min departure time intervals, and exclude trips with travel time or the number of lane changes more than 3 standard deviations from the mean of all trips in the interval. The number of remaining trips is 7,824.

3. Lane changing frequency and travel time distribution

The travel time and lane changing frequency distributions for the selected 7,824 trips are displayed in Figure 3. In Figure 3 (a), each bin has a width of 10 seconds, while in Figure 3 (b), each bar represents the number of lane changes. The mean travel time and lane changing frequency are 259 seconds and 2.31 times, respectively. Based on (Knoop et al., 2012) and (Ahmed et al., 2019), we expect lane changes to occur approximately once every 2 km, with this value halving for the weaving segment. On the M1 section, lane changing takes place on average once every 1.74 km, as the selected stretch includes a weaving area and a lane restriction area, which together account for one-tenth of the total stretch length, thereby increasing the frequency of lane changing.

Figure 3: Travel time and lane changing frequency distribution of 7,824 trips

(a) Travel time **(b) Lane changing frequency**



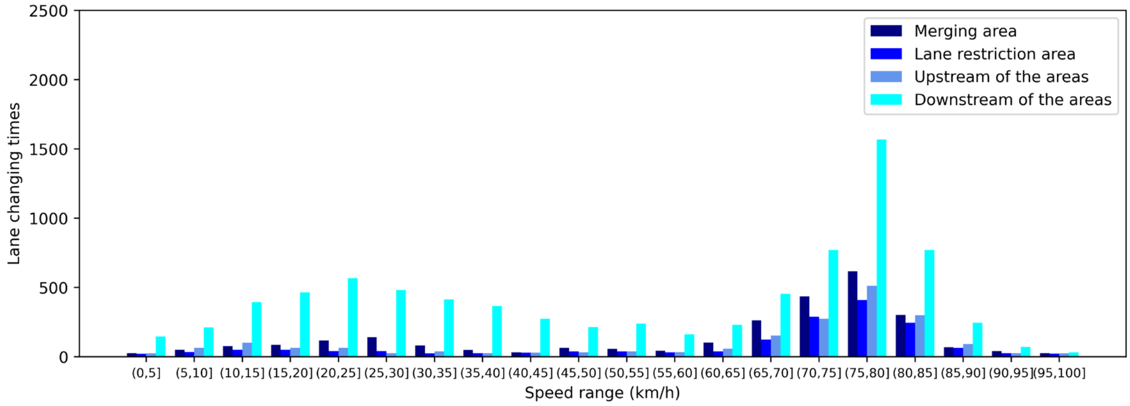
The distribution of travel time is logically right-skewed with a long tail, as indicated by most studies (Gao and Levinson, 2022). This distribution implies that unusually long travel times due to traffic congestion or unexpected delays are rare. High lane changing frequency is also rare. The similarity in probability distribution may suggest a connection between congestion and lane changing. Knoop et al. (2012) indicated that lane changing frequency increases with vehicle density and assumed that the time interval of lane changing occurrence is exponentially distributed, which is the equivalent condition of a Poisson process. In general, there is a positive correlation between lane changing frequency and the extent of congestion, meaning that when lane changing conditions are met, drivers prefer to enhance their driving environment through lane changes.

3. Individual impact of lane changing on speed

In this section, we analyze the changes in driving speed after individuals perform lane changes in different areas of the selected motorway stretch. We extract 15,319 lane changes from the selected 7,824 trips, which occur upstream of the areas (0-0.8 km from the beginning of the section), in the lane restriction area (0.8 km-1.0 km), in the merging area (1.2 km-1.4 km), and downstream of the areas (1.4 km-4.0 km), respectively. The area between the lane restriction area and the merging area is not discussed here because it is short in length and has no special properties.

We categorize these lane changes by driving speeds ranging from 0 km/h to 100 km/h in intervals of 5 km/h. The distribution of the number of lane changing occurrences in different speed ranges of different areas is displayed in Figure 4.

Figure 4: The distribution of the number of lane changing occurrences in different speed ranges of different areas

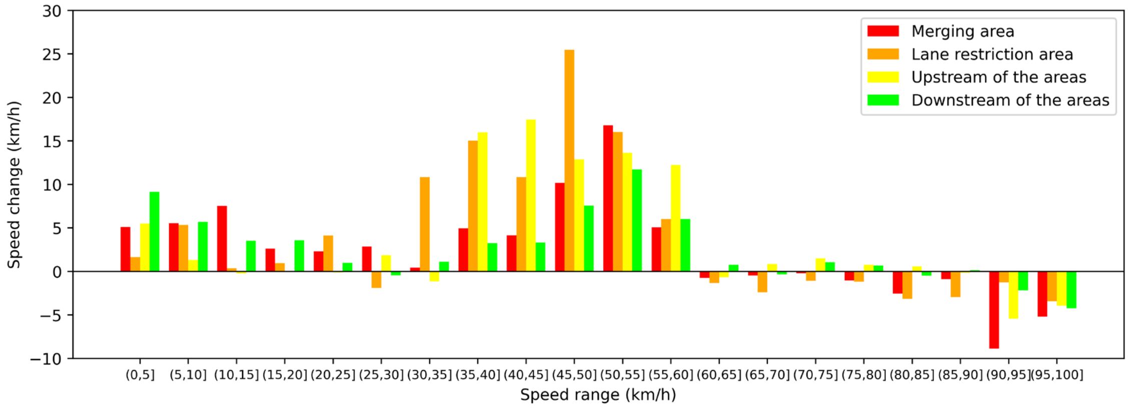


In Figure 4, we observe that for lane restriction, merging, and general areas, lane changing occurrences are concentrated around two speed ranges: 20 km/h to 25 km/h and 75 km/h to 80 km/h. For speed ranges significantly lower than 20 km/h to 25 km/h, severe congestion prevents the necessary vehicle gap conditions for drivers to change lanes, resulting in fewer lane changes within these ranges. For speed ranges much greater than 75 km/h to 80 km/h, drivers are close to free-flow speeds and do not need to change lanes to improve driving conditions, leading to fewer lane changes in these ranges as well.

Additionally, there is a valley between these two speed ranges, around 45 km/h to 50 km/h where lane changing is less common. This phenomenon can be attributed to drivers being in a lane changing dilemma in this speed range. It is unlike the lower speed range on the left side, where drivers are more eager to change lanes to improve driving conditions due to their current dissatisfaction (Ji et al., 2022), nor is it like the higher speed range on the right side, where drivers can easily find vehicle gaps that meet lane changing requirements when traveling at higher speeds with longer headways (Li and Chen, 2017).

As a result, drivers in this speed range are more inclined to maintain their lanes. For various speed ranges in different motorway stretch areas, each contains at least 20 lane changes, with an average of 191 lane changes. We calculate the mean value of speed changes in different speed ranges of different areas. For each lane change, we compute the average speed within 8 seconds before and after the occurrence and obtain the speed change value. The distribution of speed changes in different speed ranges of different areas is shown in Figure 5.

Figure 5: The distribution of the speed changes in different speed ranges of different areas



As shown in Figure 5, the distribution of speed changes can be categorized into three regions. The first region corresponds to speed ranges less than 20 km/h to 25 km/h. After executing lane changes, drivers experience a significant increase in their driving speeds. This is because the vehicles are in a stop-and-go traffic state within these speed ranges (Yeo and Skabardonis, 2009). However, the speed gain is not a sustained benefit.

The second region includes speed ranges near 45 km/h to 50 km/h. In this range, vehicle speeds increase considerably after changing lanes, suggesting that drivers have escaped lanes with more severe congestion. However, when combined with Figure 4, it is evident that the proportion of lane changing in this area is the lowest, indicating that only a small number of lane changing behaviors yield substantial driving condition benefits.

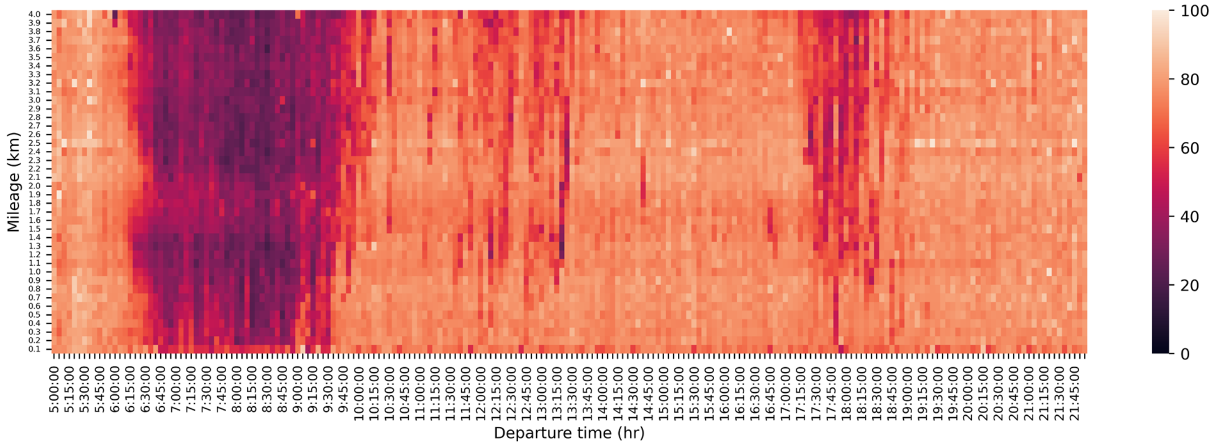
The third region comprises speed ranges greater than 60 km/h to 65 km/h, which account for the largest proportion of lane changing, up to 60%. Within these speed ranges, most lane changing behaviors result in zero or even negative benefits to driving speed, especially when speeds exceed 90 km/h to 95 km/h. This is because in most cases, there are differences in the driving speeds of different lanes (Mehar et al., 2013), and after performing a lane change from the current lane with better driving conditions, it is more likely to change to a lane with poorer driving conditions. Consequently, for individual trips, changing lanes does not bring significant benefits for drivers in most cases.

5. System impact of lane changing on speed

To test the hypothesis that there is a mutually reinforcing relationship between lane changing and congestion from a system perspective, we examine the spatio-temporal distribution of vehicle speed and lane changing rate for the selected 7,824 trips. We select the data from the time period from 5:00 am to 10:00 pm to ensure the reliability of the results across different time intervals due to the number of trips for each departure time interval exceeding 20.

Figures 6 and 7 illustrate the spatio-temporal maps of speed and lane changing rate, respectively. The speed is calculated as the average value of trajectory points for all trips at the corresponding time and spatial intervals, while the lane changing rate is determined by dividing the number of lane changes occurring at the corresponding time and spatial intervals by the total number of trips. The spatial interval is set at 100 meters.

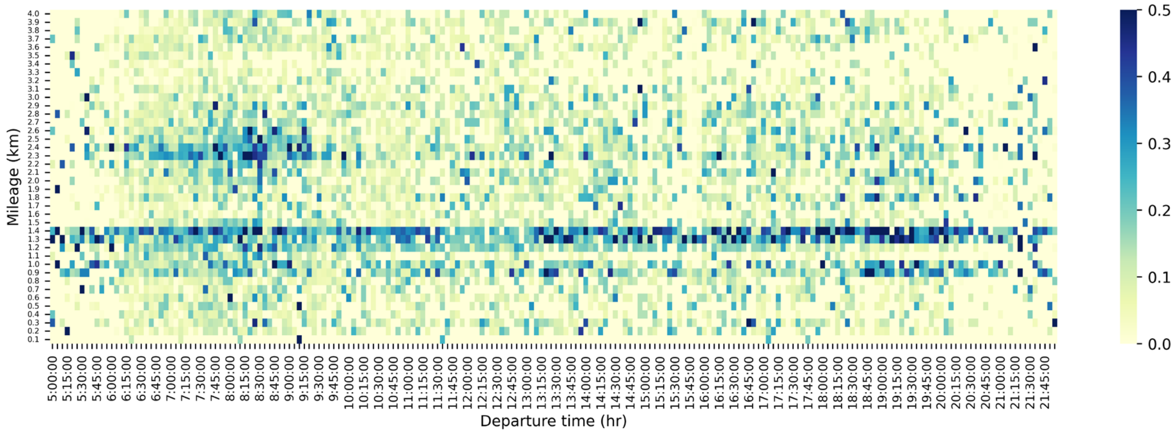
Figure 6: The spatio-temporal map of speed (km/h)



As shown in Figure 6, there are three peak travel periods within the selected timeframe of 5:00 am to 10:00 pm, including the morning peak (6:00 to 10:00), noon peak (11:30 to 13:30), and afternoon peak (17:00 to 19:00), with the morning and afternoon peaks being more pronounced. From Figure 7, we observe that the lane changing rate in special areas is generally higher than that in general areas, particularly during off-peak congestion periods. In lane restriction and merging areas, the lane changing rate is higher during non-peak periods compared to peak periods. In contrast, general areas exhibit the opposite trend.

This implies that during off-peak congestion periods, drivers intentionally change lanes in special areas in accordance with traffic rules, as vehicle gaps that meet lane changing conditions are more easily available. However, during peak congestion periods, decreased speed and vehicle gaps make it more difficult to meet lane changing conditions, resulting in a reduced lane changing rate. In general areas, drivers change lanes due to speed disturbances, leading to higher lane changing rates during peak congestion periods compared to off-peak periods. This finding aligns with previous empirical studies examining the relationship between lane changing rate and density at non-merging and merging sites (Knoop et al., 2012).

Figure 7: The spatio-temporal map of lane change rate



Building on results shown above, we conduct a Granger causality test (Granger, 1969) on speed (V) and lane changing rate (C) over time. According to Granger causality test results, we observe that an increase in lane changing rate results in a decrease in speed for all areas during both peak and off-peak periods. Additionally, during both peak and off-peak periods, a decrease in speed also contributes to an increase in lane changing rate for all areas.

This relationship is more substantial in general areas. Consequently, from a systems perspective, there is a bi-directional causal relationship between speed and lane changing rate in most situations, which supports our earlier hypothesis of a mutually reinforcing relationship between these two factors.

During more congested peak periods and in more prevalent general areas, the decline in driving speed due to congestion and speed disturbances increases the likelihood of drivers engaging in lane changes. In turn, a higher lane changing rate interrupts traffic flow and slows down vehicles in the vicinity of the lane change, perpetuating the overall speed degradation.

This insight informs congestion management policies, suggesting that general areas during peak congestion should discourage lane changes. By doing so, the mutually reinforcement leading to continuous deterioration of driving conditions may be mitigated, ultimately improving overall motorway performance.

Combined with insights from Section 4, future research could employ modeling and simulation techniques to offer detailed guidance on lane change penalties, tailored to specific speed ranges, time periods, and areas, in order to reduce the frequency of lane changes. The comparison of the simulation results of traditional lane-changing models with the empirical results presented in this paper will be very interesting, and we believe, can be tested in future research.

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