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DRIVING BEHAVIOUR AT MOTORWAY RAMPS AND WEAVING SEGMENTS BASED ON EMPIRICAL TRAJECTORY DATA

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ABSTRACT
In the vicinity of ramps, drivers make route choices, change lanes and in most cases also adjust their speeds. This can trigger anticipatory behaviour by the surrounding vehicles, which are also reflected in lane changes and/or changes in speed. This phenomenon is called turbulence and is widely recognised by the scientific literature and various design guidelines. However the knowledge about the characteristics of turbulence is limited. This study investigates the microscopic characteristics of driving behaviour around 14 different on-ramps (3), off-ramps (3) and weaving segments (8) in The Netherlands, based on unique empirical trajectory data collected from a video camera mounted underneath a hovering helicopter. The data analysis reveals that lane changes caused by merging and diverging vehicles create most turbulence, that an increase in the amount of traffic results in a higher level of turbulence and that an increase in the available length for merging and diverging results in a lower level of turbulence. The results of this study are useful for improving the road design guidelines and for modelling driving behaviour more realistically.

keywords: turbulence, microscopic, empirical, on-ramp, off-ramp, weaving

1. INTRODUCTION

In the vicinity of motorway ramps, multiple manoeuvres are performed by drivers who enter the motorway, who exit the motorway, or who cooperate or anticipate on entering or exiting vehicles. These manoeuvres involve lane changes, changes in speed, and changes in headways. This results in changes in lane flow distribution (Knoop et al. 2010; Van Beinum et al. 2017), greater speed variability and changes in headway distribution of the different lanes, with presumably a greater share of small gaps on the outside lane. In the literature and in motorway design guidelines, this phenomenon is referred to as turbulence. According to the Highway Capacity Manual (HCM 2010) turbulence is always present in traffic. A raised level of turbulence is expected around motorway ramps (Van Beinum et al. 2016; HCM 2010) and has a negative influence on the motorway's capacity and traffic safety (Abdel-Aty et al. 2005; Golob et al. 2004; HCM 2010; Kondyli and Elefteriadou 2012; Lee et al. 2003b, 2003a; Chen and Ahn 2018). In free flow conditions the level of turbulence is expected to increase a few hundred meters upstream of a ramp and to dissolve a few hundred meters downstream of the ramp (Van Beinum et al. 2016). This concept is shown in the theoretical framework in FIGURE 1.

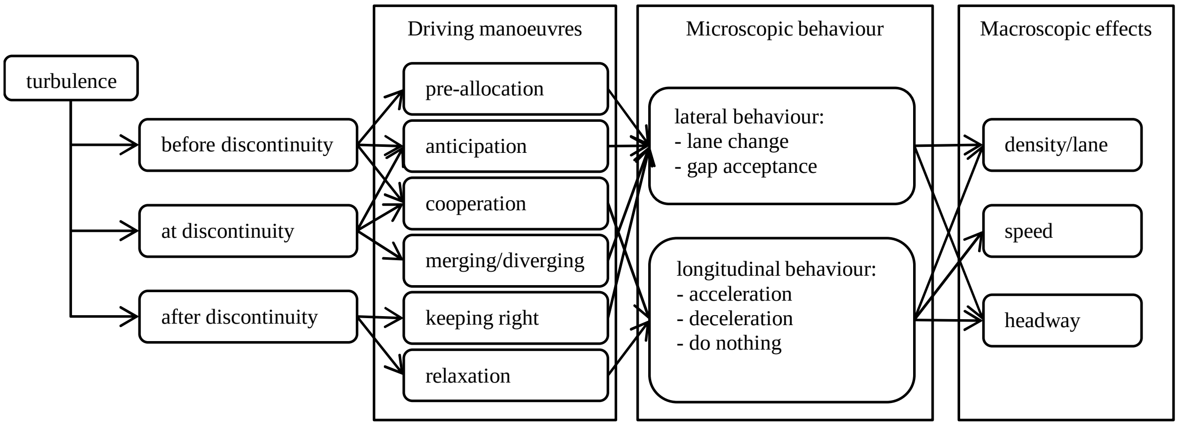

FIGURE 1: Theoretical framework for turbulence (Van Beinum et al. 2016).

Both literature and freeway design guidelines agree that the level of turbulence is influenced by road design, traffic volume, and driver behavior. Several researchers have tried to assess the impacts of different manoeuvres on traffic safety and traffic operations and the influence of design characteristics on these aspects. An overview of these studies is given in (Van Beinum et al. 2016). The available research on the characteristics of turbulence is limited and different values for the location where turbulence starts and ends are found in different studies (HCM 2010; Kondyli and Elefteriadou 2012; Van Beinum et al. 2017). Also the available research regarding the microscopic characteristics of the different manoeuvres is limited. To gain a better understanding of the different manoeuvres that contribute to turbulence more research is needed, preferably based on empirical data. Following this, the main research questions of this study are:

- How and to what extent do the different manoeuvers contribute to the raised level of turbulence?
- How is the raised level of turbulence affected by the amount of traffic and the motorway's design characteristics?
- Where does the raised level of turbulence start and end?

To answer these questions, the driving behaviour of the vehicles that perform the different manoeuvres was studied. For this study we have collected empirical trajectory data of individual vehicles at 14 different on-ramps (3), off-ramps (3) and weaving sections (8) in The

Netherlands. The data was collected under free flow conditions, using a video camera mounted under a hovering helicopter.

The insights from this research can be used to improve microscopic simulation models and motorway design guidelines (Marczak et al. 2014; Daamen et al. 2010; Schakel et al. 2012; Hill et al. 2015; Marczak and Buisson 2014).
This paper is structured as follows: Section 2 gives a summary of the currently available knowledge in the literature regarding turbulence related driving behaviours; Section 3 presents the method used to answer the research questions; Section 4 presents the results of the performed analysis; and Section 5 and 6 discuss and summarize the conclusions arising from the analysis.

2. LITERATURE REVIEW

The goal of the literature review is to summarize the available knowledge regarding turbulence related driving manoeuvres around ramps and their impact on microscopic behaviour, corresponding to the theoretical framework as shown in FIGURE 1. To this end, the literature study is structured as follows: first the different manoeuvres that contribute to turbulence are discussed in more detail, followed by the manoeuvre's microscopic aspects in terms of lateral and longitudinal behaviour. This section concludes by discussing the length of the ramp influence area on turbulence.

2.1. Manoeuvres

According to the theoretical framework displayed in FIGURE 1, different manoeuvres are related to motorway turbulence. These different manoeuvres are graphically explained in FIGURE 2.

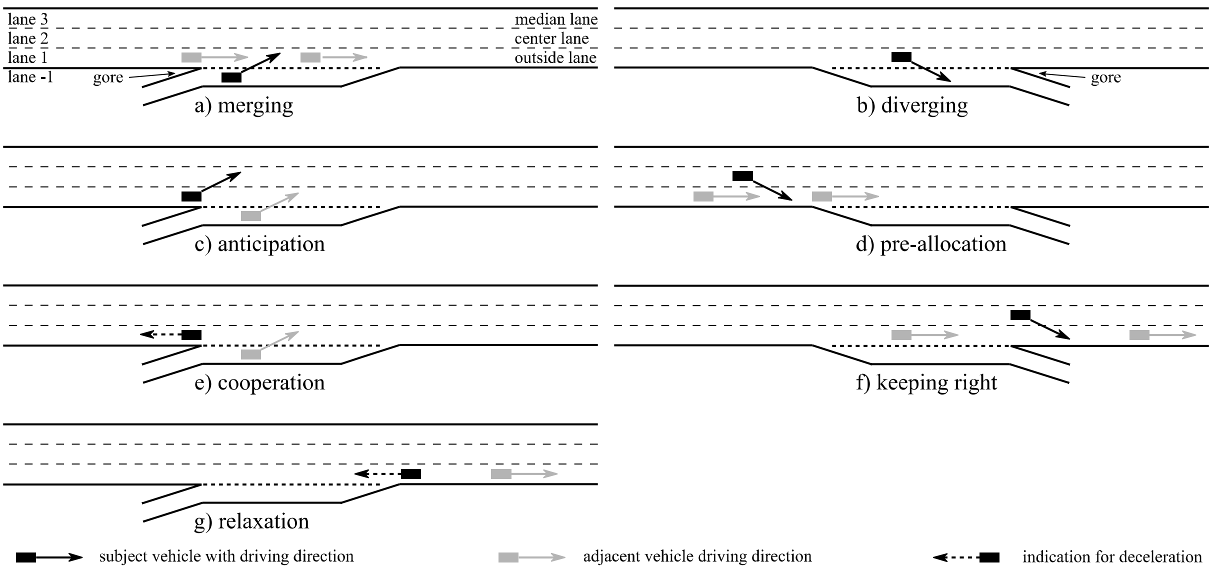

FIGURE 2: Type of manoeuvres around discontinuities.

A merge is performed by a vehicle that drives on the acceleration lane and changes lanes to enter the motorway. Studies on merging in the past 10 years show that merging is a complex combination of merging plan choice, gap acceptance, target gap selection, and acceleration decisions (Choudhury et al. 2009). Merging is also regarded to be a major cause for capacity drops at on-ramps (Leclercq et al. 2016; Chen and Ahn 2018). Furthermore, a substantial proportion of crashes on motorways occur in the vicinity of ramps (Lee and Abdel-Aty 2008, 2009). Many researchers have studied the mechanisms of merging behaviour. Daamen et al. (2010) studied empirical trajectory data and found that at free flow most of the lane changes take place in the first half of the acceleration lane. Calvi and De Blasiis (2011) used a driving simulator and found that the merging length (distance between where a lane change starts and where it ends) increases as the traffic volume increases. The length of the acceleration lane did not show a significant effect on driving behaviour (Calvi and De Blasiis 2011).

A diverging manoeuvre is performed by a vehicle driving on the outside lane and changes lanes to the deceleration lane to exit the motorway. This manoeuvre takes place at off-ramps and weaving segments. Muñoz and Daganzo (2002) found that motorway capacity decreases when more vehicles take the exit. They used empirical loop detector data from a US freeway. Martínez et al. (2011) studied video records and found that the speed on exit lanes is 20km/h lower than on the through going main lanes. El-Basha et al. (2007) used a radar to measure speeds and found that exiting traffic also has a negative effect on the speed of through going traffic. Ahn et al. (2010) studied empirical loop detector data from different off-ramps and found that diverging traffic causes lane-changing manoeuvres which result in deviations in flow compared to the average flow over a longer period of time.

Anticipation is performed when a driver changes lanes towards the median lane to make way for a lane changing vehicle (Kita 1999; Schakel et al. 2012; Cassidy and Rudjanakanoknad 2005). In literature this type of lane change is also referred to as a courtesy lane change. Zheng et al. (2011) studied NGSIM data (NGSIM 2015) and showed that a lane change, for example due to merging, is a primary trigger for additional lane changes by adjacent vehicles. In this way initial lane changes are found to be responsible for transforming a small raised level of turbulence to substantial turbulence. To the best of our knowledge no other empirical studies regarding anticipation are available.

Pre-allocation is performed by drivers who want to take the next motorway exit and pre-position themselves upstream of the off-ramp by changing lanes towards the outside lane (Toledo et al. 2009; Choudhury 2007). In (Van Beinum et al. 2017) we studied empirical loop detector data from several motorway off-ramps in The Netherlands and found that the lane flow distribution starts to change at about 1,000 m upstream of the off-ramp gore. This change was attributed to pre-allocation and coincides with the location of route signs along the motorway (which are positioned at 1,200 m and 600 m upstream of an off-ramp). To the best of our knowledge no other empirical studies are available that focus on the characteristics of pre-allocation.

In The Netherlands drivers are bound to the right side rule by which they are obliged to change lanes to the outside lane when there is sufficient space to do so (RVV 1990). Overtaking takes place on the inside of the motorway. This will naturally result in situations where faster vehicles drive on the inside lanes and slower vehicles drive on the outside lanes of the motorway (Daganzo 2002). To the best of our knowledge no empirical studies are available which focus on the implications of keeping right.

A vehicle cooperates when it increases its headway to provide a larger gap for a vehicle that wants to change lanes in front (Kim and Coifman 2013; Choudhury et al. 2009; Hidas 2005). Choudhury et al. (2009) proposed a model which takes lane changing under cooperation into account. The authors used NGSIM data (NGSIM 2015) to validate this model. Although this study showed promising results, further research was recommended to validate the transferability of the model in different traffic states, ranging from very congested to free flow (Choudhury et al. 2009). Zheng et al. (2013) used the same NGSIM trajectory data to calibrate cooperation in the model by Laval and Leclercq (2008). This model was later reformulated and calibrated by Duret et al. (2011), who used the model as a method to systematically identify the impact of cooperation on lane changes. Hill et al. (2015) studied freeway lane change behaviour using trajectory data from an instrumented vehicle and found that drivers are willing to cooperate with merging vehicles. The authors speculate that the same holds true

for all lane changing vehicles in uncongested conditions but the results were inconclusive. It was recommended to analyse more data during uncongested conditions.
At ramps vehicles are willing to accept very short headways as they enter or exit the motorway. After the merge the driver will increase its headway to more comfortable values further downstream. This phenomenon is called relaxation (Schakel et al. 2012; Laval and Leclercq 2008; Laval and Daganzo 2006; Duret et al. 2011). Daamen et al. (2010) studied trajectory data from several on-ramps in The Netherlands and observed very short net headways which increase over time. The authors related this to relaxation behavior. Duret et al. (2011) studied the NGSIM trajectory data and found that after 15 seconds of relaxation an equilibrium was reached. However, due to inferior results, further research on mandatory lane changes in the outside lane was recommended by the authors. Schakel et al. (2012) proposed a lane change model (LMRS) which incorporates relaxation. The model was calibrated using empirical loop detector data from a Dutch two-lane motorway and was proven to be accurate for free flow conditions. The authors recommended that future research should incorporate other locations with different speed limits and more lanes (Schakel et al. 2012).

2.2. Mandatory and discretionary lane changes

Merging, diverging, pre-allocating, anticipating and keeping right require lane changes and gap acceptance. In the literature distinction is made between mandatory lane changes (MLC) and discretionary lane changes (DLC) (Minderhoud 1999; Laval and Daganzo 2006; Kesting et al. 2007; Choudhury 2007; Yang and Koutsopoulos 1996; Hill et al. 2015; Pan et al. 2016). A MLC is executed when a driver must change lane due to a strategic route choice. A DLC occurs when a driver seeks for better driving conditions, such as to gain speed (or travel time) advantage. A MLC is expected to be performed in a shorter period of time and with smaller accepted gaps than a DLC (Kusuma et al. 2015). In a field test wherein different participants drove an instrumented vehicle it was found that lane change durations of DLC to the right and to the left do not differ significantly. Also, no significant difference was found between average MLC (merging manoeuvres were excluded) and DLC durations. The authors however recommend to further verify the results using an enriched dataset. Drivers who perform a MLC are willing to accept small gaps and new followers are willing to accept small headways (Schakel et al. 2012; Laval and Leclercq 2008; Laval and Daganzo 2006; Duret et al. 2011; Daamen et al. 2010). This will result in shifting the headway distribution to the left.

2.3. Utilization of the weaving segment length

A weaving segment is a motorway discontinuity where an auxiliary lane connects a merge segment (on-ramp) and a diverge segment (off-ramp) (HCM 2010). Marczak et al. (2014) analysed empirical trajectory data from an urban motorway weaving segment in Grenoble, France. They found that in free flow conditions only 60% of the total weaving segment length is used for weaving, which leaves 40% of its length unused. They also found that vehicles changing lane from the acceleration/deceleration lane to the main road accept smaller gaps than vehicles changing lane from the main road to the acceleration/deceleration lane. In the discussion the authors state that the length of a weaving segment might not be of significant relevance for estimating the capacity. However, their results were not compared to weaving segments with different lengths. Kusuma et al. (2015) studied trajectory data from video recordings together with traffic flows and speed from loop detectors in the UK and found that 91% of the traffic decelerates at the beginning of weaving segment to cooperate with the merging and diverging traffic, 48% of the lane changing vehicles change lanes in the first 25% of the weaving segment.

2.4. Increased level of turbulence upstream and downstream of the ramp

The literature and design guidelines agree that upstream and downstream of a ramp a raised level of turbulence is present. This area is referred to as the ramp influence area (HCM 2010) and determines the required ramp spacing to avoid traffic operations and traffic safety disturbances. It has been shown that the level of turbulence is expected to increase upstream and to decrease downstream of a ramp. There is however no consistency when it comes to the length of this influence area (Van Beinum et al. 2016). To the best of our knowledge there are only two empirical studies available which indicate the boundaries of the ramp influence area. Kondyli and Elefteriadou (2012) studied instrumented vehicle observations and found that the ramp influence area starts at 110 m upstream and ends at 260 m downstream of the gore of a ramp. (Van Beinum et al. 2017) studied loop detector data from multiple ramps and found that the ramp influence area starts at 200 m (on-ramp) or 900 m (off-ramp) upstream and ends at 900 m (on-ramp) downstream of the ramp gore. it was recommended that in future research the turbulence influence length should be studied using empirical trajectory data of individual vehicles.

2.5. Research gaps

Several research gaps were identified in the literature:

- No studies consider the relation between all the turbulence related manoeuvres. There are several studies available which consider one or more manoeuvres but, to the best of our knowledge, there is no literature available which considers all manoeuvres simultaneously. For all the different manoeuvres only the characteristics of merging, diverging and lane changing are well described in literature. The characteristics and mechanisms of pre-allocation, cooperation, anticipation, keep-right and relaxation are yet not well understood, as well as the cohesion between the different manoeuvres. Such understanding is necessary for modelling vehicle interactions realistically.
- There is a debate on weaving segment length. According to the motorway design guidelines the level of turbulence is expected to be dependent on the available length for merging (HCM 2010; Rijkswaterstaat 2017) but empirical studies suggest that the length of a weaving segment might not have a significant influence on road capacity, due to an inefficient use of the total weaving segment length (Marczak et al. 2014). This seems contradicting and requires further research.
- Currently available empirical studies have limitations regarding the available data. Instrumented vehicle studies suffer from a limited number of participants and therefore also limited validity (Hill et al. 2015). Studies using loop detector data fail to capture the behavioural characteristics of drivers at an individual level (e.g. location and duration of lane changes) (Schakel et al. 2012; Van Beinum et al. 2016). The currently available trajectory data captures only a limited length of a motorway (Daamen et al. 2010), and is only available for a limited number of locations with limited range of characteristics, such as available length for lane changes, amount of traffic, legal speed limits and amount of heavy vehicles (e.g. trucks) (Marczak et al. 2014; Duret et al. 2011; NGSIM 2015).

3. METHOD

In this study we have analysed driving behaviour during the different manoeuvres which are related to turbulence. Empirical microscopic data, describing the position (x, y, t) of every vehicle at every time step (trajectories of each individual vehicle) was collected and used for analysis. The different manoeuvres were identified from the data and were assessed on microscopic behaviour.

3.1. Data collection

Empirical trajectory data from 14 sites in the Netherlands were used for analysis. The trajectories were collected using a camera mounted underneath a hoovering helicopter, comparable to the method described in (Hoogendoorn et al. 2003), but using a 5120 x 3840 pixel camera and a 15mm Zeiss lens, which enabled us to capture a road stretch of approximately 1,200m - 1,500m from an altitude of approximately 500m. The images were corrected to compensate for the radial distortion that manifests in form of the “barrel” or “fish-eye” effect. The intrinsic characteristics of the lens were calibrated using a method comparable to OpenCV (OpenCV 2018). The image positions in pixels were converted to accurate world positions in meters by relating recognisable objects in the captured images to their locations in Google Maps. The measurements were taken on the 6th of June and the 7th of July 2016, under sunny weather conditions, between 14:00 and 17:00 hours (which is the build up towards the evening peak hour), under free flow conditions, for 30 minutes at each site. The distance of 1,200m - 1,500m coincides with the findings from our earlier study (Van Beinum et al. 2017), where we found that an increased level of turbulence at on-ramps starts at approximately 200m upstream of the ramp gore and ends approximately 900m downstream of the ramp gore. At off-ramps these values are respectively 1,000 m upstream of the ramp gore and approximately 600m downstream of the ramp gore.
The sites were selected by the following criteria: for an on-ramp: no other discontinuity exists within a range of 1,000m upstream and 3,000m downstream; for an off-ramp no other discontinuity exists within a range of 3,000m upstream and 1,000m downstream; and weaving segment length should be between 500m (minimum length according to the Dutch design guidelines (Rijkswaterstaat 2017)) and about 1,200m, so the total length can be measured by the helicopter camera. The following additional characteristics were desired: a) number of through lanes (2 and 3); b) variability in the amount of trucks; c) variability in the traffic flow, and d) legal speed limit (100km/h and 130km/h). An overview of the different sites with their characteristics is given in TABLE 1.

TABLE 1 Site Characteristics

Road	Site name GPS coordinates	type	Config.	length* [m]	speed limit [km/h]	number of vehicles through flow	 F/C	 on	 off	 on/off	number of trucks
A13	Delft 52.014718, 4.373768	off-ramp	3+1	250	100	2.569	0.78	-	270	-	123
A59	Terheijden 51.655155, 4.750176	off-ramp	2+1	250	130	1.599	0.57	-	150	-	200
A16	Zonzeel 51.639134, 4.697074	off-ramp	3+1	210	130	1.943	0.69	-	395	-	444
A13	Delft 52.014498, 4.374516	on-ramp	3+1	300	100	2.654	0.81	323	-	-	168
A59	Terheijden 51.655327, 4.750221	on-ramp	2+1	320	130	1.422	0.51	88	-	-	109
A16	Zonzeel-north 51.651250, 4.688500	on-ramp	3+1	340	130	1.679	0.58	221	-	-	508
A4	Bergen op Zoom-east 51.501793, 4.313943	weaving	2+1	500	120	1.582	0.35	147	148	494	163
A4	Bergen op Zoom-west 51.502537, 4.313162	weaving	2+1	400	120	1.434	0.55	142	85	356	118
A59	Klaverpolder-north 51.696689, 4.645896	weaving	2+1	600	130	1.239	0.55	205	73	33	154
A59	Klaverpolder-south 51.695868, 4.645407	weaving	2+1	500	130	1.760	0.74	131	446	89	274
A16	Princeville-east 51.576286, 4.727040	weaving	3+1	1.000	130	2.396	0.58	107	316	518	629
A16	Princeville-west 51.576906, 4.726322	weaving	3+1	1.100	130	2.082	0.52	272	160	325	410
A15	Ridderkerk-north 51.856599, 4.621377	weaving	3+1	700	130	2.158	0.61	122	110	152	446
A15	Ridderkerk-south 51.856330, 4.620257	weaving	3+1	1000	130	2.868	0.78	107	186	309	555

* Length of acceleration lane (on-ramp), deceleration lane (off-ramp) or weaving segment

3.2. Processing raw data

The trajectory data originates from video footage (12 fps), which were processed with automated vehicle recognition software to *x*, *y*, *t* - coordinates, which represent the centre of the vehicle at a specific time. The raw data was processed to reduce the noise due to measurement errors and inaccuracies. FIGURE 3(a) shows 4 different issues in the data that were encountered. The automatic vehicle recognition and vehicle following software sometimes loses track of the vehicle due to objects overhead (e.g. a viaduct). When the vehicle is recognized again, it was sometimes recognized as a new vehicle (issue 1), as a different, wrong, vehicle (issue 3) or as the same, correct, vehicle further downstream (issue 4). Also unrealistic x- and -y values were measured (issue 2). These unrealistic values are caused by shadows besides the vehicle, that were sometimes recognized as part of the vehicle, or by vehicles driving closely next to each other that were recognized as one vehicle.
These issues in the data where repaired as follows. First unrealistic x- and y-values were filtered from the dataset. Unrealistic x-values are values where vehicles are moving backwards and unrealistic y-values are the outliers. This solves issue 2. Also overlapping x and y-values for equal time entries were removed. After the filtering process all trajectories where cut into parts. Cuts were applied when the trajectory data has a gap. This solves issue 3. After cutting, the trajectories were merged again by using an iterative search process. Two trajectories were merged into one when 1) the trajectory to merge with, starts at a short distance from where the subject trajectory ends and 2) when the speed difference between the end of the subject trajectory and the start of the potential trajectory is small. This search is repeated for increasing distances and for increasing speed differences. This solves issue 1 and 4. Finally all missing data points in the trajectories were interpolated and the trajectories were smoothed using a polynomial regression filter (Toledo et al. 2007). FIGURE 3(b) shows the trajectories after processing.

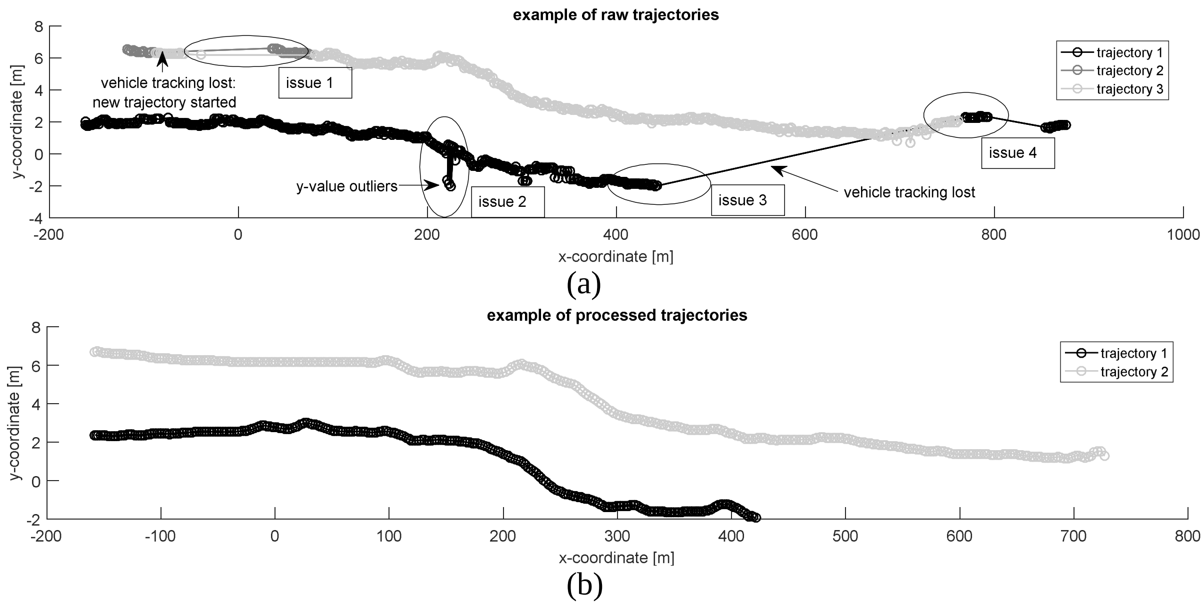

FIGURE 3: Example of raw (a) and processed trajectories (b).

3.3. Identification of manoeuvres

The different manoeuvres were identified in the dataset by using the criteria shown in TABLE 2. For each individual vehicle that performs a specific manoeuvre, microscopic characteristics were stored in a database for further analysis, being: lane change location, lane change direction, accepted gap, headway and speed.

TABLE 2 Manoeuvre Identification Criteria

manoeuvre	origin	destination	lane change	location of manoeuvre	extra criteria
merging	lane -1*	lane 1	to inside	at acceleration lane	only entering traffic
diverging	lane 1	lane -1	to outside	at deceleration lane	only exiting traffic
pre-allocating	lane 2, 3	lane 1	to outside	upstream of off-ramp	only exiting traffic
cooperation	lane 1	lane 1	none	upstream and at ramp	cooperating vehicle has same leader in a 10 seconds period before a merging or pre-allocating vehicle moves in front
anticipation	lane 1	lane 2, 3	to inside	upstream and at ramp	merging or pre-allocating vehicle in front
relaxation	lane 1	lane 1	none	downstream of on-ramp	1) only entering traffic 2) vehicle has same leader in a 10 seconds period after it has merged
keeping right	lane 2, 3	lane 1,2	to outside	whole segment	-

* The lane coding correspondents with the lane coding in FIGURE 2.

Not all lane changes towards the left could be categorized to a specific manoeuvre class. For example a lane change where a vehicle overtakes another vehicle to improve its driving conditions, without being triggered by a merging or pre-allocation vehicle that moves in front. These lane changes were labelled as other (left).

3.4. Data analysis

The location and intensity of lane changes were investigated for merging, diverging, pre-allocation, anticipation, keeping right and other (left). To do so the number of lane changes where determined for 25 m bins.

Merging and diverging only takes place at the acceleration and deceleration lane. Some entering vehicles make additional lane changes to the inside of the motorway. These are labelled as secondary merges. Secondary merges take place downstream of the ramp and contribute directly to the increased level of turbulence that is caused by entering traffic. However, the further downstream of the ramp a merged vehicle will get, the less a secondary merge is related to the primary merge and the more it will be related to a discretionary lane change to improve driving conditions. For the analysis we assume that lane changes related to secondary merges no longer contribute to the raised level of turbulence when the intensity of secondary merges gets below 2 lane changes per 25m.
Pre-allocation takes place upstream of the ramp and is expected to be influenced by the position of routing signs, which are placed at 1.200m and 600m upstream of the studied ramps. The remaining pre-allocating lane changes are expected to take place just prior to the ramp.
For lane changes that involve keeping right and lane changes towards the inside (left side) of the motorway, which could not be attributed to a specific manoeuvre, it was assumed that these are always present in the traffic stream and are not directly caused by entering or exiting traffic. However, these lane changes can be triggered by entering or exiting traffic. For these lane changes the average intensity outside the ramp influence area is of interest. For the analysis the ramp influence area was, for practical reasons, assumed to be restricted to an area that starts 200m upstream of the start of the ramp and ends 200m downstream of the end of the ramp. The average number of lane changes outside the influence area was used to identify the locations where the number of lane changes is above average. An overview of the aspects that were analysed for each manoeuvre is given in TABLE 3.

Both traffic flow and the available length for changing lanes are expected to have an impact on: 1) lane change location and intensity, 2) the size of accepted gaps for MLC and DLC and 3) the need for anticipation, cooperation and relaxation. The impact of the available length for lane changes was studied by comparing results from different weaving segments with different lengths. The impact of traffic flow was studied by comparing the results of different on-ramps, off-ramps and weaving segments with different flows.

Cooperation and anticipation were studied by comparing the headway and speed that were measured prior to the manoeuvre and after the manoeuvre. The following moments were chosen: 1) for cooperation at 10 s before the moment a vehicle merges and at the moment of the merge and 2) for relaxation at the moment of merging and 10 s after the merge. For relaxation only the on-ramp data was studied, because relaxation is expected most at locations where vehicles merge. For cooperation also the influence of weaving segment length was studied. The 10s period was chosen based on the area that is covered by the video images. This ranges from approximately 300 m upstream of the gore to approximately 600 m downstream of the gore. When assuming that merging vehicles change lanes near the gore and drive with a speed of approximately 30 m/s (108 km/h), it is possible to investigate headways in a period of 10 s before the merging area until 20 s after the merge area.

TABLE 3 Overview of analysis

Analysis	aspect	type of ramp
Location and frequency of lane changes		
merge and diverge	location where lane changes take place	on-ramp off-ramp
	the percentage of total number of LC that involve merging or diverging	
Pre-allocation	percentage of diverging vehicles that pre-allocate	off-ramp
	percentage of diverging vehicles that pre-allocate at 600m upstream, where the road sign is.	
	percentage of diverging traffic that is already driving on the outside lane at the beginning of the measured area	
anticipation	anticipation as percentage of total number of LC	on-ramp
	location of first anticipation LC	
secondary merge	percentage of merging vehicles that are secondary merges	on-ramp
	location where intensity of LC gets below 2LC/25m	
keep right and uncategorised left	average intensity of LC outside ramp area	on-ramp off-ramp
	location where intensity of LC gets above average intensity of LC upstream of ramp	
	location where intensity of LC gets below average intensity of LC down-stream of ramp	
Impact of weaving segment length and traffic flow		
merge and diverge	cumulative distribution of number of LC over the total available length for merging and diverging for different weavings segment lengths and different traffic flows	on-ramp off-ramp weaving segment
cooperation	difference in headway and speed distribution between the moment a vehicle changes lanes in front and becomes a new leader, and 10 seconds before that LC	on-ramp weaving segment
relaxation	difference in headway and speed distribution between the moment the subject vehicle merges and 10 seconds after that merge	on-ramp
difference between MLC and DLC for merge, secondary merge, di-verge, keep right	distribution of accepted gaps for different	on-ramp off-ramp weaving segment

4. RESULTS

The goal of this section is to present the analysis results that are used to answer the research questions. To this end this section is structured as follows: In the first part the results regarding the contribution of the different manoeuvers to a raised level of turbulence and the location where the raised level of turbulence starts and ends are shown in terms of location and frequency of lane changes. In the second part the results regarding the impact of the amount of traffic and the motorway's design on the level of turbulence are shown in terms of utilization of the available length for merging and diverging and gap acceptance.

4.1. Location and frequency of lane changes

The lane change locations and number of lane changes are displayed in FIGURE 4. The results if the analysis are summarised in TABLE 4.

The results show that the majority of the lane changes occur at the acceleration lane or deceleration lane. This effect is stronger for off-ramps than for on-ramps, which indicates that the ramp influence area for on-ramps is larger than for off-ramps. Of all the merging vehicles about a third of the vehicles make additional lane changes towards the left (secondary merges). The location where the intensity of secondary merges is reduced to an intensity of less than 2 lane changes per 25 m appears to be related to the traffic flow. The location with the highest flow (Delft) gives the longest distance (575m).

Most of the diverging vehicles change lanes directly after the start of the deceleration lane. On average 96% of the vehicles change lanes in the first half of the deceleration lane. Diverging vehicles appear to pre-allocate at a relatively long distance upstream of the off-ramp. More than 85% of the diverging vehicles are already driving on the outside lane at when entering the measured area. At the off-ramp of Terheijden an increased number of pre-allocation lane changes is found at 600m upstream of the off-ramp gore. In total 6% of the diverging vehicles pre-allocate at this position. A second location with an increased number of pre-allocation related lane changes is found at 400m upstream of the gore (Zonzeel).

The first lane change identified as anticipation was recorded at 100m upstream of the on-ramp and on average 4% of all lane changes was identified as anticipation. The lane change location seems not to be effected by traffic flow.

Lane changes identified as keeping right and uncategorised lane changes to the left are present over the whole length of the measured motorway segments. Outside the assumed 200m ramp influence area the average number of keep right lane changes are relatively constant. However, the average is a little lower for the site with a low traffic flow (Terheijden). The amount of keeping right related lane changes increases within the ramp influence area. This is especially the case for the off-ramps. The number of keeping right lane changes seems to be related to the number of exiting vehicles: a higher number of exiting vehicles corresponds to a higher number of keeping right lane changes. The distance over which the average number of keeping right lane changes is above average, is relatively constant for on-ramps and off-ramps but its location differs. At on-ramps the area with an increased average is measured further downstream than at off-ramps. The same holds for the uncategorised lane changes to the left. Again the distance over which average number of lane changes is increased is comparable for on-ramps and off-ramps but the locations differs. For on-ramps the area is measured further downstream than for off-ramps.

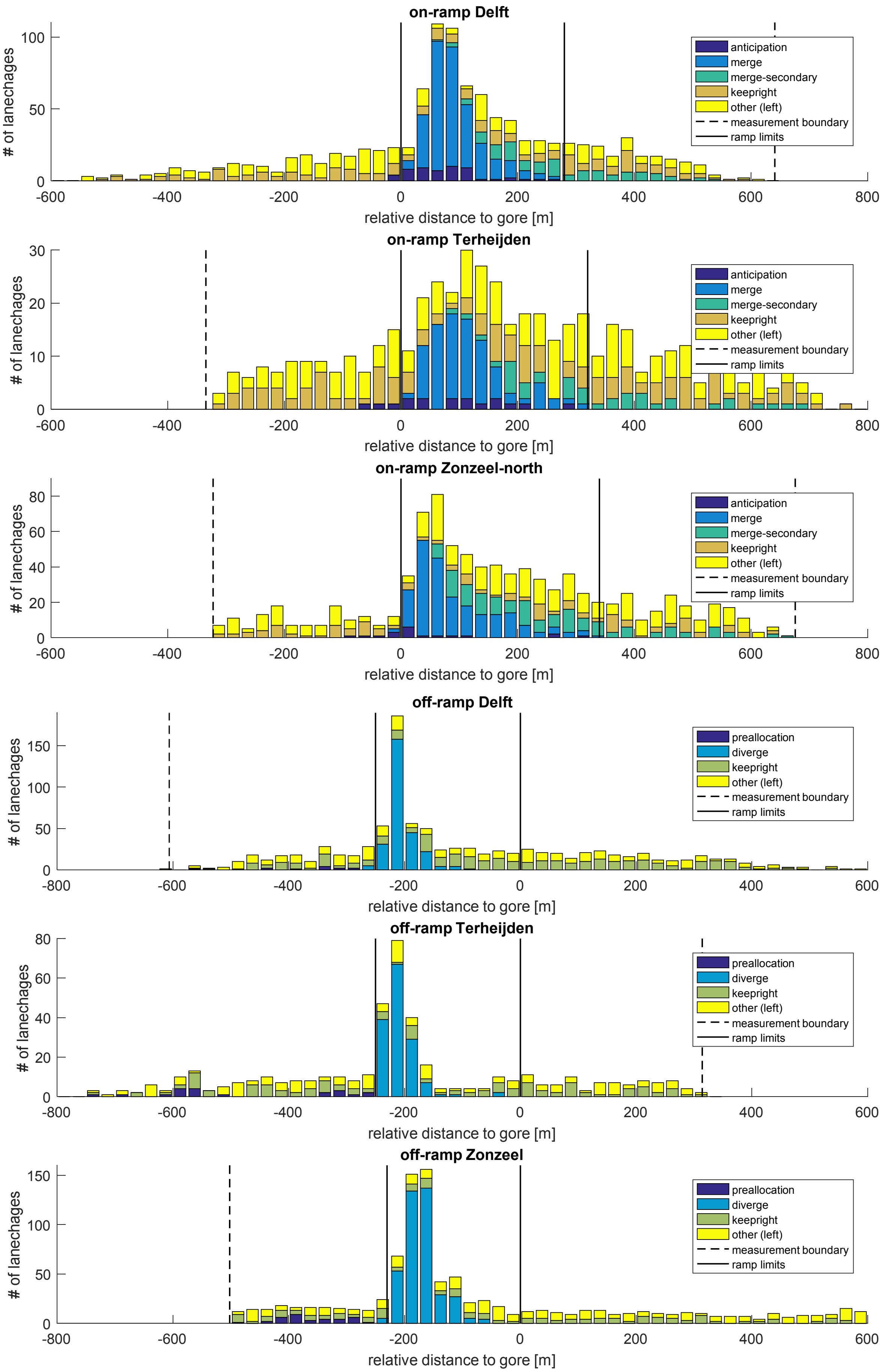

FIGURE 4: Lane change locations near on-ramps and off-ramps.

TABLE 4 Analysis results of lane change location and intensity

	on-ramp			off-ramp		
	Delft	**Terheijden**	**Zonzeel**	**Delft**	**Terheijden**	**Zonzeel**
Flow/Capacity ratio	0.81	0.51	0.58	0.78	0.57	0.69
merge as percentage of total number of LC	55%	33%	41%	-	-	-
percentage merges which are secondary merges	26%	32%	41%	-	-	-
downstream location where number of sec. merge < 2 LC/25m	475m	425m	575m	-	-	-
diverge as percentage of total number of LC	-	-	-	47%	61%	58%
percentage of diverging veh. that are already in lane 1 at start	-	-	-	96%	86%	91%
percentage of diverging veh. which pre-allocate at -600m	-	-	-	-	6%	-
anticipation as percentage of total number of LC	9%	6%	4%	-	-	-
location of first anticipation LC	-25m	-75m	-100m	-	-	-
Average number of keep right LC/25m outside 200m zone	3.0	2.9	3.2	2.9	1.6	2.7
Average number of keep right LC/25m at acc. lane	7.0	3.8	3.4	11.9	3.5	5.9
first loc. where number of keep right LC/25m is above average	-425m	-300m	-250m	-475m	-600m	-500m
last loc. where number of keep right LC/25m is above average	525m	550m	500m	375m	250m	325m
Average number of uncategorised left LC/25m outside 200m zone	3.4	4.5	7.8	3.1	2.1	5.0
Average number of uncategorised left LC/25m at acc. lane	8.3	6.4	13.1	10.0	3.9	10.1
first loc. where number. of uncategorised left LC/25m is above avg.	-400m	-200m	-300m	-500m	-675m	-475m
last loc. where number of uncategorised left LC/25m is above avg.	525m	675m	575m	450m	275m	625m

4.2. Impact of weaving segment length and traffic flow

Utilization of the available length for merging and diverging

Most of merging and diverging lane changes were performed in the first part of an acceleration lane, deceleration lane or weaving segment. FIGURE 5 shows that most lane changes are performed in the first 25% of the lane. The corresponding percentages are displayed in TABLE 5. The figure shows distributions with comparable shapes for a scenario with a low traffic flow. However, a two sample Kolmogorov Smirnov (KS) test showed that the difference between the distributions is significant. In the scenario with a high traffic flow the distribution shapes start to deviate at F(X)=0.5. For both a high and a low traffic flow on the motorway the use of a long weaving segment by merging vehicles is comparable (KS-test: n1=107, n2=122, p=0.624).

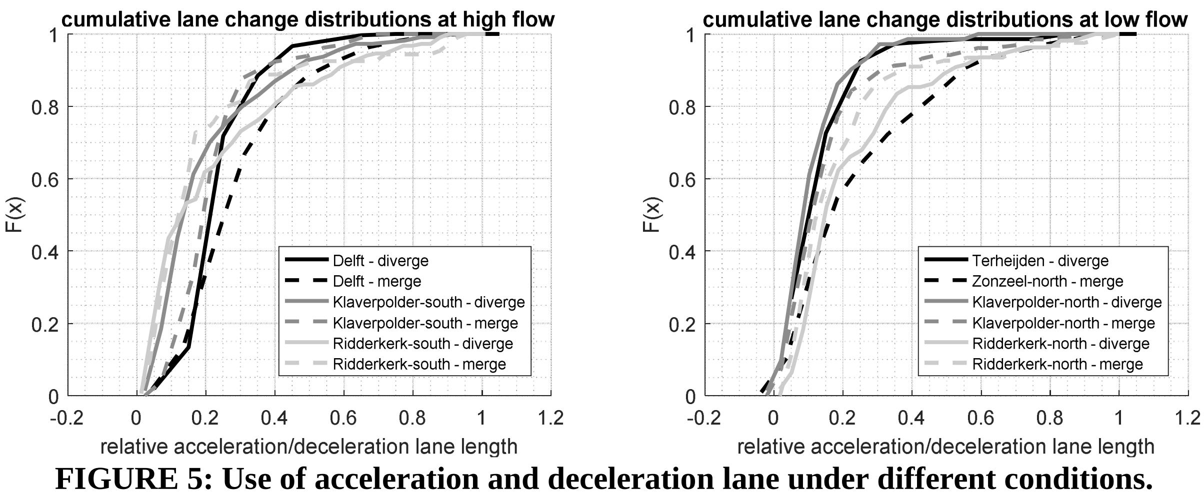

FIGURE 5: Use of acceleration and deceleration lane under different conditions.

TABLE 5 Utilization of the available length for weaving

	Percentage of lane changes performed in first 25% of the lane	
	High traffic flow (0.74 ≤ F/C ≤ 0.81)	**Low traffic flow (0.55 ≤ F/C ≤ 0.61)**
off-ramp - diverge	80%	95%
on-ramp - merge	65%	68%
short weaving - diverge	80%	95%
short weaving - merge	85%	90%
long weaving - diverge	73%	74%
long weaving - merge	80%	86%

In FIGURE 6 headway and speed distributions are compared. The first line represents the distribution at the moment another vehicle merges in front (t = 0s). The second line shows the distribution 10 seconds prior to this moment (t = -10s). This comparison is done for both sites with a relative high traffic flow and sites with a relative low traffic flow. TABLE 6 shows the descriptive statistics of the headway progression and the results of a two sample KS-test. The results show no cooperative behaviour. Both the headway and speed distributions do not significantly differ at t = 0s and t = -10s, regardless the flow or the length of the weaving segment.

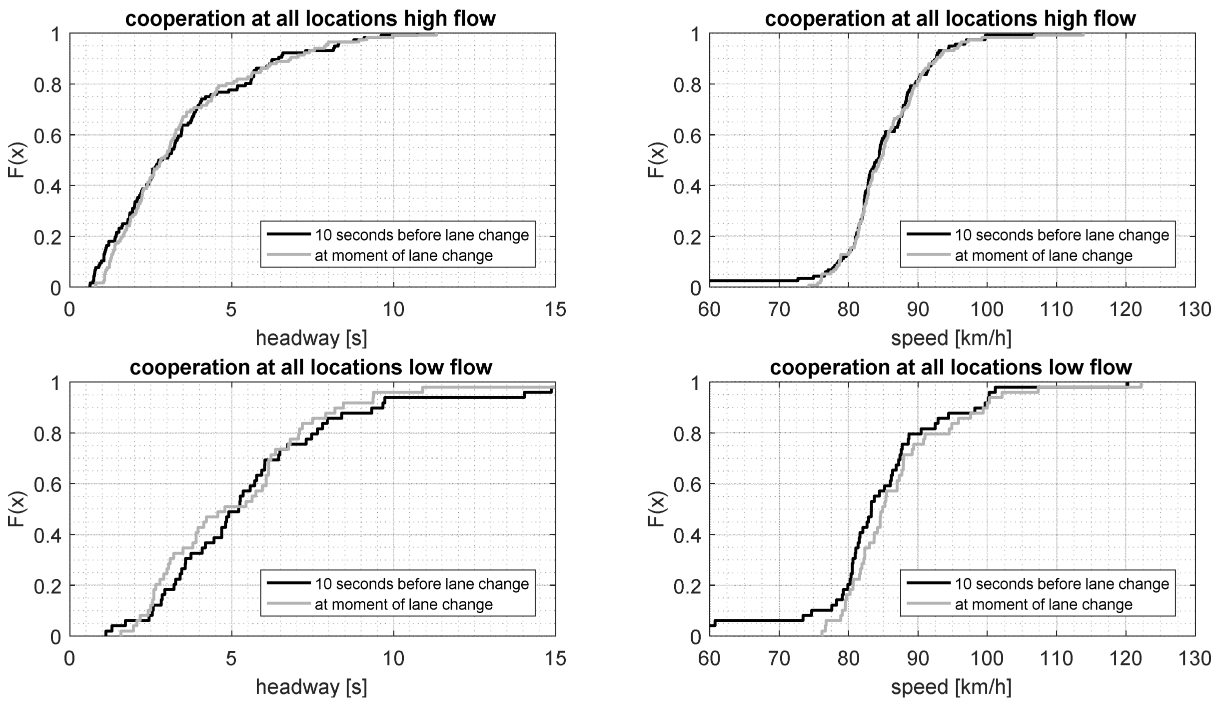

FIGURE 6: Headway and speed progression of cooperating vehicles.

TABLE 6 Descriptive statistics of headway progression of cooperating vehicles

Site		n	mean at t=0s [sec]	mean at t=10s [sec]	std. at t=-10s [sec]	std. at t=0s [sec]	p-value KS-test
Headway	on-ramp Zonzeel-north	31	6.1	5.5	2.9	3.0	**0.559**
	weaving Ridderkerk-north	6	4.4	5.0	3.2	3.1	**0.810**
	weaving Klaverpolder-north	12	5.1	4.7	3.7	2.4	**1.000**
	all locations - low flow	49	5.6	5.3	3.2	2.9	**0.665**
	on-ramp Delft	97	3.3	3.2	2.2	2.1	**0.778**
	weaving Ridderkerk-south	5	4.3	4.7	2.9	3.4	**1.000**
	weaving Klaverpolder-south	14	3.7	4.4	2.5	2.4	**0.862**
	all locations - high flow	116	3.4	3.4	2.2	2.2	**0.541**
Speed	on-ramp Zonzeel-north	31	83.2	85.3	10.9	6.9	**0.944**
	weaving Ridderkerk-north	6	81.0	84.4	5.2	3.1	**0.318**
	weaving Klaverpolder-north	12	87.8	94.0	16.2	11.7	**0.786**
	all locations - low flow	49	84.1	87.3	11.9	8.8	**0.494**
	on-ramp Delft	97	84.2	85.5	9.1	5.9	**0.883**
	weaving Ridderkerk-south	5	86.0	84.1	4.1	5.5	**1.000**
	weaving Klaverpolder-south	14	83.8	85.8	12.4	8.1	**0.541**
	all locations - high flow	116	84.2	85.5	9.4	6.1	**0.938**

The different headway and speed distributions for relaxation at on-ramps are displayed in FIGURE 7. The black line represents the distribution at the moment the subject vehicle merges from the acceleration lane to lane 1 (t=0s). The grey line shows the distribution 10 seconds after to this moment (t=10s). The descriptive statistics for the headway progression are shown in TABLE 7, as well as the results of a two sample KS-test.
The results shown that the headways show a slight increase after t=0s for all 3 on-ramps. However, only for the on-ramp of Delft the difference is significant. The measured mean speeds also show an increase but this difference is not significant.

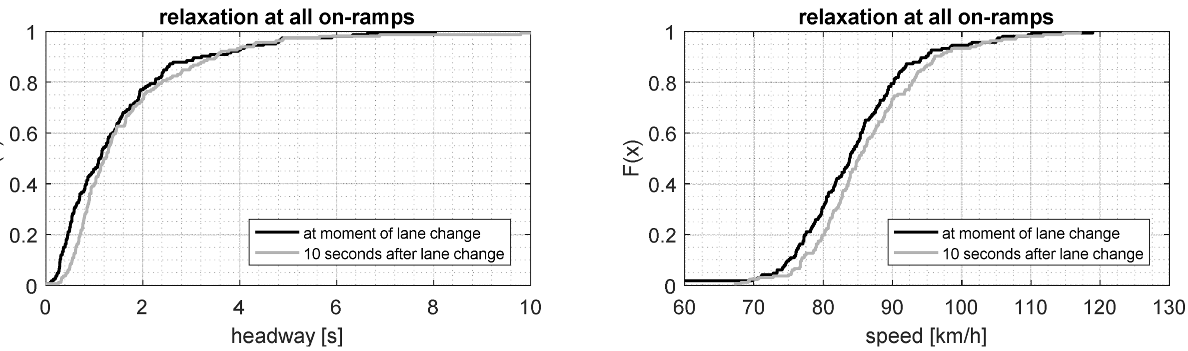

FIGURE 7: Headway and speed progression under relaxation.

TABLE 7 Descriptive statistics of headway progression of relaxation

Site		n	mean at t=0s [sec]	mean at t=10s [sec]	std. at t=0s [sec]	std. at t=10s [sec]	p-value KS-test
Headway	on-ramp Delft	115	1.2	1.4	1.0	0.9	0.005
	on-ramp Terheijden	22	2.4	2.7	2.1	2.5	**1.000**
	on-ramp Zonzeel-north	29	2.0	2.1	1.7	1.9	**0.996**
	all on-ramps	166	1.5	1.7	1.4	1.5	0.008
Speed	on-ramp Delft	115	83.3	86.0	7.8	6.8	**0.054**
	on-ramp Terheijden	22	90.1	93.1	17.6	14.3	**0.821**
	on-ramp Zonzeel-north	29	82.9	83.1	5.9	6.2	**0.996**
	all on-ramps	166	84.1	86.5	9.6	8.5	**0.099**

Gap acceptance for merging at different designs and speeds

FIGURE 8 displays the cumulative distribution functions of accepted gaps (net headways) during merging, secondary merging, diverging and keeping right. Four scenarios are displayed: gap acceptance at long weaving segments, under high and low flow, and gap acceptance at short weaving segments under high and low traffic flow conditions. The descriptive statistics for these distributions are shown in TABLE 8. For each scenario the accepted gaps of MLC (merge and diverge) and DLC (secondary merge and keeping right) are compared. The results of the comparison is shown in TABLE 9. To give an indication of the impact of the weaving segment length the distribution of accepted gaps of merging traffic at on on-ramp is taken as a reference. The accepted gap distributions show that gap acceptance at a long weaving segment, under low traffic flow conditions, is comparable to merging at an on-ramp at low traffic flow conditions. The mean accepted gap is between 5.5 and 7.5 seconds. For the other scenarios in FIGURE 8 the shapes of the distributions seem to be similar, but the results of the KS-test do not support this for most cases. In the scenario with a long weaving segment and high traffic flow conditions, the difference might be explained by the high volume of trucks in the weaving segment "Ridderkerk-South" and the low volume of trucks at the on-ramp of "Delft". For the scenario with a long weaving segment length and high traffic flow conditions and the scenario with a short weaving segment and low traffic flow conditions, the accepted gap distribution for diverging stands out. This can be explained by the amount of entering and exiting traffic, as shown in TABLE 1. In the long weaving segment "Ridderkerk - south" the amount of entering traffic is low (416 vehicles), which explains a relatively large average accepted gap. In the short weaving segment "Bergen op Zoom - east" the entering flow is high (641 vehicle), which explains a relatively small average accepted gap. When comparing merging (MLC) and secondary merging (DLC) the results show that on average smaller gaps are accepted for merging. The only exception is the scenario with the short weaving segment and the low traffic flow conditions. Here the average accepted gap for secondary merging is smaller, but for merging and secondary merging the average accepted gap is relatively large due to the small amount of traffic.

The results of a cross comparison between weaving segments with comparable lengths and flows are shown in the second part of TABLE 9. The KS-test results show that the accepted gap distributions at long weaving segments are reasonably comparable for both high and low traffic flow conditions. The same holds for gap acceptance when weaving under high traffic flow conditions. The distributions for both the long and short weaving segment are comparable at high flow conditions. Except for the accepted gap distribution for diverging.

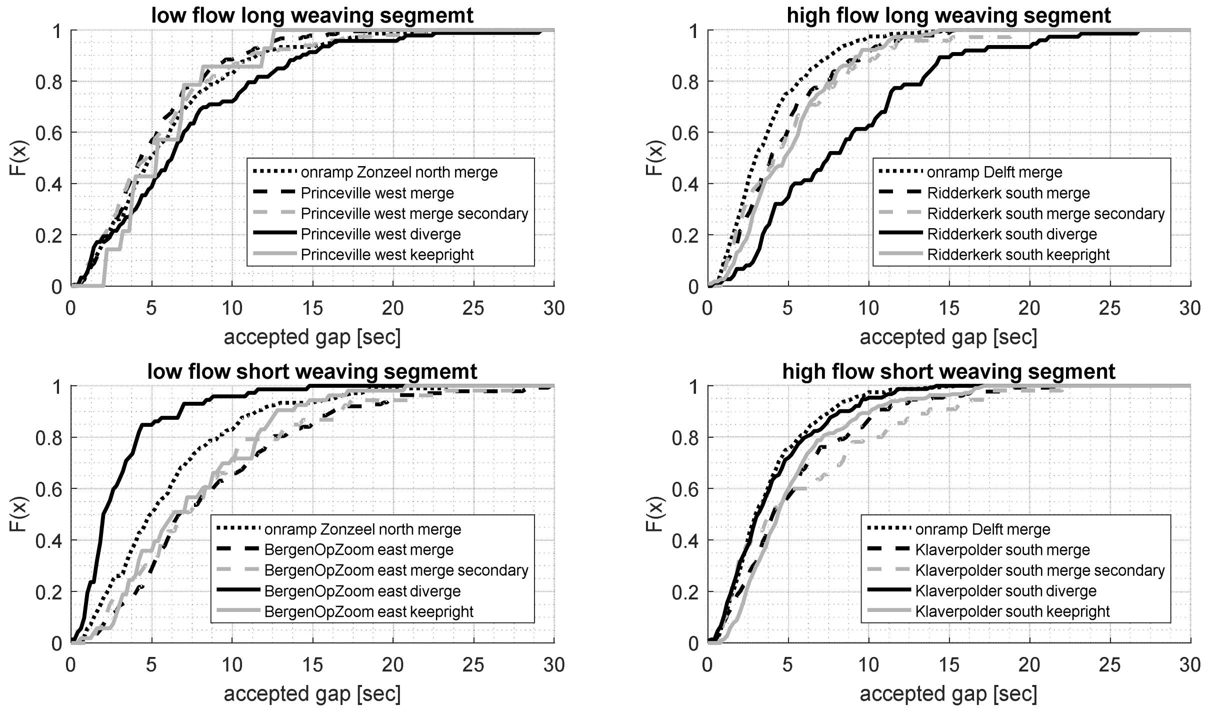

FIGURE 8: Comparison of MLC and DLC under different conditions.

TABLE 8 Descriptive statistics of accepted gap distributions

site and manoeuvre	n	mean	std.	site and manoeuvre	n	mean	std.
low flow and long weaving segment				**high flow and long weaving segment**			
onramp Zonzeel-north merge	212	6.36	5.02	onramp Delft merge	322	3.95	2.68
Princeville-west merge	183	5.46	3.59	Ridderkerk-south merge	95	4.78	3.26
Princeville-west merge secondary	201	6.05	5.05	Ridderkerk-south merge secondary	72	5.34	4.05
Princeville-west diverge	93	7.40	5.48	Ridderkerk-south diverge	75	8.69	5.61
Princeville-west keeping right	15	5.66	3.51	Ridderkerk-south keeping right	115	5.31	3.09
low flow and short weaving segment				**high flow and short weaving segment**			
onramp Zonzeel-north merge	212	6.36	5.02	onramp Delft merge	322	3.95	2.68
Bergen op Zoom-east merge	139	9.06	6.22	Klaverpolder-south merge	130	5.55	4.15
Bergen op Zoom-east merge secondary	54	8.88	6.47	Klaverpolder-south merge secondary	55	6.13	5.28
Bergen op Zoom-east diverge	72	3.22	2.74	Klaverpolder-south diverge	153	4.15	2.99
Bergen op Zoom-east keeping right	53	7.68	4.51	Klaverpolder-south keeping right	217	5.40	3.51

TABLE 9 Results statistical comparison gap acceptance

		Scenario 1	Length [m]	F/C	n	Scenario 2	Length [m]	F/C	n	p
Long weaving segment length	low flow	onramp Zonzeel-north merge	340	0.58	212	Princeville-west merge	1100	0.52	183	**0.259**
		onramp Zonzeel-north merge	340	0.58	212	Princeville-west merge sec.	1100	0.52	201	**0.303**
		onramp Zonzeel-north merge	340	0.58	212	Princeville-west diverge	1100	0.52	93	**0.221**
		onramp Zonzeel-north merge	340	0.58	212	Princeville-west keeping right	1100	0.52	15	**0.987**
		Princeville-west merge	1100	0.52	183	Princeville-west merge sec.	1100	0.52	201	**0.661**
		Princeville-west diverge	1100	0.52	93	Princeville-west keeping right	1100	0.52	15	**0.643**
	high flow	onramp Delft merge	300	0.81	322	Ridderkerk-south merge	1000	0.78	95	0.038
		onramp Delft merge	300	0.81	322	Ridderkerk-south merge sec.	1000	0.78	72	0.015
		onramp Delft merge	300	0.81	322	Ridderkerk-south diverge	1000	0.78	75	0.000
		onramp Delft merge	300	0.81	322	Ridderkerk-south keeping right	1000	0.78	115	0.000
		Ridderkerk-south merge	1000	0.78	95	Ridderkerk-south merge sec.	1000	0.78	72	**0.922**
		Ridderkerk-south diverge	1000	0.78	75	Ridderkerk-south keeping right	1000	0.78	115	0.000
Short weaving segment length	low flow	onramp Zonzeel-north merge	340	0.58	212	Bergen op Zoom-east merge	500	0.35	139	0.000
		onramp Zonzeel-north merge	340	0.58	212	Bergen op Zoom-east merge sec.	500	0.35	54	0.013
		onramp Zonzeel-north merge	340	0.58	212	Bergen op Zoom-east diverge	500	0.35	72	0.000
		onramp Zonzeel-north merge	340	0.58	212	Bergen op Zoom-east keeping right	500	0.35	53	**0.086**
		Bergen op Zoom-east merge	500	0.35	139	Bergen op Zoom-east merge sec.	500	0.35	54	**0.723**
		Bergen op Zoom-east diverge	500	0.35	72	Bergen op Zoom-east keeping right	500	0.35	53	0.000
	high flow	onramp Delft merge	300	0.81	322	Klaverpolder-south merge	500	0.74	130	0.001
		onramp Delft merge	300	0.81	322	Klaverpolder-south merge sec.	500	0.74	55	0.005
		onramp Delft merge	300	0.81	322	Klaverpolder-south diverge	500	0.74	153	**0.914**
		onramp Delft merge	300	0.81	322	Klaverpolder-south keeping right	500	0.74	217	0.000
		Klaverpolder-south merge	500	0.74	130	Klaverpolder-south merge sec.	500	0.74	55	**0.300**
		Klaverpolder-south diverge	500	0.74	153	Klaverpolder-south keeping right	500	0.74	217	0.001
weaving segment length	long	Princeville-west merge	1100	0.52	183	Ridderkerk-south merge	1000	0.78	95	**0.410**
		Princeville-west merge sec.	1100	0.52	201	Ridderkerk-south merge sec.	1000	0.78	72	**0.710**
		Princeville-west diverge	1100	0.52	93	Ridderkerk-south diverge	1000	0.78	75	**0.125**
		Princeville-west keeping right	1100	0.52	15	Ridderkerk-south keeping right	1000	0.78	115	**0.858**
	short	Bergen op Zoom-east merge	500	0.35	139	Klaverpolder-south merge	500	0.74	130	0.000
		Bergen op Zoom-east merge sec.	500	0.35	54	Klaverpolder-south merge sec.	500	0.74	55	0.017
		Bergen op Zoom-east diverge	500	0.35	72	Klaverpolder-south diverge	500	0.74	153	0.016
		Bergen op Zoom-east keeping right	500	0.35	53	Klaverpolder-south keeping right	500	0.74	217	0.002
flow	low	Princeville-west merge	1100	0.52	183	Bergen op Zoom-east merge	500	0.35	139	0.000
		Princeville-west merge sec.	1100	0.52	201	Bergen op Zoom-east merge sec.	500	0.35	54	0.005
		Princeville-west diverge	1100	0.52	93	Bergen op Zoom-east diverge	500	0.35	72	0.000
		Princeville-west keeping right	1100	0.52	15	Bergen op Zoom-east keeping right	500	0.35	53	**0.232**
	high	Ridderkerk-south merge	1000	0.78	95	Klaverpolder-south merge	500	0.74	130	**0.486**
		Ridderkerk-south merge sec.	1000	0.78	72	Klaverpolder-south merge sec.	500	0.74	55	**0.610**
		Ridderkerk-south diverge	1000	0.78	75	Klaverpolder-south diverge	500	0.74	153	0.000
		Ridderkerk-south keeping right	1000	0.78	115	Klaverpolder-south keeping right	500	0.74	217	**0.518**

5. DISCUSSION

The level of turbulence is defined as the frequency and intensity of individual changes in speed, headways, and lanes (i.e. lane-changes) (Van Beinum et al. 2016). The results show that the largest contribution to turbulence is given by the intensity of lane changes. Only small changes in headway and speed were found for both cooperation and relaxation. For changes in speed, the differences were found to be not significant. For changes in headway, only the change in headway during relaxation under high traffic flow conditions was found to be significant. Nevertheless, it is expected that the effects of cooperation, anticipation and relaxation will increase as the traffic flow increases, since these manoeuvres are more likely to occur in (near) saturated or congested traffic.

In this paper, we found that the frequency of lane changes was found to be highest around ramps: 50% of all lane changes in the vicinity of ramps take place at the acceleration and deceleration lane, which is only 20-25% of the measured length of motorway. Pre-allocation and

anticipation were found to be of little influence for turbulence. The intensity of these lane changes is low and mainly take place at a close distance from the ramp. This suggests that the ramp influence area is smaller than currently perceived in the different guidelines (Rijkswaterstaat 2017; HCM 2010). This is especially the case for off-ramps where only pre-allocating vehicles provide a little increase in the level of turbulence. For on-ramps mainly secondary lane changes create turbulence downstream of the ramp. These secondary lane changes might also explain the increased intensity of keeping right lane changes downstream of the on-ramp.
Not all measured lane changes can directly be linked to entering or exiting traffic. Lane changes to the inside and outside of the motorway, which are not triggered by entering or exiting vehicles nearby, are present over the whole measured area with an average of lane changes per 25 m that ranges between 2 and 8. This indicates that turbulence is always present in traffic, which is consistent with (HCM 2010). However, it was found that the rate of these lane changes increases in the vicinity of ramps.

A higher traffic volume results in a higher level of turbulence. Shorter gaps are accepted for MLC under high traffic flow conditions which results in small initial headways which gradually increase over time (relaxation). A longer weaving segment length has a positive effect on the level of turbulence. Drivers make use of a longer distance to select a suitable gap which results in larger accepted gaps for MLC. This is in line with the findings of (Calvi and De Blasiis 2011). However when a weaving segment gets longer this effect gets smaller, since only the first part of the weaving segment is used. More than 85% of the lane changes for merging and diverging are performed in the first 50% of the weaving segment length. This coincides with previous findings (Daamen et al. 2010; Marczak et al. 2014). Weaving segment lengths longer than 1,000m are not expected to provide a significant additional benefit.

6. CONCLUSIONS

This study focusses on driving behaviour near motorway ramps (on-ramps, off-ramps and weaving segments). Different manoeuvres are identified that are performed by drivers that either enter the motorway, exit the motorway or anticipate / cooperate with entering or exiting vehicles. These manoeuvres create an increased level of turbulence that starts upstream of the ramp, is at its highest at the ramp and decreases downstream of the ramp. The study shows that the increased level of turbulence, in free flow conditions, is mainly characterised by increased numbers of lane changes. Changes in speed and headway are limited. Only for relaxation a significant change was found under high traffic flow conditions. Most of the lane changes are attributed to merging and diverging and take place at the acceleration lane or deceleration lane. Further upstream and downstream the intensity of lane changes is much less. Especially for off-ramps, where only pre-allocation was shown to be of influence. Pre-allocation related lane changes are small in number and seem to be correlated to the location of routing signs. At on-ramps anticipation generates lane changes upstream of the ramp but only at a maximum distance of 25m - 100m. Downstream of the on-ramp secondary lane changes are performed. 26%-41% of the merging vehicles perform additional lane changes towards the median lane after they have merges. These lane changes are performed until about 475m - 575m downstream of the ramp.

The findings related to the start and end of turbulence are shown in TABLE 10 and are compared to previous studies. The prescribed upstream values in the HCM are slightly larger than found in our study. This coincides with the findings of (Kondyli and Elefteriadou 2012). The downstream values are comparable. The prescribed values for on-ramps in the Dutch design guidelines (Rijkswaterstaat 2017) are reasonably consistent with our findings. For off-ramps the upstream value is slightly higher when the impact of the routing sign is not taken into account.

TABLE 10 Ramp influence areas

on-ramp		off-ramp		source
upstream [m]	downstream [m]	upstream [m]	downstream [m]	
25-100	475-575	400-600*	200-375	this study
200	900	1,000	-	(Van Beinum et al. 2017)
110	260	-	-	(Kondyli and Elefteriadou 2012)
460	460	460	460	(HCM 2010)
150	750	750	150	(Rijkswaterstaat 2017)

* location of routing sign

The use of the available road length by merging and diverging vehicles is rather constant. Most vehicles make only use of the first part of the acceleration lane or deceleration lane, regardless of the traffic flow or the available length (which ranged between 210m - 250m for off-ramps and 300m - 340m for off-ramps). Comparable behaviour is observed at weaving segments (with lengths ranging from 400m - 1,100m). Both entering and exiting vehicles make use of only the first part of the weaving segment, which results in an accumulation of lane changes in the first part and only a few lane changes in the last part of the weaving segment. This corresponds to findings in other studies (Marczak et al. 2014; Kusuma et al. 2015).

Based on the analysis of our dataset, both road design and traffic flow have shown to affect the use of the acceleration lane and deceleration lane. When the length of a weaving segment is increased, more length is used for merging. Road design and traffic flow seem to hardly affect gap acceptance. We found significant difference in the mean accepted gaps between low and high traffic flow at short weaving segments, but not at long weaving segments. For long weaving segments similar accepted gap distributions were found for both high flow and low flow traffic conditions. At short weaving segments a significant difference was found between the two distributions. Therefore, the results are not conclusive.

Our findings give an interesting insight into the characteristics of the different manoeuvres that contribute to turbulence. It shows where turbulence starts and ends, but more importantly: it shows how the different manoeuvres are performed and how these are affected by motorway design and traffic flow. This study is based on a large dataset of trajectories from individual vehicles driving in the vicinity of ramps. This information is essential for gaining more understanding on driving behaviour which can be used for improving our microscopic simulation models and for improving our design guidelines. It is recommended to use this data to improve the modelling of the different manoeuvres and the interaction between vehicles that perform these manoeuvres. Some of the studied manoeuvres have been given much attention in literature, such as merging and diverging, but for other manoeuvres much less research has been performed. Examples of manoeuvres that require further research are: pre-allocation, secondary merges and keeping right. Moreover it is recommended to further investigate the variability in behaviour among drivers (e.g. the level of risk different drivers are willing to take) and its impact on traffic flow characteristics and safety. Our final recommendation is to put more effort in investigating the impact of road (design) characteristics on driving behaviour. For example the impact of horizontal alignment, vertical alignment, number of lanes and lane width on lane change behaviour.

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