Transportmetrica A: Transport Science

ISSN: 2324-9935 (Print) 2324-9943 (Online) Journal homepage: https://www.tandfonline.com/loi/ttra21

Macroscopic traffic flow changes around ramps

Aries van Beinum, Marco Hovenga, Victor Knoop, Haneen Farah, Fred Wegman & Serge Hoogendoorn

To cite this article: Aries van Beinum, Marco Hovenga, Victor Knoop, Haneen Farah, Fred Wegman & Serge Hoogendoorn (2018) Macroscopic traffic flow changes around ramps, Transportmetrica A: Transport Science, 14:7, 598-614, DOI: 10.1080/23249935.2017.1415997

To link to this article: https://doi.org/10.1080/23249935.2017.1415997

Accepted author version posted online: 12 Dec 2017.
Published online: 28 Dec 2017.

TRANSPORTMETRICA A: TRANSPORT SCIENCE, 2018
VOL. 14, NO. 7, 598–614
https://doi.org/10.1080/23249935.2017.1415997

Macroscopic traffic flow changes around ramps

Aries van Beinum[a], Marco Hovenga[b], Victor Knoop[a], Haneen Farah[a], Fred Wegman[a] and Serge Hoogendoorn[a]

[a]Department of Transport and Planning, Delft University of Technology, Delft, Netherlands; [b]Department of Traffic and Roads, Witteveen+Bos, Deventer, Netherlands

ABSTRACT

Traffic is more turbulent around motorway ramps due to route choice-related lane changes and anticipatory or cooperative manoeuvres. These manoeuvres result in changes in speed and headways and have a negative influence on traffic safety and capacity. However, the distance upstream where turbulence starts and the distance downstream where it dissolves are yet unknown. In this paper, we propose a new method for detecting the start and end distances of turbulence. This method relies on the analysis of large quantities of empirical loop detector data from multiple on-ramps and off-ramps at different sites. By comparing the traffic operations near ramps to those on a regular motorway section, the length of the turbulence influence area can be estimated. The scope of the research is limited to three-lane motorways in the Netherlands, and shows that the distribution of traffic over the motorway lanes is a useful indicator for turbulence.

ARTICLE HISTORY
Received 22 May 2017
Accepted 7 December 2017

KEYWORDS
Turbulence; macroscopic; loop detector; motorway; design

Introduction

Entering and exiting traffic on-ramps and weaving areas causes lane changes in the traffic flow on motorways. These lane changes are not only performed by entering and exiting traffic but can also be a reaction of through-going traffic attempting to avoid or to make space for the entering traffic. Other behaviours can be decelerating or accelerating to increase or decrease the headway with the vehicle in front (HCM 2010). The collective name given to these responses is 'turbulence' (Abdel-Aty and Pande 2005; Golob, Recker, and Alvarez 2004; Kondyli and Elefteriadou 2011, 2012; Lee, Hellinga, and Saccomanno 2003). Turbulence is a common phenomenon in traffic (HCM 2010). The level of turbulence increases around motorway locations where mandatory lane changes occur, such as at on-ramps (Kondyli and Elefteriadou 2011), off-ramps and weaving areas. Turbulence has been shown to have a negative impact on both traffic safety and traffic operations (Abdel-Aty and Pande 2005; Golob, Recker, and Alvarez 2004; HCM 2010; Lee, Hellinga, and Saccomanno 2003).

CONTACT Aries van Beinum a.s.vanbeinum@tudelft.nl Faculty of Civil Engineering and Geosciences, Department of Transport and Planning, Delft University of Technology, Stevinweg 1, P.O. Box 5048, 2600 GA Delft, Netherlands

In Beinum et al. (2016), we proposed the following definitions for turbulence in the vicinity of discontinuities, such as ramps:

(1) *Turbulence*: individual changes in speed, headways and lanes (i.e. lane changes) in a certain road segment, regardless of the cause of the change;
(2) *Level of Turbulence*: the frequency and intensity of individual changes in speed, headways and lane changes in a certain road segment, over a certain period.

Turbulence is relevant for road design and should be taken into account by applying sufficient ramp spacing and sufficient road length for weaving traffic (AASHTO 2011; FGSW 2008; HCM 2010; Rijkswaterstaat 2014; The_Highways_Agency et al. 1994). There are different approaches to determine the required distance for ramp spacing (Fitzpatrick et al. 2011), such as decision and manoeuvre time, required length for road signs and providing sufficient weaving length (HCM 2010). The general concept behind these approaches is that turbulence around ramps will intensify when the available road length for lane changing becomes shorter (Bared, Edara, and Kim 2006; Pilko et al. 2007).

The actions of individual merging or diverging vehicles create turbulence near the ramp. The ramp influence area experiences a higher rate of lane changing than is normally present on ramp-free sections of a motorway (HCM 2010). Thus, the *Level of Turbulence* is expected to increase before (upstream of) and to decrease after (downstream of) a ramp. Kondyli and Elefteriadou (2012) found that turbulence due to merging manoeuvres begins 110 m upstream of the gore. The gore is the painted white triangle which indicates that the road splits or merges. The default design of a motorway interchange is shown in Figure 1. According to the HCM (2010), the merge influence area occurs between approximately 460 m (1500 ft.) upstream and 460 m downstream of the gore. To the best of our knowledge, other literature that describes the start or the end of a raised level of turbulent traffic is not available.

The goal of this paper is to provide a method to determine empirically at what distance a raised level of turbulence starts upstream of a ramp and at what distance downstream of a ramp it dissolves. The length-of-motorway over which the level of turbulence is raised is relevant for road design guidelines. The spacing of successive ramps is determined based on this length. This is to prevent that the capacity of the motorway near an on-ramp or an off-ramp decreases too much and becomes a bottleneck when the traffic flow increases. However, little is known about this length, which hampers establishing solid design guidelines. Therefore, additional research is needed to gain more knowledge about this length to validate or improve our current motorway design guidelines. This additional research should be based on empirical data and should be generic for different situations, such as different traffic volumes.

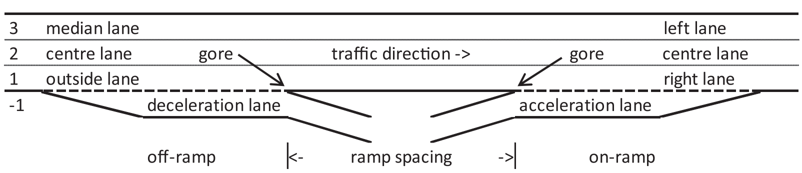

Figure 1. The default design for motorway on-ramps and off-ramps.

Background

When traffic volume exceeds the motorway capacity, traffic congestion occurs and the risk of crashes increases. This often happens in the proximity of on-ramps and off-ramps (Lee and Abdel-Aty 2008) because of the changes in demand and capacity at these locations. For example, the on-ramp flow has an important impact on the formation of the stop-and-go traffic flow near the ramp (Leclercq et al. 2016; Ngoduy 2008; Tang et al. 2008, 2009).

Turbulence which is created by entering or exiting traffic, and the courtesy or anticipatory-related manoeuvres which are performed by through-going motorway traffic, reduces the motorway's capacity (Abdel-Aty and Pande 2005; Golob, Recker, and Alvarez 2004; HCM 2010; Lee, Hellinga, and Saccomanno 2003). The Dutch legal traffic regulations state that a lane-changing vehicle (for example, an entering vehicle) has to give priority to vehicles in the target lane (Daamen, Loot, and Hoogendoorn 2010; Knoop et al. 2017). Nevertheless, vehicles on that target lane sometimes show courtesy to entering traffic by changing lane towards the median lane and sometimes also by reducing speed to create a larger gap which the entering vehicle can merge into.

At off-ramps, exiting vehicles must change lanes to the outside lane of the motorway (if not already driving there) to access the deceleration lane. The increased traffic density on the outside lane and possible deceleration of exiting traffic may cause through-going motorway vehicles to change lanes to the centre or median lane to avoid exiting traffic (HCM 2010; Kondyli and Elefteriadou 2011).

It can be concluded from the above studies that lane changes are an important element of turbulence. In literature, lane changes are categorized as discretionary, mandatory or cooperative. Discretionary lane changes are performed by drivers to improve their position in the traffic stream (Kondyli and Elefteriadou 2012). Mandatory lane changes are performed as a result of strategic route choice decisions, such as to enter or to exit the motorway (Kondyli and Elefteriadou 2012; Minderhoud 1999). Cooperative lane changing is characterized by a follower that slows down (Hidas 2005) or changes lanes (Daamen, Loot, and Hoogendoorn 2010; Knoop et al. 2010) to allow the subject vehicle to enter. Also, entering vehicles are sometimes willing to accept very short gaps as they enter the motorway, but 'relax' to more comfortable values shortly thereafter (Laval and Leclercq 2008; Marczak and Buisson 2015; Smith 1985; Sultan et al. 2002).

Conceptual framework of turbulence

The behaviour of individual vehicles (microscopic behaviour) has a macroscopic effect on the traffic stream. For example, a lane change will result in a changed density per lane and a changed headway distribution per lane. Acceleration and deceleration may also result in a changed headway distribution and speed differences between different vehicles. This concept is illustrated in Figure 2.

According to this theoretical framework, three different macroscopic effects are to be expected to occur at on-ramps and off-ramps: (1) change in density, (2) change in speed and (3) change in headway (distribution).

Daamen, Loot, and Hoogendoorn (2010) found that through-going motorway traffic creates room for merging drivers (cooperative lane changing) at the location of the merge by changing lanes from the outside lane to an inside lane of the motorway. This behaviour will

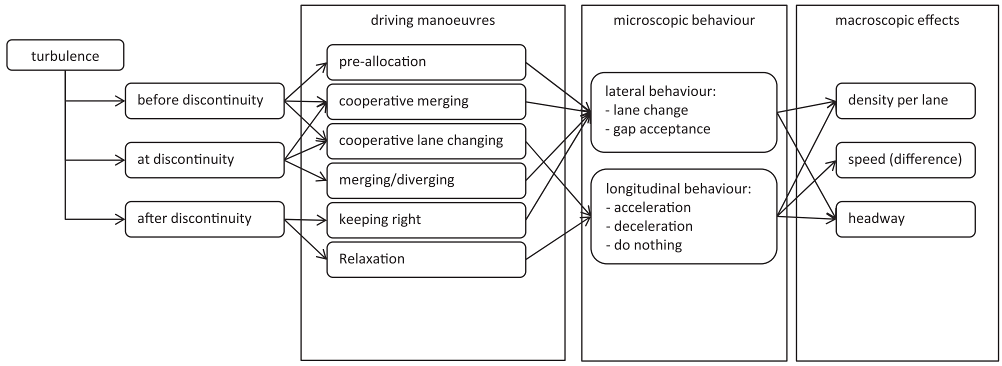

Figure 2. Theoretical framework for turbulence (Beinum et al. 2016).

change the distribution of traffic over the different lanes (lane flow distribution), compared to a normal continuous stretch of motorway. It will also result in a lower fraction of flow on the outside lane just upstream of the on-ramp. Knoop et al. (2010) found that the lane flow distribution is different at on-ramps compared to a regular continuous situation for densities greater than 10 veh/km. This is in part explained by cooperative lane changing. They also found that the fraction of flow on the median lane gets higher when the fraction of flow on the outside lane gets lower. The fraction of flow in the centre lane hardly changes. This phenomenon is also mentioned in the HCM (2010) and also found by Carter, Rakha, and Aerde (1999). At off-ramps, the opposite takes place. Just upstream of an off-ramp, the fraction of flow on the outside lane is expected to be higher compared to an outside lane on a normal continuous stretch of motorway (Amin and Banks 2005).

One common assumption in driving behaviour is that vehicles drive at a certain desired speed. A well-known theory that describes the macroscopic effects of desired speed is Daganzo's behavioural theory of multi-lane traffic (Daganzo 2002a, 2002b). Daganzo categorizes drivers into aggressive (rabbits) and non-aggressive (slugs) drivers, and categorizes lane types into shoulder lanes and passing lanes. In free flow conditions, rabbits will travel faster than slugs, with the rabbits all in the passing lane and the slugs all in the shoulder lane. Nevertheless, several studies have raised some doubts about this theory and suggest, contrary to Daganzo, that drivers are motivated by more than just the desired speed (Amin and Banks 2005; Banks et al. 2003; Banks and Amin 2003). A more complete theory should also consider factors such as lane and ramp configurations, average vehicle spacing and lane-changing behaviour. Despite the discussion about the theory, it is safe to state that when a driver is not able to drive at the desired speed, a lane change may be imminent if possible.

In the European mainland countries, drivers are bound to the right-side rule by which it is mandatory for drivers to change lanes to the right if there is sufficient space to do so. Overtaking takes place on a left lane. This will naturally result in a situation where faster vehicles drive on the left and slower vehicles drive on the right side of the motorway (Daganzo 2002a). In the vicinity of an on-ramp or off-ramp, mandatory lane changes also take place as well as courtesy-related discretionary lane changes. When faster vehicles change lanes towards the outside lane and slower vehicles change lanes towards the median lane, the mean speed on all lanes may change due to the mixing of desired speeds.

Table 1. Distance between on-ramp and off-ramp prescribed in different guidelines.

Country	Distance	Design criteria
The Netherlands (Rijkswaterstaat 2014)	750 m	Design speed
Germany (FGSW 2008)	1100 m[a]	Minimum value for isolated intersection planning
USA (AASHTO 2001)	600 m[b]	Road category: freeway
	480 m[c]	Road category: freeway
UK (The_Highways_Agency et al. 1994), Vol.6, Sec. 2, Cpt 4.7	450 m[d]	3.75V, where V = design speed = 120 km/h

[a]250 m acceleration lane + 600 m between acceleration and deceleration lane + 250 m deceleration lane.
[b]System to service interchange (weaving).
[c]Service to service interchange (weaving).
[d]May be increased to the minimum requirements for effective signing and motorway signaling.

Motorway design guidelines

Ramp spacing is an important part in motorway design and in design guidelines. The basic principle is that there should be sufficient spacing between succeeding ramps to cope with turbulence in the traffic stream. Different guidelines use different approaches for dealing with turbulence. For example, the AASHTO Green Book (AASHTO 2001) uses a set of minimum values for ramp spacing and the Dutch guidelines (Rijkswaterstaat 2014) use a criterion called 'turbulence length', which is the required distance between successive discontinuities. The prescribed lengths differ per type of discontinuity and per guideline. For example, Table 1 shows the different prescribed distances between an on-ramp followed by an off-ramp (measured from gore to gore) according to four different guidelines.

Literature and guidelines agree on the existence and importance of turbulence and state that a raised level of turbulence is present in a certain influence area upstream and downstream of a ramp. This influence area is relevant for determining the required ramp spacing to avoid traffic operations and traffic safety problems. There is, however, no consistency when it comes to the length of this influence area. Some recommended values on the length to be considered are given: 457 m downstream of the gore of an on-ramp and 457 m upstream of an off-ramp (HCM 2010); 110 m upstream and 260 m downstream of the gore of a ramp (Kondyli and Elefteriadou 2012); 150 m upstream/750 m downstream of an on-ramp and 750 m upstream/150 m downstream of an off-ramp (Rijkswaterstaat 2014). This inconsistency may be explained by differences in driving behaviour in different countries, which is a cultural element and in some cases influenced by legislation.

Literature and guidelines show that the level of turbulence is expected to increase upstream and to decrease downstream of a ramp and that changes in lane flow distribution and changes in speed are indicators for turbulence. However, the distance upstream where turbulence starts and the distance downstream where it dissolves are yet unknown. As our study was conducted in the Netherlands, we expect that the turbulence influence areas specified in the Dutch design guidelines give a good indication of where a raised level of turbulence starts and dissolves. However, this will be tested in this study.

Research setup

For this study, we used empirical loop detector data from different on-ramps and off-ramps at several three-lane motorways in the Netherlands. These detectors provide 1-minute

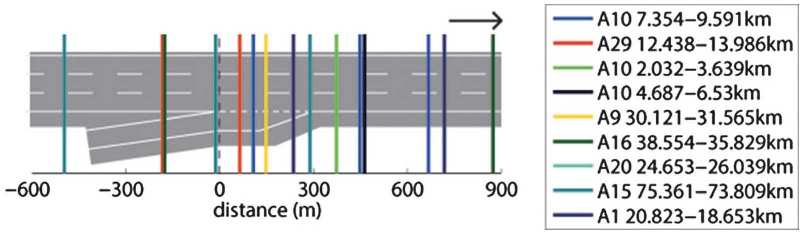

Figure 3. Combined loop detectors from different sites.

aggregated flow and mean speed data for each lane, which are used to calculate an approximate density. We have limited this study to free flow conditions only.

Since loop detectors in the Netherlands are spaced with a distance of about 300–500 m, it is not possible to observe a detailed gradual change in traffic characteristics. To tackle this problem, an innovative approach was applied in which data from different detectors at different sites are combined. The basics of this principle are shown in Figure 3.

To the best of our knowledge, no other use of this method is found in the literature. Our hypothesis is that data from loop detectors at different sites can be combined to study changes in the traffic flow for specific situations (e.g. ramps) when road design and traffic flow characteristics are similar. When the driving behavioural patterns of the driver population are similar, the macroscopic traffic flow characteristics at other similar sites will be comparable.

Accurate identification of changes in speed and flow requires that the detectors are spaced at small distances. A lane change takes about 5 s (Hill, Elefteriadou, and Kondyli 2015), which corresponds to a distance of approximately 140 m at 100 km/h. A difference in speed of 5 m/s takes about 150 m at an acceleration or deceleration rate of 1 m/s^2 and an initial speed of 100 km/h. Therefore, we aim for a minimum spacing of 150 m between trajectories.

The first step in our research is to test whether combined macroscopic loop detector data, that are collected from loop detectors at different sites, are suitable for studying macroscopic traffic flow changes at specific situations.

The second step in our research is to study the location where a raised level of turbulence starts and where it dissolves by comparing the measured traffic characteristics at a continuous stretch of motorway (basic motorway) to characteristics at ramps (on-ramp and off-ramp). The measured characteristics are the traffic flow distribution and the average speeds at the lane level.

Data collection and processing

The data were collected using loop detectors from different basic motorways, on-ramps and off-ramps. Loop detector data in the Netherlands are accessible online at the NDW website (NDW 2015). To meet the similarity demands for road design characteristics and traffic flow characteristics, various site criteria and data filters were applied. This resulted in a selection of sites, detectors and measurement periods.

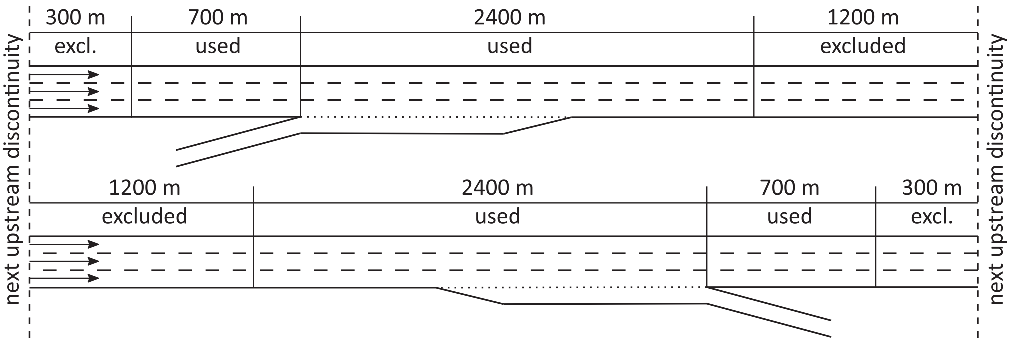

Figure 4. Discontinuity spacing criteria of on-ramp and off-ramp.

Site selection criteria

The different sites must have comparable characteristics, such as design, legal speed limit and traffic composition. The sites should also be at a sufficient distance from other motorway elements that could influence the macroscopic traffic characteristics. Criteria were applied for motorway characteristics (number of lanes, presence of peak hour lanes, variable speed limits), design (acceleration/deceleration lane length) and the distance to the nearest discontinuity upstream and downstream.

Number of lanes, motorway characteristics and design

Our innovative approach was applied for one common type of motorway in the Netherlands: a standard motorway with three-lane carriageways and a legal speed limit of 100 km/h. Motorways which are equipped with peak traffic lanes or variable speed limits were excluded. Since the length of an acceleration lane or deceleration lane is expected to have an important effect on the stability of the main carriageway traffic flow (Ngoduy 2008), sites where the ramp has not been constructed according to the Dutch design guidelines were also excluded. The selected motorways are all located in the western part of the Netherlands.

Distance to the nearest discontinuity upstream and downstream

To prevent the results being biased by other motorway elements further upstream or downstream, sufficient spacing to the nearest discontinuity upstream and downstream is required. The spacing criteria used in this study are the result of a trade-off between a large spacing and the number of sites that meet the criteria. The chosen values are shown in Figure 4. For an on-ramp, the minimal distance downstream to the next discontinuity is 1000 m and the minimal distance upstream is 3600 m, measured from the gore. When these criteria are met, the detectors within the area of 700 m upstream and 2400 m downstream of the gore were used for the experiment. The same principle holds for the selection of on-ramps and off-ramp detectors.

Data collection and filtering

The measurements were taken at days with comparable conditions, such as period of year, weather, daylight, amount of commuting and recreational traffic, and traffic

density. A total of 34 days were selected. Unrealistic measurements were filtered from the dataset.

Weather characteristics

April 2013 and 2014 were selected as input months because these months were neither winter nor summer months, had only a few rainy days and had no extreme temperatures. Days with ($>$ 10 mm) rainfall were excluded. In these months, the macroscopic traffic flow characteristics were expected to be an average.

Traffic characteristics

Only work days were selected. All weekend days and holidays were excluded. Fridays before the holidays were also excluded because traditionally many people in the Netherlands start traveling to their vacation destinations on those days.

Traffic density

Macroscopic changes in the traffic stream take place when vehicles enter or leave the motorway, and when these vehicles influence the driving behaviour of the surrounding vehicles. Therefore, macroscopic traffic conditions depend on the density and the analysis needs to be restricted to a certain density bin. The density should be high enough for entering vehicles to influence through-going motorway traffic. On the other hand, the density should not be too high to avoid measurements in congested traffic conditions. Knoop et al. (2010) found that on a three-lane motorway changes in lane flow distribution are significant for densities between 10 and 130 veh/km. In our database, the measured densities range between approximately 15 and 80 veh/km (over all lanes). In this study, we have chosen three different density bins for the analysis. The study focusses on a moderate density bin of 33–39 veh/km. The results for this density were compared to the results for a low-density bin (25–27 veh/km) and a high-density bin (50–52 veh/km). Although harder to observe directly, density was chosen over traffic flow because density is more reliable for excluding congested traffic conditions than traffic flow.

Unrealistic entries

Unrealistic measurements were excluded from the dataset by applying two filters. The first filter excluded measurements with speeds above 220 km/h or below 80 km/h. High mean speeds could indicate a defect in the loop detector and mean speeds below 80 km/h could indicate congestion. Loops which are suspected to be defective were excluded entirely. The second filter excluded measurements with deviating data characteristics. Two criteria were used: (1) the relation between traffic density and fraction of flow and (2) the speed distribution. The traffic density on a lane is expected to increase when the fraction of flow on that lane increases. A different relation could indicate a defect in the loop detector. The speed distribution is expected to have a single peak at approximately 100 km/h (the legal speed limit). A distribution with multiple peaks, or a significantly lower mean could suggest a temporary lower speed limit due to, for example, an incident. All days which showed multimodal distributions were excluded for that specific detector.

Selected sites

The selected detectors and the characteristics of the filtered data are shown in Tables 2–4.

Table 2. Data characteristics basic motorway.

Site	Road	Detector	Rel. dist. to first detector (m)	*n*	Mean speed (km/h)	Std. speed (km/h)	Mean flow (veh/h)	Std. flow (veh/h)
1	A15	1	0	1032	102.5	2.98	3807	186
1	A15	2	1100	2340	102.1	3.09	3794	195
2	A4	1	0	3716	103.1	2.56	3799	173
2	A4	2	300	3778	102.9	2.59	3796	176
2	A4	3	600	3746	103.7	2.69	3830	175
2	A4	4	1100	3690	100.6	2.73	3656	172
2	A4	5	1500	3518	101.4	2.69	3761	175
3	A15	1	0	1014	104.0	3.18	3842	179
3	A15	2	600	256	103.1	3.14	3814	189
3	A15	3	1100	778	103.1	3.14	3810	187
3	A15	4	1600	402	104.4	3.19	3851	191
4	A16	1	0	3383	100.9	2.69	3739	178
4	A16	2	400	3496	101.5	2.70	3763	178

Table 3. Data characteristics on-ramp.

Site	Road	Detector	Dist. to gore (m)	*n*	Mean speed (km/h)	Std. speed (km/h)	Mean flow (veh/h)	Std. flow (veh/h)
7	A15	2	−498	1806	105.5	2.91	3879	175
2	A29	2	−186	948	102.4	3.16	3824	182
6	A16	2	−177	3170	100.4	2.95	3764	184
7	A15	3	−14	1953	104.0	2.85	3830	176
2	A29	1	63	794	102.0	2.94	3770	188
1	A10	2	107	1755	99.4	2.36	3627	164
5	A9	1	146	3215	97.9	2.12	3584	155
8	A1	1	234	3855	105.7	3.13	3885	189
7	A15	1	287	2888	102.6	3.47	3713	197
3	A10	1	373	3127	104.2	2.95	3747	181
4	A10	1	462	3394	101.9	2.79	3690	170
1	A10	1	666	3689	100.8	2.68	3663	169
8	A1	2	717	3842	106.1	3.04	3873	189
6	A16	1	872	4202	101.3	2.91	3734	181

Table 4. Data characteristics off-ramp.

Site	Road	Detector	Dist. to gore (m)	*n*	Mean speed (km/h)	Std. speed (km/h)	Mean flow (veh/h)	Std. flow (veh/h)
3	A4	2	−2061	3746	103.7	2.69	3830	175
3	A4	1	−1681	3778	102.9	2.59	3796	176
3	A4	5	−1427	3716	103.1	2.56	3799	173
3	A4	4	−997	3723	104.9	2.68	3856	175
5	A10	5	−991	3604	104.0	2.77	3791	173
5	A10	2	−831	3471	107.4	2.95	3917	180
4	A1	1	−821	3465	107.0	3.16	3909	191
5	A10	3	−700	3556	102.3	2.94	3739	174
3	A4	3	−676	3675	102.8	2.69	3767	174
2	A1	1	−610	1561	104.0	2.51	3845	165
5	A10	6	−571	3270	96.8	2.84	3526	166
5	A10	1	−390	3126	96.2	2.85	3493	168
3	A4	6	−254	3749	101.6	2.69	3695	174
2	A1	2	−222	1681	103.5	2.58	3818	166
5	A10	4	−218	3281	97.4	2.74	3509	168
1	A10	1	−170	3199	101.2	2.58	3694	164
1	A10	3	253	3230	98.8	2.25	3620	156
1	A10	2	676	3278	97.1	2.41	3554	159

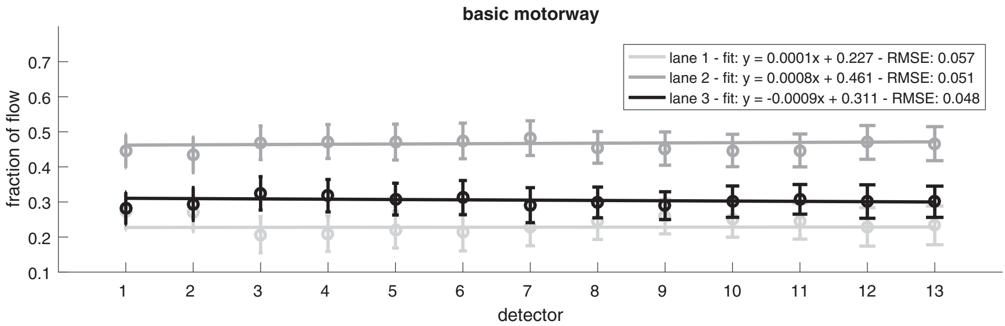

Figure 5. Lane flow distribution at a basic motorway.

Results

Combining loop detectors at different sites

The measured fraction of flow on the different lanes of a basic motorway is found to be comparable for different loop detectors at different sites. Figure 5 displays the average and the standard deviation of the measured fraction of flow for each basic motorway detector. The continuous lines represent a linear weighted least squares fit. The polynomial coefficients as well as the RMSE values are displayed in the figure's legend. The first polynomial coefficient shows that the slope of the line approaches zero. The coefficient for lane 1 does not deviate significantly from zero. The low RMSE values indicate a good fit. Both the slope and the RMSE indicate that different detectors at different sites give comparable results.

The measured deviations from the average speeds are all within a range of 3.8 km/h, which is a maximum deviation of 1.9% from the average speed. The mean and standard deviation of the speed measurements are shown in Figure 6. Again, the continuous line represents a linear weighted least squares fit and the polynomial coefficients as well as the RMSE values are displayed in the legend. The dotted lines represent the minimum and maximum measured mean speed. The first polynomial coefficient shows that the slope of the line is slightly negative. The slope deviates significantly from zero, which indicates that the measured speeds differ per detector. When site 2 is taken as a reference, Table 2 shows that the measured mean speed at a single site can range between 100.6 and 103.7 km/h. The measured mean speeds at all the other detectors, except at site 2, are also within this speed range. The measured speeds at site 2 are slightly higher (max. 104.4 km/h).

Effects of turbulence

Figure 7 shows the mean and standard deviation for the measured mean speeds at on-ramps and off-ramps. The dotted lines indicate the highest and lowest measured mean speed at the basic motorway. It shows that the measured mean speeds at on-ramps and off-ramps vary more than the measured mean speeds at the basic motorway.

The measurements at on-ramps show a drop in speed in the first 200 m downstream of the gore. Further downstream two measurements show a higher speed than measured at the basic motorway. The measured speeds at off-ramps are even more varied. At about 600 m prior to the off-ramp, lower speeds are measured compared to the basic motorway. At

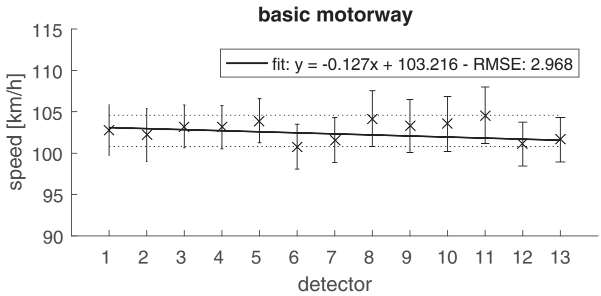

Figure 6. Mean and standard deviation of speeds at a basic motorway.

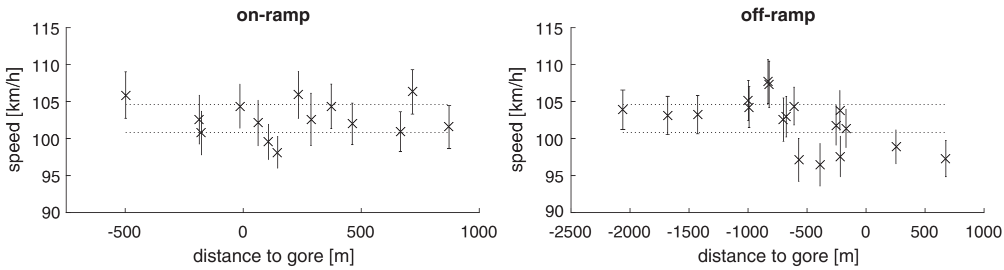

Figure 7. Mean and standard deviation of speeds at on-ramps and off-ramps.

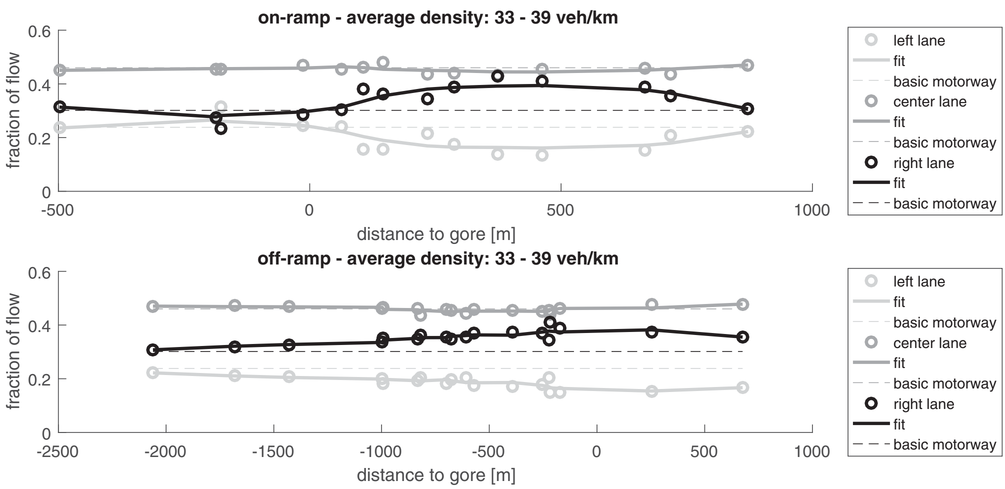

Figure 8. Lane flow distribution at ramps.

about 750 m prior to the off-ramp, higher speeds are measured and at about 250 m and 650 m downstream of the gore lower speeds are measured.

The lane flow distribution has been calculated for both the on-ramp and the off-ramp. The fraction of flow is calculated per lane for each detector and is compared to the basic motorway. Figure 8 shows the results. The calculated fractions of flow are depicted by an 'o'. The thick line represents a fit (moving average over 5 points) and the dashed line represents the average value measured on the basic motorway.

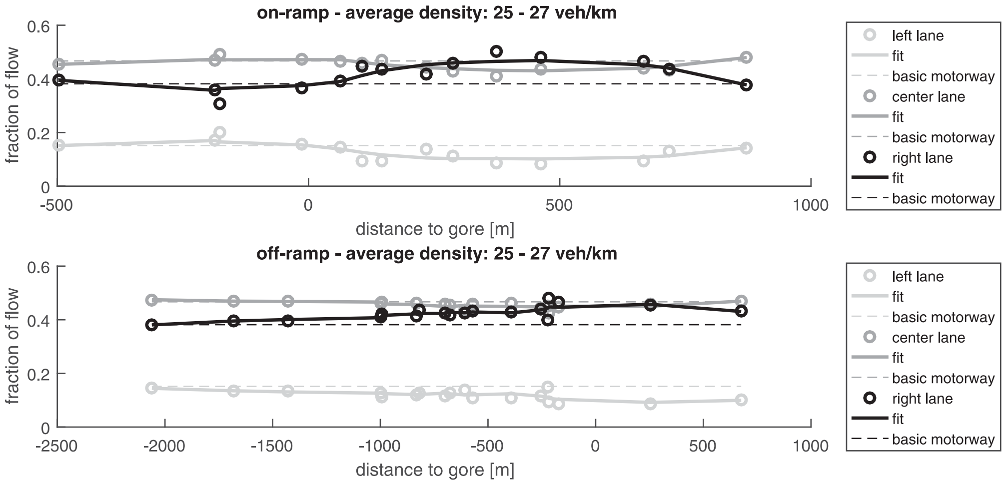

Figure 9. Lane flow distribution at ramps with low density.

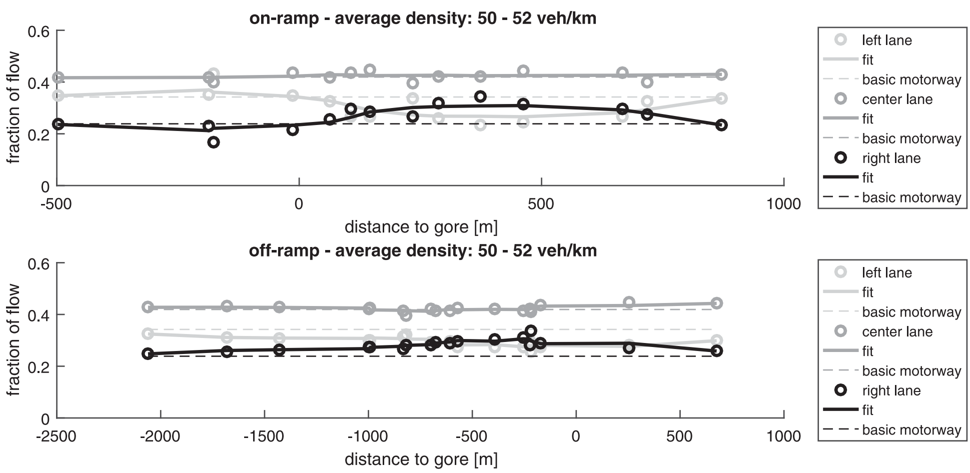

Figure 10. Lane flow distribution at ramps with high density.

The results show that the lane flow distribution changes near on-ramps and off-ramps. At on-ramps, the changes start at about 300–200 m upstream where there is a slight shift of traffic from the right lane towards the left lane. Downstream of the on-ramp gore the fraction of flow on the right lane increases. This effect gradually reduces further downstream and is back to normal at about 900 m downstream.

At off-ramps, the changes start about 1000 m upstream with a slight shift of traffic from the left to the right lane. At 250 m upstream of the gore, the change in the fraction of flow is at its highest and seems to be gradually reducing further downstream. However, at 600 m downstream the lane flow distribution is still not comparable to that of the basic motorway.

The lane flow distributions near ramps for lower or higher densities show comparable changes. Figure 9 shows the lane flow distribution for a density bin of 25–27 veh/km, and Figure 10 shows the lane flow distribution for a density bin of 50–52 veh/km.

Discussion

The lane flow distribution appears to be a macroscopic indicator for turbulence around on-ramps and off-ramps. At on-ramps, drivers tend to move to the left just prior to the start of the acceleration lane, which might be the result of cooperative or anticipatory behaviour. Just downstream of the on-ramp, the fraction of flow on the right lane increases, which is most likely the result of entering traffic.

Drivers tend to pre-allocate to the right lane before taking the motorway exit. The first change in fraction of flow is measured at 1000 m upstream of an off-ramp gore and reaches a maximum on the right lane at the deceleration lane, which is to be expected since most lane changes occur at the deceleration lane. Just downstream of the deceleration lane, the fraction of flow on the right lane is expected to decrease again, since exiting traffic will no longer be driving on the right lane. The data, however, do not show this. The data trend seems to progress towards the original values, but at 600 m downstream of an off-ramp gore the original values are not reached.

This study shows some interesting macroscopic changes in the traffic stream around ramps, compared to a basic motorway section. A change in the lane flow distribution at around 200 m upstream of an on-ramp and 1000 m upstream of an off-ramp seems very plausible considering that a driver on the motorway who is approaching an on-ramp will only change lanes due to entering traffic if there is any entering traffic. A motorway driver can clearly see entering traffic at about 200 m upstream of the gore. Motorway drivers who want to exit the motorway at the next off-ramp may pre-allocate by changing lanes after the exit sign on the side of the motorway. In the Netherlands, the first exit sign is normally positioned at about 1200 m upstream of an off-ramp. A second exit sign is positioned at 600 m upstream. This is where the change in lane flow distribution is almost at its peak.

The left lane and the right lane display the majority of changes in the lane flow distribution. The fraction of flow on the centre lane shows hardly any changes and is the highest of the three lanes. These findings are comparable to previous studies (Carter, Rakha, and Aerde 1999; HCM 2010; Knoop et al. 2010).

Speed is shown to be less stable around on-ramps and off-ramps than at basic motorway sections. Changes in speed are higher around off-ramps than around on-ramps. This could be explained by the difference in the type of manoeuvre. Entering the motorway requires accelerating to the legal speed limit while exiting requires decelerating to a safe speed for taking the first curve of the off-ramp after the deceleration lane.

The location of the measured speed drop in the first 200 m downstream of the on-ramp gore corresponds with the location of the acceleration lane and the lower speed may be caused by entering traffic. The location of the speed drop 600 m prior to the off-ramp might be caused by pre-allocating exiting traffic. The higher speeds which are measured at about 750 m prior to the off-ramp might be caused by drivers who want to overtake vehicles that are pre-allocating towards the outside lane.

Our findings regarding the length over which the traffic stream is influenced by a ramp are based on a three-lane standard motorway only, under similar traffic and weather conditions. These findings are not compared to other motorway configurations or measurements in different conditions; therefore, they do not describe a general nature of turbulence. In Table 5, our results are compared to earlier findings. This comparison shows that our findings at on-ramps are comparable to the findings of Kondyli and

Table 5. Ramp influence areas.

On-ramp		Off-ramp		
Upstream (m)	Downstream (m)	Upstream (m)	Downstream (m)	Source
200	900	1000	–	This study
110	260	–	–	Kondyli and Elefteriadou (2012)
460	460	460	460	HCM (2010)
150	750	750	150	Rijkswaterstaat (2014)

Elefteriadou (2012) (the upstream value) and the Dutch motorway design guidelines (Rijkswaterstaat 2014). The influence length mentioned in the HCM deviates from our findings. These differences may, however, be partially explained by cultural differences in driving behaviour.

No valid off-ramp loop detectors between 700 and 1000 m were available and the spread of detectors between −170 m and 676 m is more than the required 150 m. This study, therefore, does not make clear at which distance the basic motorway values are reached downstream of off-ramps. Another limitation for the off-ramp measurements is that the last three data entries (at −170, 253 and 676 m) originate from the same site (site 1). Since the measurements for both speed and lane flow distribution from the downstream off-ramp detectors seem implausible, site 1 may for some reason not be representative. This could be explained by a large number of heavy vehicles, which are not included in this study because the number of heavy vehicles could not be retrieved from the loop detector data. A relatively large number of trucks could explain both the lower measured mean speed and the greater amount of traffic on the right lane.

When our findings are compared to the motorway design guidelines for ramp spacing, it is shown that the use of a single ramp influence length, as assumed in HCM (2010), does not correspond to the measured change in lane flow distribution. The measured changes in lane flow distribution are not symmetrically distributed around the acceleration or deceleration lane and are different for on-ramps and off-ramps. At on-ramps, the lane flow distribution mainly changes downstream of the ramp and at off-ramps it changes mainly upstream of the ramp. This principle corresponds to the method that is used in the Dutch guidelines (Rijkswaterstaat 2014), which uses specific upstream and downstream turbulence lengths which are different for on-ramps and off-ramps. Guidelines that use a fixed distance for ramp spacing, such as AASHTO (2001), FGSW (2008), The_Highways_Agency et al. (1994), are potentially useful. However, for the case displayed in Table 1, the desired ramp spacing between an on-ramp followed by an off-ramp the prescribed spacing ranges between 450 and 1100 m. Our findings show a change in lane flow distribution that ends at 900 m downstream of the on-ramp and starts at 1000 m upstream of the on-ramp. This means that a distance of 1900 m is required for a situation with no overlap of ramp influence areas; and therefore, none of the mentioned guidelines provides a situation with no overlap of ramp influence areas. This raises the question to what extent these areas can overlap and what the consequences of such an overlap are.

Conclusions

This study shows that combining data from different loop detectors at different sites is a useful method for studying macroscopic traffic characteristics at comparable sites. Sites

with comparable characteristics, such as the number of lanes, acceleration and deceleration lane lengths, types of lanes (e.g. peak hour lanes), average flow and speed limits, have comparable traffic flow characteristics such as actual speed and distribution of traffic over the different lanes. This enables us to get denser data than the standard interval of 300–500 m by which successive loop detectors are spaced.

The results show that the lane flow distribution on a three-lane motorway starts to change at about 200–300 m upstream of an on-ramp gore and remains until a maximum of about 500 m downstream of the gore. After 500 m, it changes back to a level comparable to that on a basic motorway section. At 900 m downstream of the gore, the lane densities are back to the original level. At an off-ramp, the fraction of flow starts to change at about 1000 m upstream of the gore, which corresponds with the first exit sign at 1200 m upstream of the off-ramp that introduces the upcoming motorway exit. The distance downstream of an off-ramp gore at which the lane flow distribution is back to the original basic motorway values could not be found. This is due to a limited number of loop detectors that fit our selection criteria and probably due to the lack of information about the number of heavy vehicles.

Our findings are useful for reflecting on motorway design guidelines, where the Dutch guideline (Rijkswaterstaat 2014) proves to provide reasonably accurate ramp influence area for a three-lane motorway. However, when it comes to designing a motorway based on turbulence, the question arises to what extent areas with a raised level of turbulence can overlap, this requires further research. Also, our measurements are taken for only one motorway configuration and in good weather conditions. A guideline, however, should provide a safe road design for all motorway configurations and should also take into account bad weather conditions. This should be considered when these results are used for design guideline purposes. Further research with an extended scope in configurations and environmental conditions is recommended. Also, an attempt to model the driving manoeuvres that lead to the observed phenomena is recommended.

The data showed a change in lane flow distribution and a change in speed compared to a basic motorway. The results show that drivers change lanes from the left lane to the centre lane and from the centre lane to the right lane, where the fraction of flow on the centre lane remains constant. However, loop detector data give no information on the frequency and direction of these lane changes, i.e. from which lane to which lane. Further research on this topic based on individual vehicle trajectory data is recommended.

Acknowledgements

The authors are grateful to the anonymous referees for their suggestions to improve the paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work is supported by the Dutch national road authority: Ministerie van Infrastructuur en Milieu.

References

AASHTO. 2001. “A Policy on Geometric Design of Highways and Streets.”.

AASHTO. 2011. “A Policy on Geometric Design of Highways and Streets.”.

Abdel-Aty, M., and A. Pande. 2005. “Identifying Crash Propensity Using Specific Traffic Speed Conditions.” *Journal of Safety Research* 36: 12–108.

Amin, M., and J. Banks. 2005. “Variation in Freeway Lane Use Patterns with Volume, Time of Day, and Location.” *Transportation Research Record: Journal of the Transportation Research Board* 1934: 132–139.

Banks, J. H., and M. Amin. 2003. “Test of Behavioral Theory of Multilane Traffic Flow: Queue and Queue Discharge Flows.” *Transportation Research Record: Journal of the Transportation Research Board* 1852: 159–166.

Banks, J. H., M. R. Amin, M. Cassidy, and K. Chung. 2003. “Validation of Daganzo’s Behavioral Theory of Multi-Lane Traffic Flow: Final Report.”

Bared, J. G., P. K. Edara, and T. Kim. 2006. “Safety Impact of Interchange Spacing on Urban Freeways.” Paper presented at the compendium of papers DVD, Annual Meeting of the Transportation Research Board, Washington, DC.

Beinum, A. V., H. Farah, F. Wegman, and S. Hoogendoorn. 2016. “Critical Assessment of Methodologies for Operations and Safety Evaluations of Freeway Turbulence.” *Transportation Research Record: Journal of the Transportation Research Board* 2556: 39–48. doi:10.3141/2556-05.

Carter, M., H. Rakha, and M. V. Aerde. 1999. “Variability of Traffic-Flow Measures Across Freeway Lanes.” *Canadian Journal of Civil Engineering* 26 (3): 270–281.

Daamen, W., M. Loot, and S. P. Hoogendoorn. 2010. “Empirical Analysis of Merging Behavior at Freeway on-Ramp.” *Transportation Research Record: Journal of the Transportation Research Board* 2188 (1): 108–118.

Daganzo, C. F. 2002a. “A Behavioral Theory of Multi-Lane Traffic Flow. Part I: Long Homogeneous Freeway Sections.” *Transportation Research Part B: Methodological* 36 (2): 131–158. doi:10.1016/S0191-2615(00)00042-4.

Daganzo, C. F. 2002b. “A Behavioral Theory of Multi-Lane Traffic Flow. Part II: Merges and the Onset of Congestion.” *Transportation Research Part B: Methodological* 36 (2): 159–169. doi:10.1016/S0191-2615(00)00043-6.

FGSW. 2008. “Richtlinie für die Anlage von Autobahnen (RAA).” In *Ausgabe*.

Fitzpatrick, K., R. Porter, G. Pesti, C.-L. Chu, E. Park, and T. Le. 2011. “Guidelines for Spacing Between Freeway Ramps.” *Transportation Research Record: Journal of the Transportation Research Board* 2262: 3–12.

Golob, T. F., W. W. Recker, and V. M. Alvarez. 2004. “Freeway Safety as a Function of Traffic Flow.” *Accident Analysis & Prevention* 36 (6): 933–946.

HCM. 2010. “Transportation Research Board of the National Academies.”

Hidas, P. 2005. “Modelling Vehicle Interactions in Microscopic Simulation of Merging and Weaving.” *Transportation Research Part C: Emerging Technologies* 13 (1): 37–62.

Hill, C., L. Elefteriadou, and A. Kondyli. 2015. “Exploratory Analysis of Lane Changing on Freeways Based on Driver Behavior.” *Journal of Transportation Engineering* 141 (4), doi:10.1061/(ASCE)TE.1943-5436.0000758.

Knoop, V. L., A. Duret, C. Buisson, and B. V. Arem. 2010. “Lane Distribution of Traffic Near Merging Zones Influence of Variable Speed Limits.” Paper presented at the 13th International IEEE Conference on Intelligent Transportation Systems, September 19–22. doi:10.1109/ITSC.2010.5625034.

Knoop, V., M. Keyvan-Ekbatani, M. De Baat, H. Taale, and S. Hoogendoorn. 2017. “Strategy-Based Driving Behaviour on Freeways: Findings of Test-Drive and On-Line Survey Study.”

Kondyli, A., and L. Elefteriadou. 2011. “Modeling Driver Behavior at Freeway-Ramp Merges.” *Transportation Research Record: Journal of the Transportation Research Board* 2249 (1): 29–37.

Kondyli, A., and L. Elefteriadou. 2012. “Driver Behavior at Freeway-Ramp Merging Areas Based on Instrumented Vehicle Observations.” *Transportation Letters* 4 (3): 129–142.

Laval, J. A., and L. Leclercq. 2008. “Microscopic Modeling of the Relaxation Phenomenon Using a Macroscopic Lane-Changing Model.” *Transportation Research Part B: Methodological* 42 (6): 511–522.

Leclercq, L., V. L. Knoop, F. Marczak, and S. P. Hoogendoorn. 2016. "Capacity Drops at Merges: New Analytical Investigations." *Transportation Research Part C: Emerging Technologies* 62: 171–181. doi:10.1016/j.trc.2015.06.025.

Lee, C., and M. Abdel-Aty. 2008. "Two-Level Nested Logit Model to Identify Traffic Flow Parameters Affecting Crash Occurrence on Freeway Ramps." *Transportation Research Record: Journal of the Transportation Research Board* 2083: 145–152. doi:10.3141/2083-17.

Lee, C., B. Hellinga, and F. Saccomanno. 2003. "Proactive Freeway Crash Prevention Using Real-Time Traffic Control." *Canadian Journal of Civil Engineering* 30 (6): 1034–1041.

Marczak, F., and C. Buisson. 2015. "A Macroscopic Model for Freeway Weaving Sections." *Computer-Aided Civil and Infrastructure Engineering* 30 (6): 464–477.

Minderhoud, M. M. 1999. "Supported driving: Impacts on Motorway Traffic flow." Doctoral thesis, Delft University of Technology.

NDW. 2015. "NDW website." Accessed December 21, 2015. http://ndw.dysi.nl/.

Ngoduy, D. 2008. "Operational Effects of Acceleration Lane on Main Traffic Flow at Discontinuities." *Transportmetrica* 4 (3): 195–207. doi:10.1080/18128600808685687.

Pilko, P., J. Bared, P. Edara, and T. Kim. 2007. "Safety Assessment of Interchange Spacing on Urban Freeways." *Tech Brief*.

Rijkswaterstaat. 2014. "Richtlijn Ontwerp Autosnelwegen".

Smith, S. A. 1985. *Freeway Data Collection for Studying Vehicle Interactions–Appendices H and I: US Department of Transportation*. Federal Highway Administration.

Sultan, B., M. Brackstone, B. Waterson, and E. Boer. 2002. "Modeling the Dynamic Cut-In Situation." *Transportation Research Record: Journal of the Transportation Research Board* 1803: 45–51.

Tang, T.-Q., H.-J. Huang, S. C. Wong, Z.-Y. Gao, and Y. Zhang. 2009. "A New Macro Model for Traffic Flow on a Highway with Ramps and Numerical Tests." *Communications in Theoretical Physics* 51 (1): 71–78.

Tang, T.-Q., H.-J. Huang, G. Xu, and Y. Zhang. 2008. "Wave Properties of a Traffic Flow Model on Highway with Ramps." *EPL (Europhysics Letters)* 84 (1): 14006.

The_Highways_Agency, Transport_Scotland, Transport_Wales, and The_Department_for_Regional_Development. 1994. "Design Manual for Roads and Bridges (DMRB), Volume 6, Section 2, Part 4 'The design of major interchanges'."