



Merging behaviour: Empirical comparison between two sites and new theory development [☆]



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ABSTRACT

This paper presents two empirical trajectory data sets focusing on the merging behaviour on a motorway, both in the Netherlands and in France. A careful review of the literature shows that the main theories explaining this behaviour rely on the hypothesis of gap acceptance, i.e. the fact that each driver has a certain threshold value depending on among other things the distance to the end of the acceleration lane, and when the offered gap is larger than this threshold the driver decides to merge.

We conducted a detailed comparative analysis of the two data sets examining the main variables identified in our conceptual model of merging behaviour. The contribution of this paper is that the analysis does not only focus on the accepted gaps, but it also takes into account the rejected gaps. The comparison of our observations with the critical gap formula in literature showed that this formula does not take into account the strong probability of rejecting a gap, even larger than the gap finally accepted.

Moreover, we created a logistic regression model that predicts the acceptance or rejection of a given gap, depending on the gap value and the speed difference between the merging vehicle and the putative follower. We have shown that two other factors impact the probability of rejecting or accepting a given gap, but these are significant for just one of the data sets: the distance to the end of the acceleration lane and the speed difference between the putative follower and the putative leader. This shows the impact of the local situation on the merging behaviour (e.g. traffic composition, road geometry, and traffic conditions).

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1. Introduction

Research into motorway bottlenecks has shown that driver behaviour at merging sections affects traffic operations and is the cause of breakdowns (Elefteriadou et al., 1995; Kerner and Rehborn, 1997; Yi and Mulinazzi, 2007). The breakdown events appear to be associated with interaction between the flow on the main motorway and the flow on the acceleration lane (or the ramp), which compete for the same capacity downstream the merging point.

Many models have been developed to describe and predict this process, and some of these models have been implemented in microscopic simulation models to provide a more realistic representation of traffic operations. However, due

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to a lack of microscopic empirical data these models have not been validated nor have the underlying assumptions been evaluated. In addition, no insights have been presented on the variability in merging behaviour, neither to show the effect of the road configuration nor to identify the cultural effect in driver behaviour.

The aim of this paper is therefore threefold. First of all, we compare merging behaviour on a site in the Netherlands to a site in France using microscopic empirical data. Secondly, using these empirical data and the results of the behavioural comparison we evaluate the assumptions of gap acceptance theory (underlying most of the developed merging models). After having observed that the gap acceptance theory is not able to reproduce the observed rejection of large gaps, we propose a model for accepting or rejecting a gap during a merging manoeuvre. This model is based on a logistic regression. The predictive power of the model, assessed on the two datasets, is 98%.

The empirical data have been obtained using a camera mounted underneath a helicopter. Using dedicated software the images have been stabilized and the trajectories have been automatically derived. As the trajectories have been obtained in a similar way for both sites, the analyses errors are assumed to be comparable for both data sets. To analyse merging behaviour of both sites, both simple and composite statistics (e.g. joint regression analyses) have been performed.

This paper starts with an extensive literature overview on experimental analyses of merging behaviour and models on merging behaviour. Then, a description is given of the data collection for Bodegraven (the Netherlands) and Grenoble (France). In chapter 4 the empirical data analyses are presented, starting with a conceptual framework containing our hypotheses on the merging behaviour (Section 4.1), followed by the global descriptive analyses (Section 4.2). Then, some particular relationships are studied in more detail, such as the relation between lengths of accepted/rejected gaps and merging location (Section 4.3), the relation between accepted gap and headway versus merging speed (Section 4.4), and the relation between merging speed and merging location (Section 4.5). Chapter 5 provides strong empirical evidence to reject the gap acceptance theory. In chapter 6 we therefore propose a model to predict acceptance or rejection of gaps based on the longitudinal position, the length of the gap and the difference in speed of the three vehicles involved into a merge: the putative leader, the putative follower and the merger. The paper ends with conclusions and recommendations for future research.

2. Literature review on experimental analyses and models for merging behaviour

This chapter discusses the existent literature on merging behaviour. Here, we start with an indication of the importance of merging behaviour in traffic operations (Section 2.1), followed by an overview of the experimental analyses of merging behaviour (Section 2.2). In Section 2.3 an overview of the merging models has been given, while Section 2.4 gives an overview of the definitions of the critical gap as applied in the most frequently used theory, the gap acceptance theory. We end with conclusions on the literature review.

2.1. Importance of merging behaviour in traffic operations

It is well known, and reported in many papers, that merges are one of the causes of motorway bottlenecks. Various characteristics of merges can be studied. Some authors concentrate on capacity sharing modelling and observations between the two entrances (Daganzo, 1995; Bar-Gera and Ahn, 2010; Chevallier and Leclercq, 2007). Other authors focus on the capacity drop caused by the merge i.e. the fact that when a merge is an active bottleneck, the total capacity is lower than what is observed in free flow (for examples of observations of this phenomenon, see Elefteriadou et al., 1995, 2006; Hall and Agye-mang-Duah, 1991; Chung et al., 2007). Others look at the impact lane changes, and especially those observed at merges, can have on stop and go waves (Laval, 2005; Oh and Yeo, 2012).

The fact that numerous queues occur in merges led traffic managers to propose ramp metering strategies, which are reported to be effective. The most recent on-site experimentation is reported in Bhourri et al. (2013) where they observed that the mean loss time is reduced by 3 min using control. Also the buffer time is significantly reduced.

All those researches convincingly show the importance of correct merge behaviour analyses.

2.2. Experimental analyses of merging behaviour

Fig. 1 illustrates the various variables characterising the merging process. We focus here on the merging vehicle and the vehicles surrounding him/her. We leave out the mainline drivers' lane choice modification i.e. courtesy lane changing. The merging behaviour cannot be correctly observed through point-located measurement devices such as electromagnetic loops. Therefore, authors of papers presenting phenomenological observations of the merging behaviour use trajectory measurement devices. A trajectory in our case is the set of positions occupied in the (x,y) plane over time. Two trajectory measurement methods exist: either measuring the trajectory of the merger with an equipped vehicle (using GPS) or measuring trajectories outside of the vehicle, from video camera recordings.

A few papers were published on experimental observation of lane changers' trajectories at merge locations. Tables 1a and 1b recall the main merging characteristics presented in these papers. Some papers use instrumented vehicles (Kondyli and Elefteriadou, 2010, 2011; Sarvi and Kuwahara, 2007) where the trajectory of the subject vehicle is estimated from GPS data. The GPS device is accompanied with a set of devices allowing to capture the position of the neighbouring vehicles. This

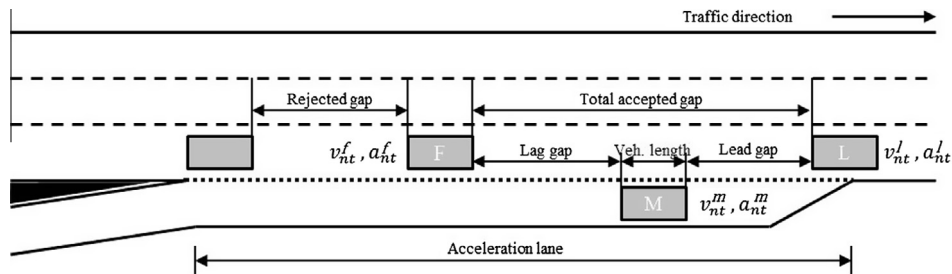


Fig. 1. Description of the variables of a merging process.

Table 1a

Papers presenting experimental analysis of merge behaviours, using mostly video camera information. (L, F, M stands for leader, follower and merger, respectively, MM for Merging Manoeuvres and RM for ramp metering).

Paper	Hidas (2005b)	Choudhury et al. (2006)	Sarvi et al. (2002)
Location	Sydney CBD (Aus) section(s?) of about 80–100 m	NGSIM datasets.I80 Emeryville, US101 Los Angeles, CA (USA)	Tokyo Metropolitan expressway (JP). Junctions Hamazaki-bashi and Inchinohachi for video analysis; second one only for instrumented vehicle
Traffic conditions	Congestion	Congestion	Congestion
Number of lanes of the motorway (of the ramp)	Not given	6 (1)	2 (2)
Type of data collection device	Video recording from traffic surveillance	Video mounted on a high building	Video mounted on high buildings
Number of observed merges	73	Not given	200
Number of different drivers	73	Not given	200 (159 cars and 41 trucks)
Duration of the measurement periods	4 h	3 * 15 min	8 h (from which some MM were selected)
Time frequency of measurements	0.2 s	0.1 s	0.15 s
Precision of measurements	1 m (positions of vehicles)	1 m (positions of vehicles)	Not given
Variables used for analysis	L, F, M: instant. V, relative V, gaps (lead and lag)	L, F, M: instant. X, V, A, relative V, gaps (lead and lag), longitudinal position of the merge	L, F, M: instant. X, V, A

Table 1b

Papers presenting experimental analysis of merge behaviours using mostly instrumented vehicle information. (L, F, M stands for leader, follower and merger, respectively, MM for Merging Manoeuvres and RM for ramp metering).

Paper	Kondyli and Elefteriadou (2010, 2011)	Wu et al. (2007)
Location	I-95 Jacksonville, FL (USA): five different merges	M27 Junction 11, Southampton (UK)
Traffic conditions	273 merges in free flow; 42 in congestion	Almost free flow
Number of lanes of the motorway (of the ramp)	3 (1 or 2, depending on the ramp)	3 (2)
Type of data collection device	Instrumented vehicle	11 video cameras
Number of observed merges	315	Camera not used to assess merger behaviour but passing traffic
Number of different drivers	31	Not given
Duration of measurement periods	1 h * 31	2 * 14 days (with and without RM)
Time freq. of measurements	0.5 s	0.1 s
Precision of measurements	Not given	Not given
Variables used for analysis	X, V of IV + lead and lag gaps (from which relative V and A are extracted)	X, V of IV + relative distance and speed of L and F, longitudinal position of the merge

experimental device led the authors to focus on the value of accepted gaps and not on the rejected ones, which could be accessed with more difficulties.

In all papers presented in the tables, the data analysis work was conducted with the aim of defining and calibrating a model. In the merge paper of Hidas. (2005b), one of the conclusions was the distinction between three types of merges: free lane change, forced lane change and cooperative lane change. For the free lane change, the author explains that provided that the lead and the lag gaps “are not less than some given acceptable space gaps” the gap will be accepted. Choudhury et al. (2007) and Kondyli and Elefteriadou (2010, 2011), observe the acceptance of a gap and they do not consider the gap rejection. Sarvi and Kuwahara (2007) focus on the acceleration and deceleration phase of the merger. For this, they combine two types of information (intra-vehicle data collection and video data collection) to calibrate their model of acceleration and deceleration of the vehicles during the merge process. Wu et al. (2007) study the impact of ramp metering on the driver's behaviour, both on the passing traffic and on the merger. They conclude that ramp metering has no impact on the passing traffic, but it has some effect on the merging characteristics: the presence of ramp metering increases the accepted gap size and reduces the merger speed.

None of the above presented papers analysed the data in observing the rejected gaps: the gaps a merger could have chosen (because they are present when he/she drives along the acceleration lane, but he/she prefers driving ahead and inserts himself into a another gap downstream, see Fig. 1). In the case of instrumented vehicles this is rather logical, because the relative distance with the putative leader and the putative follower becomes measurable only when the merger is located in between, but when a complete set of trajectories is attainable (from the NGSIM dataset for example), this is more surprising.

Finally, we have to mention a recent paper (Daamen et al., 2010) that scrutinises for the first time the statistical relations between various observable variables: longitudinal position of the merge, time headway, etc. For the first time, this paper also puts into evidence that some drivers reject acceptable gaps before merging. We see hereafter a confirmation of this important point.

Each of the papers listed above present data collected at a single location; even if Kondyli and Elefteriadou (2010) gather data on five different ramps, they are all located in the same motorway and the same city. Therefore, we cannot use those papers to evaluate if there is a country related way of merging. We will hereafter compare two data sets, one obtained in the Netherlands and already used by Daamen et al. (2010), the other one obtained inside the MOCOPo project in Grenoble, France (MOCOPo, 2012).

2.3. Merging behaviour models

When modelling merging behaviour, several techniques can be distinguished. Most models are based on gap acceptance theory, but also models based on game theory and discrete choice modelling have been developed. In the following, a short overview is given of the models developed using these techniques.

Let us concentrate on the main part of the literature: models based on gap acceptance theory. The principle of the gap acceptance theory is that a driver assesses an offered gap (distance or time between two vehicles on the main road that it is driving next to). In this assessment, the gap is compared to a so-called critical gap: if the offered gap is larger than the critical gap the gap will be accepted, otherwise it is rejected and the driver will look for another offered gap (Barceló, 2010). The critical gap depends on the characteristics of the traffic participant, the vehicle and the road, and can be expressed either in time or in distance.

The first models using gap acceptance simplify the complex dynamic interaction between the motorway traffic and the ramp traffic by assuming the ramp traffic has no influence on the motorway traffic (Michaels and Fazio, 1989; Yang and Koutsopoulos, 1996; Lee, 2006). Existing simulation models (e.g. Aimsun and Vissim) are often based on a relatively simple gap acceptance model (Xiao et al., 2005). For Vissim the exact gap acceptance model is not specified, but the increased urgency to merge towards the end of the acceleration lane is expressed in the aggressiveness of the driver (PTV, 2008). The gap acceptance behaviour in Vissim is user-definable and location specific (Bloomberg and Dale, 2000). The merging model in Aimsun can be considered as a further evolution of the Gipps lane change model (Barceló and Casas, 2005), with some extra parameters (reaction time, maximum waiting time, time distance on ramp) to indicate the growing urgency to change lanes when reaching the end of the merging lane and with increasing waiting times (Hidas, 2005a). When reaching an off-ramp, vehicles in the adjacent lane can modify their behaviour in order to allow a gap large enough for the lane-changing vehicle (Barceló and Casas, 2005), but it is not clear whether the same behaviour holds for merging vehicles.

In Sarvi and Kuwahara (2007), it is reported that none of the most frequently used commercial simulation tools is able to correctly reproduce the traffic behaviour near merges, especially in congested situations: for example PARAMICS underestimates the capacity, while Aimsun and Vissim tend to let vehicles disappear from the ramp after some blocking time.

As shown in the previous section, motorway traffic indeed shows cooperative behaviour by performing cooperative lane changing or yielding to create gaps. Several models have specifically been developed to model cooperative lane changing (Hidas, 2002) and forced merging behaviours (Ahmed, 1999; Rao, 2006). Hidas (2005b) developed a merging model that includes both cooperative and forced merge components, but the cooperative lane change part only consists of modelling the decision of the lag driver (whether or not to provide courtesy to the merging driver). Choudhury et al. (2007) includes the decision on cooperative lane change behaviour of the merging driver (whether or not to initiate or execute the courtesy lane change), but the lag driver behaviour is not included explicitly. However, many of the estimated coefficients do not seem to

be significant. Inclusion of target gap choice and speed adjustment to reach a targeted gap in the decision framework of the merging driver can help in improving the match of speed as well as ensuring a better simulation of the location of merges (Choudhury et al., 2007).

Kita and Fukuyama (1999) and Kita and Keishi (2002) were one of the first to model vehicle interactions during merging as a game, where each vehicle involved in the merge determines its actions by considering the other vehicles' alternatives. Collision risk is one of the factors the decisions are based on. However, the vehicle speeds are assumed constant during the merging process, which the previous section shows to be incorrect. In addition, the motorway vehicle may have performed cooperative behaviour before actually interacting with the merging vehicle. Wang et al. (2005) use the game theory idea proposed by Kita and Keishi (2002) and explicitly add both the nearside motorway traffic actions and the remaining distance to the end of the merging lane. In this model, both the probabilities for cooperative lane changing and for courtesy yielding are described as binomial distributions. Liu et al. (2007) developed an improved game-theoretic framework, in which vehicle speeds are no longer assumed constant, while minimum safety gaps are explicitly considered in the drivers' payoff functions. In addition, more realistic behavioural rules are proposed, such as motorway vehicles trying to maintain their initial car-following state and to minimise speed variations, while merging vehicles try to merge as fast as possible, subject to safety constraints. The drawback of this model is that the game only involves the merging vehicle and the lag vehicle; other vehicles on the motorway are left out of the process.

Kondyli and Eleftheriadou (2011) model both cooperative and forced merge components, where the cooperative part can be initiated both by the merging driver and by the lag driver. They use a discrete choice framework to model the various model components, where the model has been split into a gap acceptance model, a deceleration model (one for cooperative merging and one for free merging) and a merging turbulence model.

2.4. Critical gap definition in literature

The overview of various merging behaviour models has shown that most models are based on gap acceptance theory, while the formulations of the critical gap as well as its dynamics vary per model. This section gives more details on the critical gap used in each model, starting with an overview of influence factors per model in Table 2.

Although most authors indicate which factors have an influence on the critical gaps, the exact formulas to calculate these critical gaps are not always given. The only papers giving the formulas estimated using empirical data are Ahmed (1999), Lee (2006), Rao (2006) and Choudhury et al. (2007). As Choudhury et al. (2007) build upon the other three papers and includes the most extensive model, we limit ourselves to the formulas estimated in this paper, which is used as basis for the comparison of empirical data and gap acceptance models in chapter 5.

The paper does not only distinguish between normal, courtesy and forced merging, but the critical gap has been split into a lead gap and a lag gap, that is, a gap between the putative leader vehicle and the merging vehicle and a gap between the merging vehicle and the putative following vehicle respectively. Eq. (1) shows the equation for the lead gap G_{nt}^{lead} , while the lag gap G_{nt}^{lag} is given in Eq. (2):

$$G_{nt}^{lead} = \exp \left(\gamma^{ilead} + \frac{1.32}{1 + \exp(0.420 + 0.355v_n)} d_{nt} + 0.521 \left(1 + \frac{1}{1 + \exp(-\text{Max}(0, \Delta V_{nt}^{avg}))} \right) \right. \\ \left. - 0.505 \text{Min}(0, \Delta V_{nt}^{lead}) + \alpha_{nt}^{ilead} v_n + \epsilon_{nt}^{ilead} \right) \quad (1)$$

$$G_{nt}^{lag} = \exp \left(\gamma^{ilag} + \frac{0.439}{1 + \exp(0.0242 + 0.00018v_n)} d_{nt} + 0.208 \text{Max}(0, \Delta V_{nt}^{lag}) \right. \\ \left. + 0.184 \text{Min}(0, \Delta V_{nt}^{lag}) + 0.0545 \text{Max}(0, a_{nt}^{lag}) + \alpha_{nt}^{ilag} v_n + \epsilon_{nt}^{ilag} \right) \quad (2)$$

where $i \in \{\text{normal}, \text{courtesy}, \text{forced}\}$, γ^{ilead} and γ^{ilag} are lead and lag gap constants for merge type i , d_{nt} is the remaining distance to the end of the acceleration point (expressed in multiples of 10 m), ΔV_{nt}^{avg} is the relative speed of the average speed on the motorway with respect to the merging vehicle (in m/s), ΔV_{nt}^{lead} and ΔV_{nt}^{lag} are relative speeds of the putative leader vehicle and the putative follower vehicle with respect to the merging vehicle (in m/s) respectively, a_{nt}^{lag} is the acceleration of the putative follower vehicle, and ϵ_{nt}^{ilead} and ϵ_{nt}^{ilag} are random error terms: $\epsilon_{nt}^{ilead} \sim N(0, \sigma_{ilead}^2)$, $\epsilon_{nt}^{ilag} \sim N(0, \sigma_{ilag}^2)$ (Choudhury et al., 2007). The estimation on the data leads to the coefficients for the three merging types in Table 3.

From Table 3 it can be seen that not all coefficients have been significantly estimated, especially for the courtesy merges, probably due to the size of the dataset.

2.5. Conclusions

We have seen that ramps are very often reported as one of the main causes of motorway congestion. This type of infrastructure can be studied with the help of lane by lane flow analysis. It is suspected by most authors that the disturbance created by the merge into the mainline flow is also a key factor of the traffic characteristics near ramps, especially the capacity drop. Therefore understanding the way how vehicles insert themselves from the acceleration lane towards the main motorway section is a necessity which is now accessible, thanks to the detailed trajectory data provided by helicopter video collection.

Table 3

Coefficients for lead and lag gaps (Choudhury et al. (2007)).

	t-Statistics		t-Statistics		t-Statistics
Normal merge					
$\gamma^{normal\ lead} = -0.230$	-0.33	$\alpha_{nt}^{normal\ lead} = -0.819$	-3.12	$\epsilon_{nt}^{normal\ lead} \sim (0, 3.42^2)$	9.67
$\gamma^{normal\ lag} = 0.198$	2.87	$\alpha_{nt}^{normal\ lag} = -0.000776$	-0.01	$\epsilon_{nt}^{normal\ lag} \sim (0, 0.840^2)$	3.03
Courtesy merge					
$\gamma^{courtesy\ lead} = -0.582$	-0.20	$\alpha_{nt}^{courtesy\ lead} = -0.0540$	-0.03	$\epsilon_{nt}^{courtesy\ lead} \sim (0, 0.0109^2)$	0.08
$\gamma^{courtesy\ lag} = -1.23$	-0.07	$\alpha_{nt}^{courtesy\ lag} = -0.0226$	-0.04	$\epsilon_{nt}^{courtesy\ lag} \sim (0, 0.554^2)$	0.05
Forced merge					
$\gamma^{forced\ lead} = 3.11$	2.11	$\alpha_{nt}^{forced\ lead} = -0.0401$	-0.07	$\epsilon_{nt}^{forced\ lead} \sim (0, 7.95^2)$	5.82
$\gamma^{forced\ lag} = -2.53$	2.11	$\alpha_{nt}^{forced\ lag} = -0.0239$	0.19	$\epsilon_{nt}^{forced\ lag} \sim (0, 0.465^2)$	2.49

From the detailed literature review above, we can summarise the following key findings:

- Depending on the traffic conditions (free/congested flow) and the space availability on the shoulder lane, the merger will choose among various merges types: normal merge, forced merge or, if the motorway drivers adapt their speed and distances in between, courtesy merge.
- Most of the models rely on the idea that each gap bigger than a critical gap will be accepted. Some papers give an explicit formula of those critical gaps.
- No comparison between two sites was realised in the papers we have the opportunity to refer to.
- None of the papers listed above is studying the rejection of some gaps whose length might be bigger than the length of the gap the driver will finally chose to insert into.

As the merging process is disturbing the motorway traffic, one can imagine that if a significant part of the mergers reject gaps that are bigger than the ones they finally accept, the merging process will be even more disturbing than if all of them insert him/herself into the largest gap. Thus, observing this phenomenon is of importance for the understanding of the congestion occurring on motorways.

3. Data collection

To study merging behaviour in more detail, empirical data have been collected at a microscopic level, describing the position of every vehicle at every time step (trajectories of each individual vehicle). The data have been collected using the helicopter technique developed by Hoogendoorn et al. (2003). This technique uses a high resolution digital camera mounted underneath a helicopter gathering successive images. The length of road stretch that can be captured by the camera depends on the flying height of the helicopter, but its practical length is about 450 m. Data have been collected at two different sites, one in the Netherlands (Bodegraven) and one in France (Grenoble). This way not only the effects of different roadway configurations, but also differences in driver behaviour may be investigated. Section 3.1 gives a more detailed overview of the two collection sites, while Section 3.2 provides insight into the data collection technique, which was similar for both sites. In Section 3.3 the traffic conditions and other meta data are given for both sites.

3.1. Data collection sites: Bodegraven (the Netherlands) and Grenoble (France)

The data have been collected in Bodegraven (the Netherlands) and France (Grenoble) respectively. Fig. 2 shows the road configuration of both layouts.

In the Netherlands, the data collection site is located at the motorway A12 from Gouda to Utrecht. The acceleration lane has a length of 283 m, of which the first 200 m has a constant width, after which the acceleration lane starts to narrow down. The maximum speed on the main road is 120 km/h. The maximum speed on the road leading towards the acceleration lane is 100 km/h. The connecting road towards the acceleration lane is constructed in such a way that no speed reduction is required. The frog of the acceleration lane is extended with a stretch of about 50 m of a solid separation line between the acceleration lane and the main road. Then the block marking starts. On the main road the line marking between the right and middle lane is designed in such a way that a lane change from the middle to the right lane is prohibited but a lane change from the right lane to the middle lane is allowed, thus cooperative lane changes are still possible.

In Grenoble, the data collection site is the junction between the motorways A41 and RN87, in the south-eastern part of the city. The acceleration lane has a total length of 210 m with a progressive narrowing in the last 120 m. The speed limit is 90 km/h. As can be seen in Fig. 2b, the on-ramp is significantly curved at the beginning, but the drivers are able to accelerate before entering the ramp itself. 2 km upstream of the ramp, a traffic signal creates platoons of vehicles. Therefore, arrival pattern at the on-ramp is characteristic.

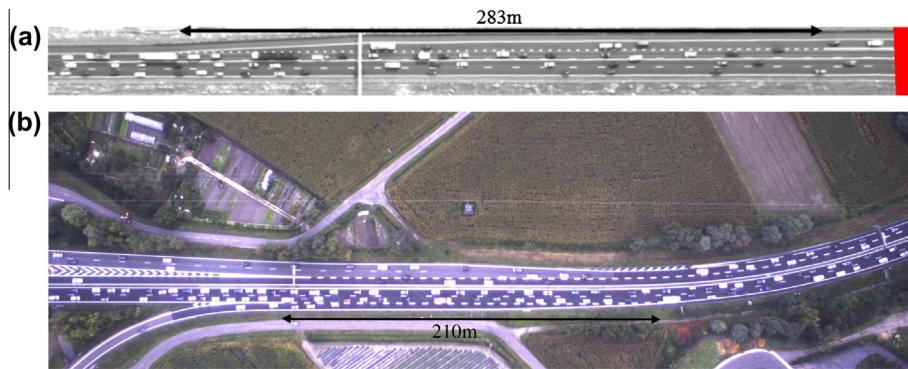


Fig. 2. Data collection site of (a) Bodegraven and (b) Grenoble. (a) Data collection site Bodegraven. (b) Data collection site Grenoble.

3.2. Data collection technique

As stated before, microscopic empirical data have been collected using a video camera attached underneath a helicopter. During a long period of time (35–60 min) the helicopter hovered above the on-ramp while recording a video with a frame rate of 15 (Bodegraven) or between 10 and 30 (Grenoble) images per second. As it is impossible for the helicopter to hover at a stable position (due to changing winds, minimal instability of the hands of the pilot and the natural willingness of the helicopter to fly forward), the first step is to stabilise the images. This stabilisation has been performed using a dedicated tool called ‘ImageTracker’ developed at the Delft University of Technology (Knoppers et al., 2012). The next step is to recognise the vehicles in the stabilised images.

This is done in three steps. First, a mean background image is defined and subtracted from each image. Then, the pixels differing from the background are identified and grouped into “blobs”. Finally, “blobs” present in successive images are linked into trajectories of a given vehicle.

3.3. Traffic conditions and other meta-data

In Bodegraven, the weather conditions during the whole data collection of 35 min on the 24th of April 2008 were dry, clouded and the viewing distance was good (Loot, 2009). The observations started at 15:00, when a high flow was present

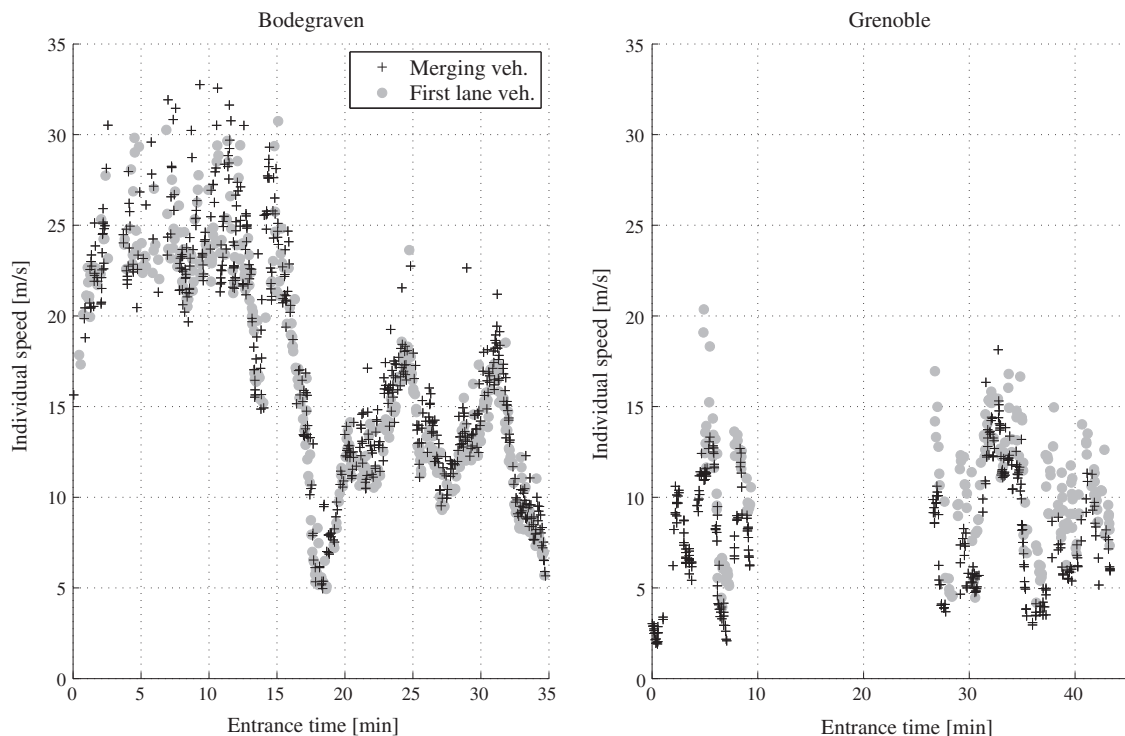


Fig. 3. Traffic conditions in Bodegraven (on the left) and Grenoble (on the right).

on the motorway, but no congestion occurred. The amount of traffic on the on-ramp is relatively high. After about 15 min a stop and go wave passed the observation location with a typical speed, coming from a downstream position. Shortly after the stop and go wave passed, congestion occurred around the on-ramp.

The weather conditions, as well, were dry and clouded for the Grenoble data collection period (14th of September 2011). The traffic is congested with a speed around 10 m per second. As said before, the merging traffic here is pulsed by the traffic signal present upstream on the merging incoming link. We chose to focus our data collection on periods where the merging traffic is sufficient to permit a correct study of the merging behaviour. Therefore, the data analysed and presented below are not continuous in time, but the traffic conditions are rather homogeneous across the observation periods.

The traffic conditions on both sites are shown in Fig. 3. Where traffic on the main motorway in Bodegraven is observed both in free flow and in congested conditions, the observations in Grenoble are restricted to congested conditions. In order to be able to compare the two sites, the remainder of this paper considers merging behaviour in congested conditions only.

4. Empirical data analyses

In this chapter we analyse the merging behaviour using datasets collected in Bodegraven and Grenoble respectively. In order to structure the data analyses, we start by introducing a conceptual framework describing the merging behaviour in Section 4.1. In this framework, the influencing factors on merging behaviour are defined, which are the basis of the descriptive analyses presented in Section 4.2. Then, some particular relationships are studied in more detail, such as the relation between lengths of accepted/rejected gaps and merging location (Section 4.3), the relation between accepted gap and headway versus merging speed (Section 4.4), and the relation between merging speed and merging location (Section 4.5).

4.1. Conceptual framework

Based on the literature study described in chapter 2 we have composed a conceptual model describing merging behaviour, see Fig. 4. In this model, the input of the decision to merge consists of the offered gaps, the road configuration (with the length of the acceleration as most important characteristic) and the characteristics of the merging driver. The output of the decision are the accepted gap and the rejected gaps, in case more than one gap was offered. When a gap has been accepted, also the location of this gap on the acceleration lane as well as the speed of the merging vehicle at the time of merging are decided, and thus outcomes of the decision process. The offered gaps are a result of the traffic conditions on the main road, and particularly on the shoulder lane, the speed and acceleration of the vehicles composing the gaps (putative leader and putative follower) and possible cooperative behaviour of vehicles on the main road, such as cooperative lane changing and courtesy yielding.

From this conceptual model, it is possible to derive the influence factors. Instead of making a long list of variables, we have chosen to structure these according to characteristics of the accepted gap, the road configuration, the offered gap and the traffic conditions (see Table 4).

In the next section, we perform some descriptive analyses on these influencing factors. For this, we focus on the characteristics of the accepted gap, the road configuration and the offered gaps, as these characteristics will most likely have a direct effect on the merging decision. Due to the accuracy of the data, we do not analyse the vehicle accelerations. In addition,

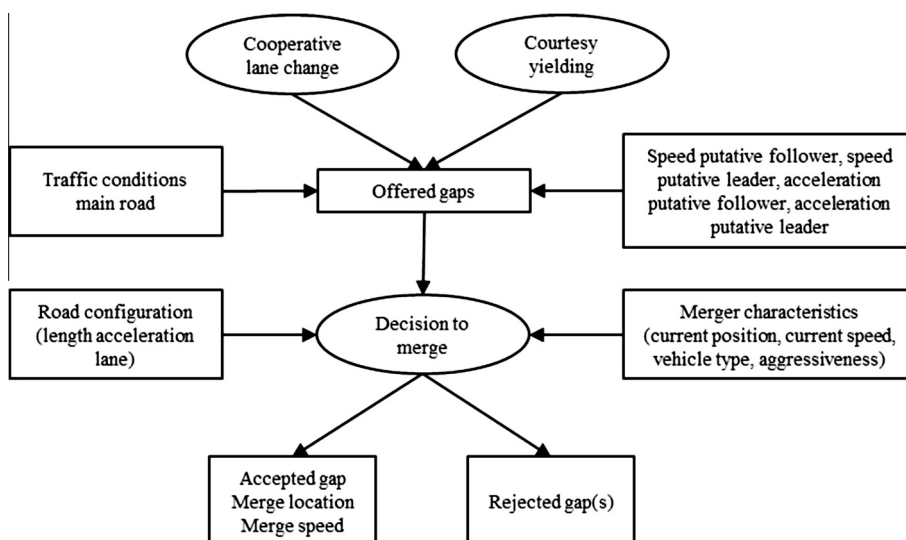


Fig. 4. Conceptual framework of merging behaviour.

Table 4

Influence factors for the merging behaviour.

Accepted gap	Rejected gap(s)	Road configuration	Offered gap	Traffic conditions
Gap length (in m)	Gap length (in m)	Length acceleration lane	Speed putative follower	Density main road
Headway (in s)	Headway (in s)		Speed putative leader	Speed main road
Location			Acceleration putative follower	Congestion/free flow
Speed merging vehicle			Acceleration putative leader	
Vehicle type				

the vehicle types are not studied, as in Grenoble the traffic mainly consists of passenger cars, so statistical analyses on heavy vehicles are not possible. This leads to the following analyses:

- Length of accepted and rejected gap (in m) – merging location.
- Speed merging vehicle – length accepted gap (in m).
- Speed merging vehicle – headway (in s).
- Speed merging vehicle – merging location.

4.2. Descriptive analyses

As indicated in the previous section, this section shows descriptive analyses on the data describing merging behaviour in congested conditions in Bodegraven and Grenoble. To see whether the merging behaviour differs between the two sites we start the analyses by showing the cumulative curves of the length of the accepted gap, the length of the rejected gap(s), the merging position and the speed of the merging vehicle, see Fig. 5.

Both the accepted gaps and the rejected gaps are larger for Bodegraven than for Grenoble, only the largest rejected gaps are similar for both sites. In addition, the variation in accepted gaps is much higher in Bodegraven than in Grenoble, which is most likely due to the traffic conditions (severity of congestion) on the main road. The merging position is expressed relative to the length of the acceleration lane, as this length is longer for Bodegraven (283 m) than for Grenoble (210 m). According to the figure, the merging positions are better distributed along the acceleration lane in Bodegraven than in Grenoble, where more vehicles seem to merge near the middle of the acceleration lane. The merging speed in Bodegraven is about 3 m/s higher than in Grenoble, as the cumulative curve is as a whole more shifted towards the higher speeds. The shape of the curve is similar for both sites.

After these first insights into the different behaviours at both sites, we continue with analyses of multiple factors, to see whether we can find a relation between these. For these analyses we focus on the factors directly describing merging behaviour, that is, the factors in the three most left columns of Table 4.

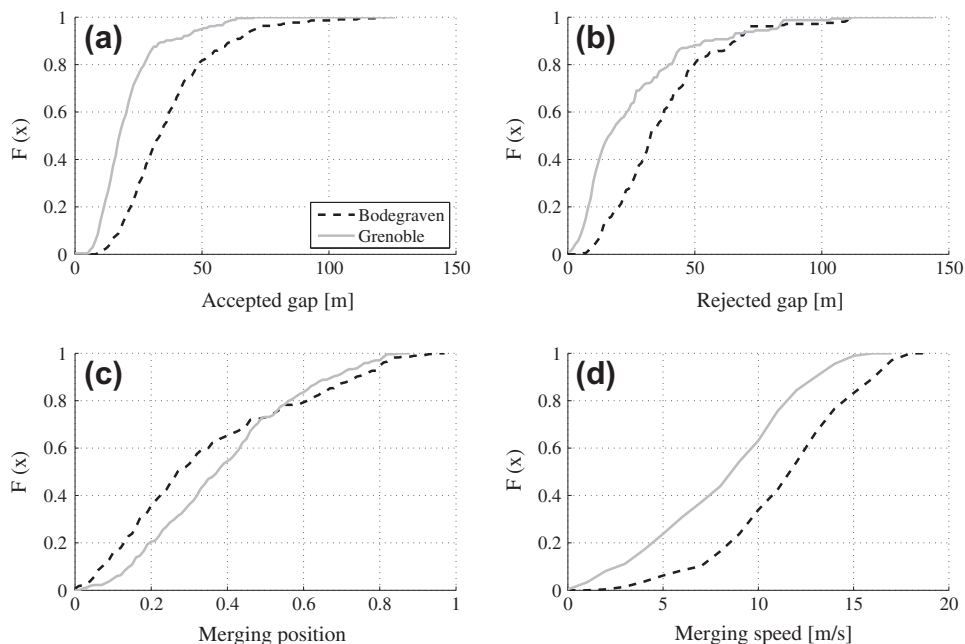


Fig. 5. Cumulative distributions for both Bodegraven and Grenoble of (a) the length of the accepted gap, (b) the length of the rejected gap(s), (c) the merging position and (d) the speed of the merging vehicle.

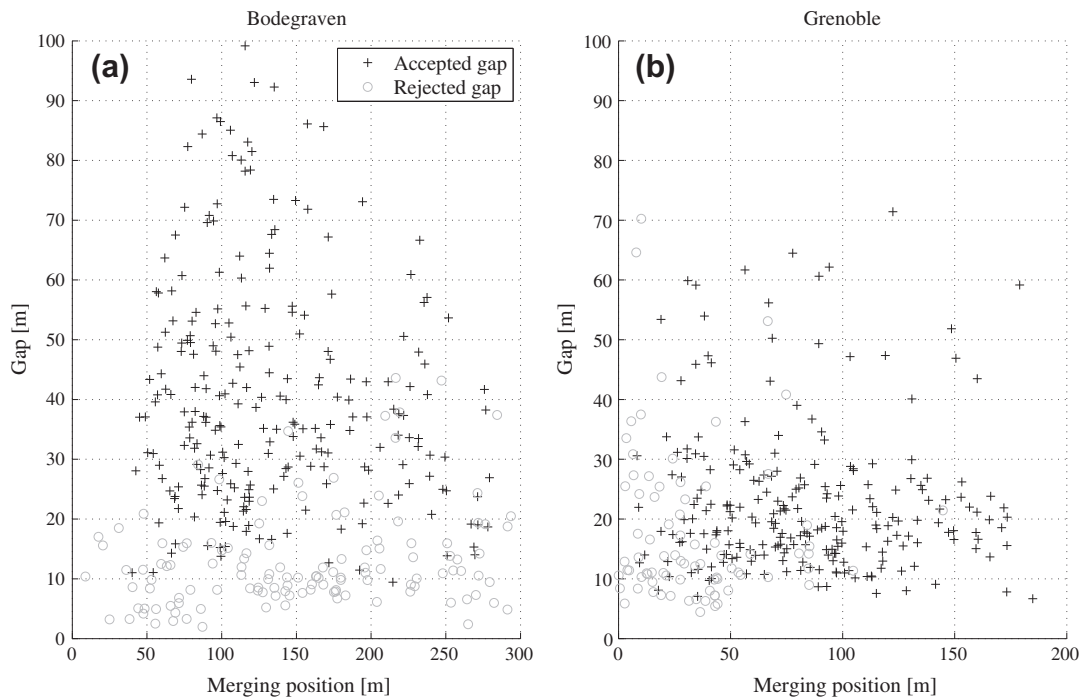


Fig. 6. Relation between gap (accepted and rejected) and merging position for (a) Bodegraven and (b) Grenoble.

4.3. Relation between the length of the accepted/rejected gap and the merging location

We start these analyses with the relation between the length of the accepted gap and the rejected gap and the location of the merge, see Fig. 6. The first immediate conclusion we can draw is that there is a concentration of rejected gaps. However, the location of the concentration is different for Bodegraven and Grenoble: where in Bodegraven the rejected gaps are in general shorter than the accepted gaps over the total length of the acceleration lane (as one would in general expect), in Grenoble the rejected gaps are concentrated at the beginning of the acceleration lane. Towards the end of the acceleration lane in Grenoble not many rejected gaps are present: it appears that when a gap is present, it is immediately accepted, independent of its length. In both locations rejected gaps are scattered with the accepted gaps, clearly showing inconsistent choice behaviour between drivers and maybe even within drivers.

4.4. Accepted gap and headway versus merging speed

The next analysis deals with the relation between accepted gap and merging speed, see Fig. 7. First of all, we can see that the observed merging speeds in Grenoble are smaller than the observed speeds in Bodegraven, which is mainly due to the congested conditions on the main road. For the Grenoble dataset, the variance in accepted gap seems to increase with

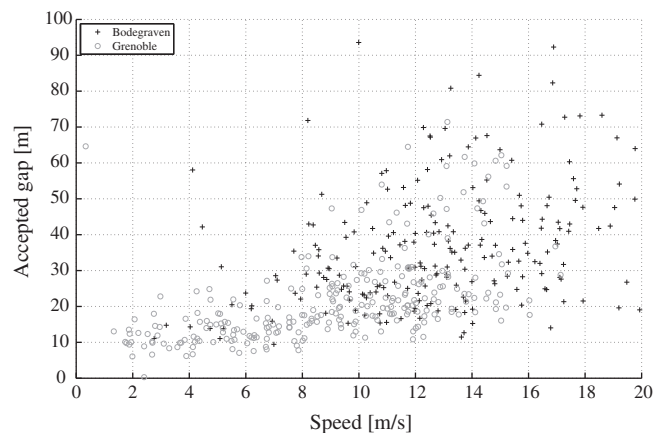


Fig. 7. Relation between accepted gap and speed of the merging vehicle.

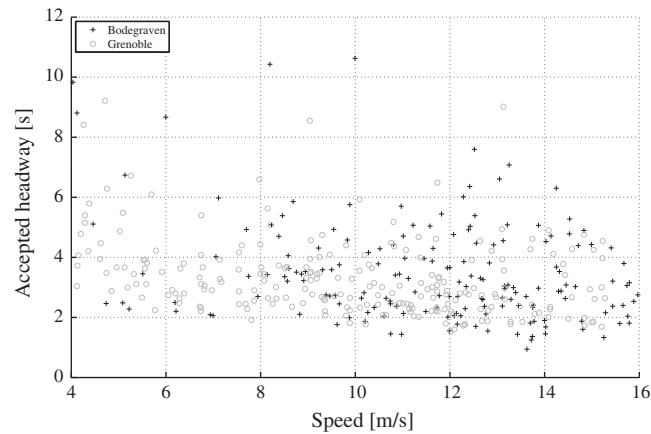


Fig. 8. Relation between headway and speed of the merging vehicle.

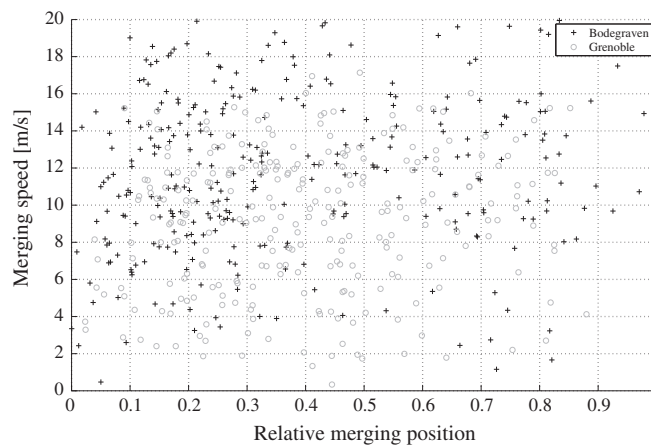


Fig. 9. Relation between merging speed and merging location.

increasing speed, while in Bodegraven this variance seems to remain constant (although less data points are observed for lower speeds). However, at both sites a slightly increasing trend can be observed: in general the accepted gaps are more or less constant at lower speeds and increase with increasing speed. In Grenoble, the accepted gap is shorter than in Bodegraven, although at larger speeds (>18 m/s) this difference seems to fade away. One could therefore argue that this difference is not so much a cultural or behavioural difference, but caused by the different traffic conditions. The occurrence of severe congestion on the main road forces drivers to accept a shorter gap than they would have been willing to accept.

Fig. 8 shows the relation between headway and merging speed. Apart from the fact that the observations in Bodegraven are concentrated on the right hand side of the figure (high merging speeds) and the observations in Grenoble on the left hand side of the figure (low merging speeds), the headways do not seem to differ much. Also, the large variance in observed headways seems to be similar for both sites, and independent from the merging speed.

4.5. Relation between merging speed and merging location

The final analysis shown in this section is the relation between merging speed and merging location, see Fig. 9. The figure clearly shows the large variance in merging speeds, without any relation to the merging position. This holds both for the site of Bodegraven and for the site of Grenoble. It is not possible to identify a difference in merging speed towards the end of the acceleration lane.

5. Validation of gap acceptance theory

This chapter discusses the validity of the gap acceptance theory based on the analyses on the empirical data shown in the previous chapter. We choose to evaluate the gap acceptance theory, as our literature review shows this theory has been most frequently applied in literature.

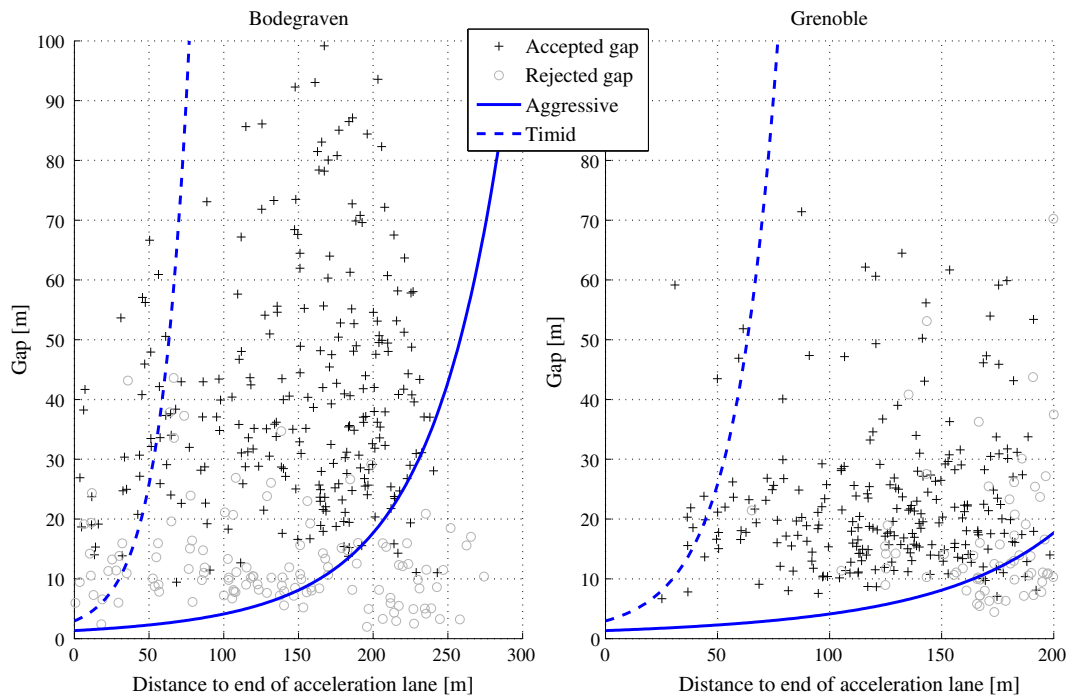


Fig. 10. Relation between gap and distance to end of acceleration lane with critical gap relations according to Choudhury et al. (2007).

As the gap acceptance theory assumes consistent driver behaviour, rejected gaps will not be larger than accepted gaps, which has already been refuted in Daamen et al. (2010). The theory also implies that if no gaps are offered larger than a critical gap, the vehicle will reach the end of the acceleration lane without having found a gap, and thus without having merged. This effect is clearly visible in microscopic simulation tools, where queues start to build up at the end of the acceleration lane. However, Fig. 9 does not show a decreased speed when merging at the end of the acceleration lane (which would be the consequence of such a queue) nor did the images show that any vehicle was not able to merge.

As stated in the literature review, Choudhury et al. (2007) are one of the few authors explicitly describing the critical gap relation. Fig. 10 represents both experimental observations and critical gap value curves resulting of the critical gap model (Choudhury et al., 2007). The meaning of the gap acceptance model is that below the continuous (respectively dashed) line, every gap is under critical and predicted to be rejected by an aggressive (respectively timid) driver. On the other hand, every gap present above the critical gap line should be accepted by a driver. Although in the observed data the type of driver cannot be identified, it is clear that the critical gap lines do not distinguish the accepted gaps from the rejected gaps. It would also imply that the driver population in Grenoble is very aggressive, as none of the rejected gaps are located on top of the critical gap line of timid drivers, whereas in Bodegraven, several rejected gaps can be found at the end of the acceleration lane that are rejected.

6. Generalised linear model to calculate probabilities to reject or accept gaps

This section presents a generalised linear model to quantify the influencing factors on the probability whether drivers accept or reject a certain gap. Two types of gaps are observed in the data (see Table 5):

- Accepted gaps correspond to the net distances between the putative leader and the putative follower in which vehicles merge coming from the acceleration lane;
- Rejected gaps correspond to the net distances between two vehicles on the shoulder lane which are passed by vehicles driving on the acceleration lane, which merge further downstream and thus reject these offered gaps.

Table 5

Sample sizes for both datasets.

	Number of accepted gaps	Number of rejected gaps	Total
Bodegraven	377	100	477
Grenoble	242	117	359
Total	619	217	836

Based on these gaps we construct a binary variable Y which equals 1 when an offered gap is accepted and 0 when the gap is rejected.

We extract from our datasets the following variables: position of the vehicle on the acceleration lane at the moment a gap is offered, offered gap length, positions of the putative leader and the putative follower, speed difference of merging vehicle and putative follower and speed difference of putative leader and putative follower. Using these variables, we apply an explanatory statistical method, the so-called Principal Component Analysis (PCA) (Govaert, 2009), to find the correlation between all variables extracted from the datasets. We thus identified the most contributing variables, being:

- X_{pos} : the position on the acceleration lane, measured from the start of the acceleration lane.
- X_{gap} : the offered gap, that is, the distance between the putative leader and the putative follower on the shoulder lane which could be used to merge by the vehicle driving on the acceleration lane.
- $X_{\Delta V_{PL-PF}}$: the difference in speed between the putative leader and the putative follower.
- $X_{\Delta V_{MV-PF}}$: the difference in speed between the merging vehicle and the putative follower.

The explanatory variables are normalised to establish a comparison between the various variables. The gap is normalised for each driver as it strongly depends on the traffic conditions and it would be difficult to analyse the results of a normalisation to the maximum gap identified in the total data set, as this gap occurs in near free flow conditions while drivers merging in highly congested conditions will not meet such large gaps. As the speed differences can be negative, the normalised values of the speeds are between -1 and 1 .

A type of generalised linear model is performed to quantify the influence of the explanatory variables $X = (X_{pos}, X_{gap}, X_{\Delta V_{PL-PF}}, X_{\Delta V_{MV-PF}})$ on the dependent variable Y . What is needed is a probability, i.e. a function that takes every value between 0 and 1. The logit function and the probit function are two classical functions which fulfil these conditions. Both the probit model and the logit model lead in practice to the same results.

Similar to Kita (1993), we choose a regression using a logit function (or simply logistic regression). The expression in our case is the following:

$$\ln \frac{p(1|X)}{1-p(1|X)} = \beta_0 + \beta_{pos}X_{pos} + \beta_{gap}X_{gap} + \beta_{\Delta V_{PL-PF}}X_{\Delta V_{PL-PF}} + \beta_{\Delta V_{MV-PF}}X_{\Delta V_{MV-PF}} \quad (3)$$

$$p(1|X) = \frac{\exp(\beta_0 + \beta_{pos}X_{pos} + \beta_{gap}X_{gap} + \beta_{\Delta V_{PL-PF}}X_{\Delta V_{PL-PF}} + \beta_{\Delta V_{MV-PF}}X_{\Delta V_{MV-PF}})}{1 + \exp(\beta_0 + \beta_{pos}X_{pos} + \beta_{gap}X_{gap} + \beta_{\Delta V_{PL-PF}}X_{\Delta V_{PL-PF}} + \beta_{\Delta V_{MV-PF}}X_{\Delta V_{MV-PF}})} \quad (4)$$

where $p(1|X)$ is the conditional probability that the offered gap is accepted ($Y = 1$) given X .

The three main advantages of the logistic regression are:

- The use of the logit model does not imply any a priori knowledge about the shape of the data distribution. Indeed, a large class of distributions (e.g. multivariate normal distribution, exponential distribution, Gamma distribution, Boolean distribution, ...) follows Eq. (3).
- The numerical implementation is easier.
- It gives asymptotically consistent parameters so that a t -test can be applied to evaluate the quality of the regression.

The results of the estimation of the coefficients for the Bodegraven data set are presented in Table 6 and for the Grenoble data set in Table 7.

Tables 6 and 7 show that the confidence intervals contain zeros for the estimate of β_{pos} in the Bodegraven data set and for the estimate of $\beta_{\Delta V_{PL-PF}}$ in the Grenoble data set, which implies that these coefficients have not been estimated significantly. To test the significance of each individual coefficient a Student t -test has been performed with as null-hypothesis that the coefficient equals 0. The p -value gives the probability that the coefficient is indeed 0. The p -values are in most cases below the 5% threshold (that is, these elements play a role) except for the estimate of β_{pos} in the Bodegraven data set and for the estimate of $\beta_{\Delta V_{PL-PF}}$ in the Grenoble data set, which are the coefficients for which the confidence intervals contain zeros. We have performed two other logistic regressions removing the coefficients which have not been estimated significantly.

Table 6

Results of the estimation of the coefficients using the Bodegraven data set.

Coefficients	Value	Standard Error	Confidence interval Lower bound	Confidence interval Upper bound	t -Statistic	p -Value
β_0	-5.3	1.6	-8.2	-2.3	-3.4	$5.6e^{-4}$
β_{pos}	2.2	1.3	-0.4	4.8	1.6	0.1
β_{gap}	10.8	1.7	7.5	14.1	6.4	$1.2e^{-10}$
$\beta_{\Delta V_{PL-PF}}$	5.8	2.1	1.6	9.9	2.7	$6.4e^{-3}$
$\beta_{\Delta V_{MV-PF}}$	-8.4	1.9	-12.2	-4.5	-4.2	$2.1e^{-5}$

Table 7

Results of the estimation of the coefficients using the Grenoble data set.

Coefficients	Value	Standard Error	Confidence interval Lower bound	Confidence interval Upper bound	t-Statistic	p-Value
β_0	-5.3	0.95	-7.2	-3.4	-5.6	$2.1e^{-8}$
β_{pos}	11.6	2.1	7.6	15.6	5.7	$1.1e^{-8}$
β_{gap}	3.9	0.9	2.1	5.8	4.1	$3.7e^{-5}$
$\beta_{\Delta V_{PL-PF}}$	0.9	1.1	-1.1	2.9	0.9	0.3
$\beta_{\Delta V_{MV-PF}}$	-7.6	1.4	-10.5	-4.8	-5.2	$1.2e^{-7}$

Fig. 11 visualises the results of the coefficient estimation for all three regressions. The figures on the left show the estimates of the coefficients for both data sets with the corresponding confidence interval, as discussed before. The figures on the right show the quality of the model by plotting the Receiver Operating Characteristic (or simply ROC curve) which gives the true positive rate versus the false positive rate. The larger the surface below the curve and the further the line is away from the line indicating the random process (dotted line in the figure), the better the predictive value of the model.

In Fig. 11a one observes that the coefficients of the offered gap, the location of the gap and the speed difference between the putative leader and the putative follower are positive. A larger gap, a gap located further towards the end of the acceleration lane and a larger speed of the putative leader with respect to the speed of the putative follower all increase the probability of accepting the gap.

The coefficient $\beta_{\Delta V_{MV-PF}}$ is negative, which means that the lower the speed of the vehicle on the acceleration lane with respect to the speed of the putative follower, the higher the probability to accept the gap. This result might seem strange, but it is coherent with the findings from the data analyses since the rejected gaps are those gaps that have been passed by the vehicle driving on the acceleration lane. Therefore, the speed of the vehicle on the acceleration lane is higher than the speed of the putative follower. This same effect has been found by Choudhury et al. (2007).

For each variable the confidence interval can be compared for the two sites. This comparison shows that the importance of speed differences ($\beta_{\Delta V_{PL-PF}}$ and $\beta_{\Delta V_{MV-PF}}$) is not significantly different in both data sets (the confidence intervals partly overlap). However, the effects of the position of the gap (β_{pos}) along the acceleration lane and the size of the gap (β_{gap}) are sig-

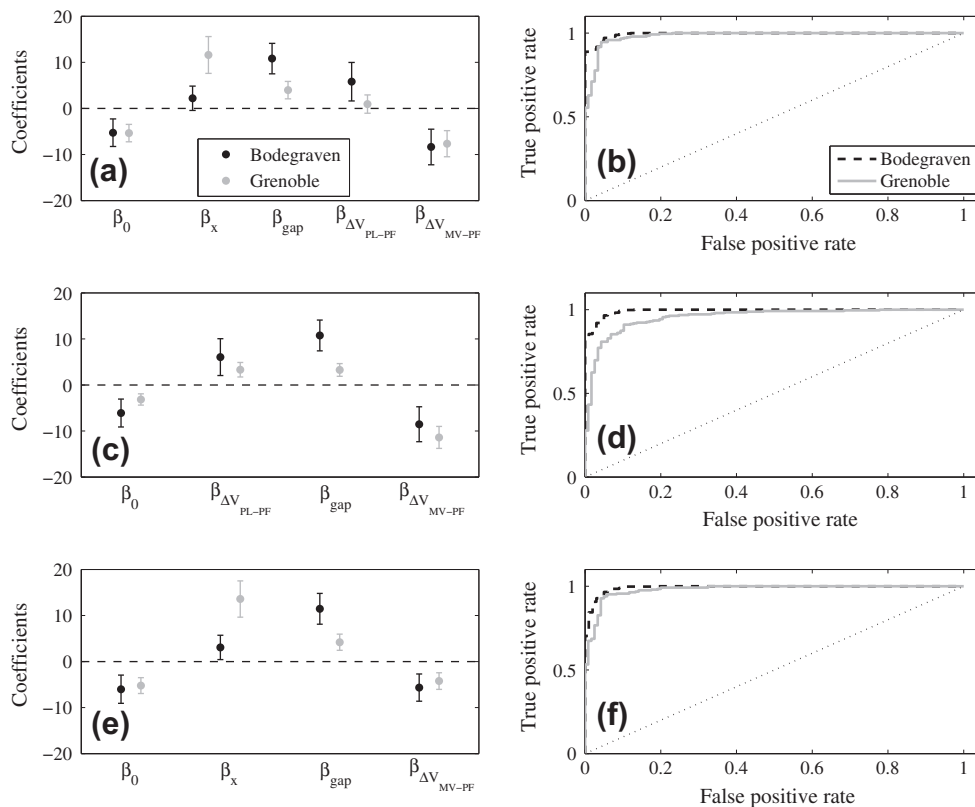


Fig. 11. Results of the logistic regression for the Bodegraven and the Grenoble data set. (a) and (b) present the results for the logistic regression with all the chosen explanatory variables. (c) and (d) (resp. (e) and (f)) show the results for the logistic regression without the position on the acceleration lane (resp. the difference in speed between the putative leader and the putative follower).

nificantly different. The position is more important in Grenoble than in Bodegraven, probably because of the shorter total length of the acceleration lane in Grenoble. The size of the gap plays a more important role in Bodegraven than in Grenoble.

Further analyses can be conducted by removing the coefficients that have not been significantly estimated from the model, see [Tables 6 and 7](#). For each of the two sites, we therefore remove one variable from the analysis: for Bodegraven we remove the position coefficient ([Fig. 11c](#)), while for Grenoble we remove the difference in speed between the putative leader and the putative follower ([Fig. 11e](#)). [Fig. 11d](#) shows that, as expected, for Bodegraven the quality of the true positive rate is not affected, but for Grenoble a decreasing predictive power is observed. For the second case, the predicting quality for the Grenoble site has not changed, whereas a slight decrease is observed for Bodegraven.

The logistic regression model we presented above is based on normalised variables of longitudinal position, speed differences and gap length. We can compare both sites together, even if the difference among them is significant. As [Kita \(1993\)](#) does not use the normalisation, we can only mention that the global tendencies are similar. We intend to expand the methodology presented here to perform further data analyses and parameter estimates on sites with different characteristics (among other things length of the acceleration lane, traffic composition and range of observed speeds).

7. Conclusions and recommendations for future research

In this paper we presented a comparative analysis of the merging behaviour on motorways of more than 600 mergers in total, of which 242 in Grenoble (France) and 377 in Bodegraven (the Netherlands). Using detailed trajectory data, we were not only able to analyse the accepted gaps, but also the rejected gaps for which we have a sample of more than 200.

We observed differences in the driver's behaviour on the two locations: the merging drivers in Grenoble (France) tend to be more aggressive, i.e. accepting smaller gaps than in Bodegraven (Netherlands). It is likely that this can be attributed to the road geometry (the acceleration lane in Grenoble is shorter than in Bodegraven), and to the congestion level on the motorway, which is higher in Grenoble.

We hereafter used those data sets and results to compare with the formulas found in literature about the critical gap. This critical gap is a threshold value: if a driver driving on the acceleration lane passes a gap on the shoulder lane larger than this critical gap, it will accept it, otherwise it is rejected. We produce a strong experimental evidence of the inadequacy of this theory with reality. Indeed some rejected gaps are over critical and should have been accepted according to those theories.

Therefore we proposed a stochastic model of gap rejection and acceptance. This was done after a logistic regression analysis of the merging behaviour, expressing the probability of accepting or rejecting a gap as a function of the distance towards the end of the acceleration lane, the length in metres of the offered gap, the difference in speed between the putative leader and the putative follower, and the difference in speed between the merging vehicle and the putative follower. Interesting to note, the distance towards the end of the acceleration lane is the most influencing factor in Grenoble, whereas in Bodegraven, the length of the possible gap is the key factor of acceptance. Using a Student's *t*-test we concluded that not all variables are significant for both data sets: the distance towards the end of the acceleration lane appears not to be significant in the Bodegraven data set, while for the Grenoble data set the difference in speed between the putative leader and the putative follower was not significant, which implies that the merging behaviour between the two sites indeed shows some differences, as stated before. The logistic regression analysis has a strong predictive power, being able to correctly predict the acceptance or rejection of gaps in more than 98% of the cases.

Other topics for future research deal with an increase of the sample studied, both by looking at free flow conditions, and by looking at data collected with an acceleration lane of different length. The type of vehicle, both of the merging vehicle and of the putative leader and the putative follower was not analysed here, due to the lack of a sufficient dataset (in particular, in Grenoble, none of the mergers is a heavy vehicle). This should also be investigated in future research.

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