Lane Distribution of Traffic Near Merging Zones Influence of variable speed limits

Victor L. Knoop and Aurélien Duret and Christine Buisson and Bart van Arem

***Abstract*— The congestion at on-ramps of motorways is due to too many vehicles wanting to merge onto the same lane. Ramp metering is usually used as control measure to influence the flows, but a variable speed limit can also have large consequences for the merging process. This paper discusses the change in lane distribution due to a VSL and explicitly considers the influence of an on-ramp. To this end, the lane distribution just upstream of an on-ramp is compared with the lane distribution elsewhere. Just upstream of an on-ramp, a significantly lower fraction of the flow uses the outside (right) compared to a part of the road without any ramps. This holds both for a situation with VSL as without VSL. Besides, VSL increases the use of the outside lane near capacity. This way, VSL influences not only the speed but also the lane distribution, and thereby possibly also the merging ratio. The consequences of this changed lane distribution are site-dependent and should be taken into account when deciding on installing a system of variable speed limits.**

I. INTRODUCTION

Traffic congestion often sets in near on-ramps. This can be due to the extra demand, but drivers on the main road are also influenced by the on-ramp. Drivers on the main road often reduce speed due to merging vehicles, but they also might change from the outside lanes towards the median lane in order to enable traffic on the on-ramp to merge onto the motorway.

Several studies have been carried out describing lane distribution (see section II). However, many of these studies focus on an equilibrium without the influence of merging traffic. This paper describes how the lane distribution changes due to an on-ramp. In terms of traffic control, the ramp inflow is usually controlled using ramp metering. However, is there can be another way to improve the motorway flow. Variable speed limit (VSL) might change the lane distribution and that, in turn, can change the merging ratio. A general framework of combining VSL with ramp metering is presented by [1], which describe how a (VSL) upstream of an on-ramp influences the traffic processes at a merge using a traffic flow model. Our paper specifies the actual effects of the VSL in terms of empirical lane distribution.

Usually ramp metering is used to control the traffic situation near on-ramps, and variable speed limit (VSL) is used for traffic control at motorway sections without ramps. However, it is expected that a VSL changes the lane distribution. Therefore, the influence of a VSL might differ from the simple effect of only reducing speed. In case more drivers use the right lane under a VSL, merging drivers are less able to merge into the traffic stream and create congestion on the on-ramp. In extreme cases, this can even lead to drivers which merge onto the main road with insufficient speed, creating heavy congestion for the through traffic. Therefore, a VSL measure can change the congestion patterns.

This paper first presents a literature review on lane distribution. Then, it presents the theory and hypothesis on the lane distribution under a Variable Speed Limit (section III. Section IV shows the set-up of the research, including the data collection (site, type of data) and the analyses which are carried out. The resulting lane distributions are presented in section V; that section also shows the similarity and the differences between the distributions for different locations and under different speed limits. The paper concludes by section VI which interprets these results and discusses the possible implications of VSL on traffic flow patterns.

II. LITERATURE REVIEW ON LANE DISTRIBUTION

In basis there are two processes: the desire to change lanes and the possibility to change lanes. In models, this can be be translated into a decision model and gap acceptance model – not necessarily with a fixed critial gap. Together, they can form a lane changing model. A formal description and implementation of a lane-changing model into a microsimulation package is given by Wang and Liu [2].

A theoretical basis for the desire and different lane flows is given by Daganzo's traffic model of slugs and rabbits [3], [4]. He assumes two categories of drivers: aggressive ones, *rabbits*, on the one hand and less aggressive ones, *slugs*, on the other. He points out how these traffic streams mix and how this can create congested patterns.

Another psychological approach is a model with equations on the utility of changing lanes. The utility of a higher speed can for instance be weighted against the disutility of acceleration and possibly deceleration for others [5]. This disutility leads to a decision to change lanes, and the combined decisions of all drivers lead to a lane distribution.

Based on a microscopic gap-acceptance theory, Wu [6] derives an relationship for the distribution over the different lanes. However, the final result of his equation depends on

This work was supported by the Netherlands Organisation of Scientific Research, NWO, and the HTAS-SPITS project and the HTAS-CCC project.

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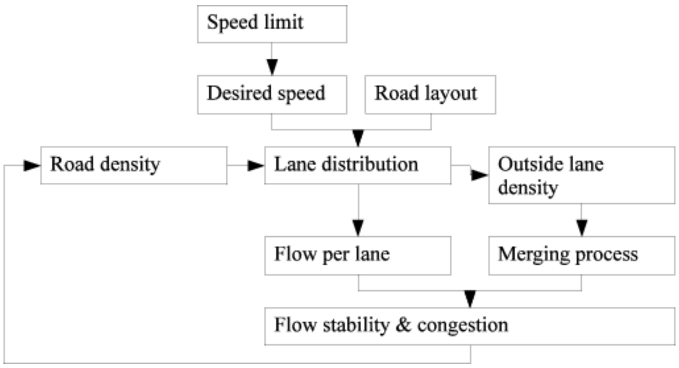


Fig. 1: A schematic view of the relevant traffic processes

the headway distribution for the vehicles which is put into the equation manually.

An earlier study [7] presents the influence of the traffic volume on the on-ramp on the lane distribution. It is concluded that, contrary to the authors' expectations, the fraction of the flow on the outside and centre lanes increases if the flow on the on-ramp increases.

This raises the question what the influence of the on-ramp is at all, and how the lane distribution changes at a location just upstream of an on-ramp compared to a non-ramp situation. This question is studied in this paper. Furthermore, the influence of a Variable Speed Limit on the lane distribution is studied.

III. THEORY AND HYPOTHESIS

There are different aspects which influence the lane distribution. These, as well as the consequences, are depicted in figure 1, and are discussed in this section.

European driving regulations require drivers to keep the outside lane (slow lane, for right hand traffic the right lane) and only change to lanes at the left during overtaking. Additionally, overtaking at the right is prohibited. However, drivers on the main road might create room for merging drivers at the location of a merge, as shown in microscopic data [8]. Consequently, we expect the outside lane to have a lower percentage of the flow just upstream of a merging location than at non-merging locations.

It can be expected that once a lower speed regulation is in place, there is less need to overtake. Therefore, we expect that drivers stick better to the outside of the road compared to a situation with a higher speed limit for the same densities.

The lane distribution influences the traffic flow. In fact, in case one of the lanes is underused, more congestion will occur. This is both supported by a theory of slugs and rabbits [4] (which suggest people might move to other lanes) as well as by "three phase traffic flow theory" [9], suggesting that as long as the speeds are not equal, not all road capacity is used. This all implies that a more equal lane distribution is beneficial for the total flow. However, if the outside lane is used too much for the merging traffic to find a gap easily, this will also create congestion. The merging vehicles will force a gap and reduce the speed of the through traffic. This will induce congestion for all traffic, as shown analytically [10]. Also, the disturbance might induce a stop-and-go wave [11].

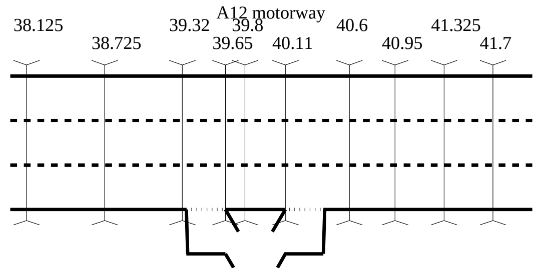


Fig. 2: Layout of the measurement site

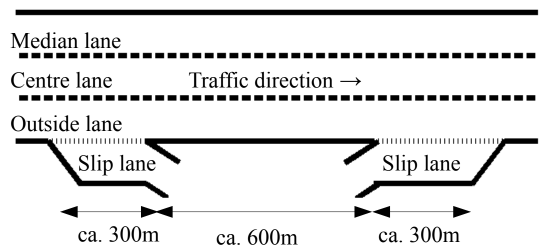


Fig. 3: The default design for motorway intersections

IV. RESEARCH SET-UP

A. Site and data

The traffic measures are taken on the A12 motorway in the Netherlands in the eastbound direction from km 38.5 to km 41.5. A figure of the stretch and the detectors is shown in figure 2. It is a three-lane motorway where congestion in peak periods is common. The left lane will be indicated with "median lane" the middle lane with "centre lane" and the rightmost of the driving lanes will be indicated with "outside lane". We use this names to avoid a misunderstanding of the word shoulder lane, which is a fourth emergency lane which is present at the right but is not available for traffic.

Furthermore, there is a 300 meter long parallel lane ("slip lane") for traffic leaving on the off-ramp. About 500 meters downstream of the end of this slip lane, the slip lane for the merging traffic starts. This layout of two consecutive ramps is the default layout for intersections in the Netherlands (as well as in many other countries). This means that even if the influence measured at the location of the on-ramp is partly due to the off-ramp, this will be similar for all similarly designed ramps. Figure 3 illustrates the default intersection, and gives the names we will be using in this paper.

For this study, we will use two detector locations. Detector 38.125 will be used as a reference detector without an influence of an on- or off-ramp. The most downstream on-ramp upstream of the shown figure is at 35.9 km. Detector 40.11 is located just upstream of the on-ramp and will therefore be used as detector where an influence of the merging can be seen.

For the site, 1-minute aggregated double loop detector data are available. The data give lane-specific flows and lane-specific time-mean speeds. Five months of data are used,

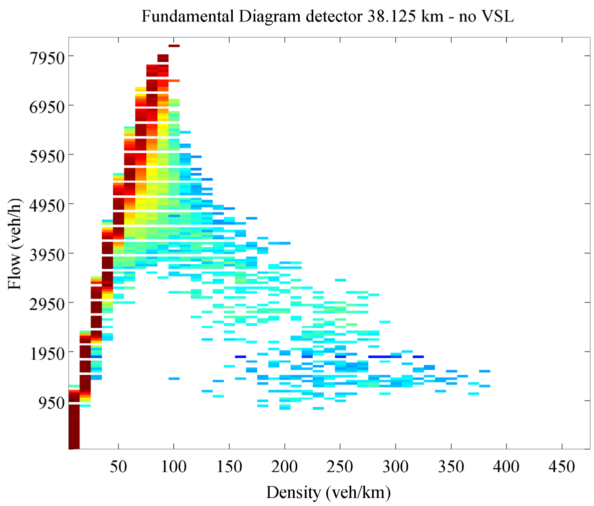


Fig. 4: Fundamental diagram in the flow-density plane

from 8 September 2009 to 7 February 2010. Weekend days and holidays were filtered out. Furthermore, data with measurement errors were filtered out, as well as data from time when the road was wet due to rain. Also heavily congested periods, where the average speed drops under 50 km/h, were filtered out. After this filtering, 48250 aggregation points are used for the analysis. The speed limit is dynamically reduced in – on average – 190 minutes. This might seem a low number, but the rain days are filtered out and moreover the congestion parts are filtered out.

We analysed the traffic pattern under the normal 120 km/h speed limit and plotted a fundamental diagram in the flow-density plane (see figure 4). From that, we found that the critical density is around 75 veh/km on this three lane motorway, equalling 25 veh/km/lane.

B. Analyses

We follow earlier researchers ([6], [7], [12] in expressing the lane distribution as function of the flow. The fraction of the flow in lane i, p_i is calculated as follows:

$$p_i = \frac{q_i}{q_{\text{tot}}} \tag{1}$$

This is not constant for all traffic states. It changes with different traffic flow values. Furthermore, it is found that an hysteresis effect exist, meaning that for the same flow values the distribution is not equal [12]. p_i can be expressed as function of speed, flow, or density. Expressing it as function of speed has the drawback that the lane distribution will change considerably in the free flow area of the fundamental diagram, and speed is more or less constant. Expressing it as function of the total flow has the drawback that for one traffic flow value, there are generally two traffic states possible, a congested and an uncongested. These will interfere if we chose to express the function $p_i(q_{\text{tot}})$. Therefore, following [12], we analyse the function $p_i(k)$, the fraction of the flow as function on the total density. This also has a disadvantage, since density is not measured directly by the double loop detectors that are available.

However, this drawback can be overcome as follows. To find the density, the flow is to be divided by the space mean average speed, u_S. However, the data only contain the time mean speed, u_T. In order to find the space mean speed, we follow [13] and compute u_S:

$$u_S \approx u_T + \frac{\sigma_T^2}{u_T} \tag{2}$$

The standard deviation of the time mean speed, σ_T is computed from a moving 5-minute average. Since the variable speed limits are not long the same value, we choose a relative short aggregation interval of 1 minute to have sufficient measurements.

C. Variable Speed Limit

On the stretch a system of variable speed limits is present. Basic idea is that once a stop-and-go wave is detected, this wave can be dissolved by limiting the inflow [14], [15]. This is done by reducing the speed limit to 60 km/h on a road stretch upstream where the traffic is still in free-flow conditions. The density does not change on this road stretch, but the speed will. This state is normally not an equilibrium state. The same holds for the traffic state occurring once vehicles drive into the zone with speed restriction. There, the flow is equal to the initial flow, but the speed is lower. It is always the case that traffic moves to a state outside the normal equilibrium by applying speed limits.

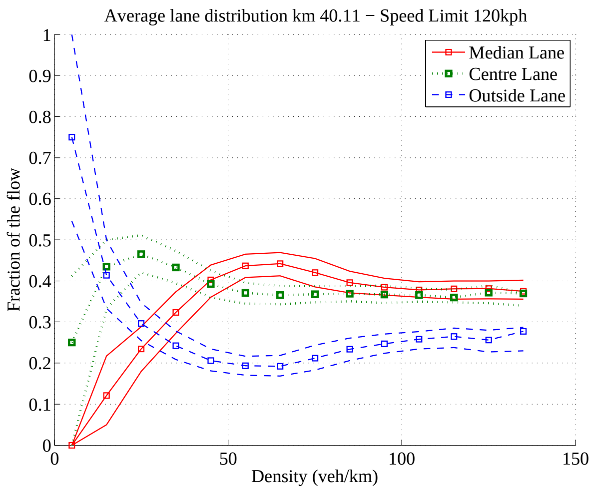
The lowest speed limit used in this algorithm is 60 km/h, which is always introduced (and removed) via speed limits of 100 km/h and 80 km/h. In order to avoid the temporal effects after introducing the speed limit, only the traffic situation under a 60 km/h speed limit is analysed. The drivers do not comply completely to the speed limit. In fact, the average speed of the drivers is 79 km/h with a standard deviation of 16 km/h.

V. LANE DISTRIBUTIONS

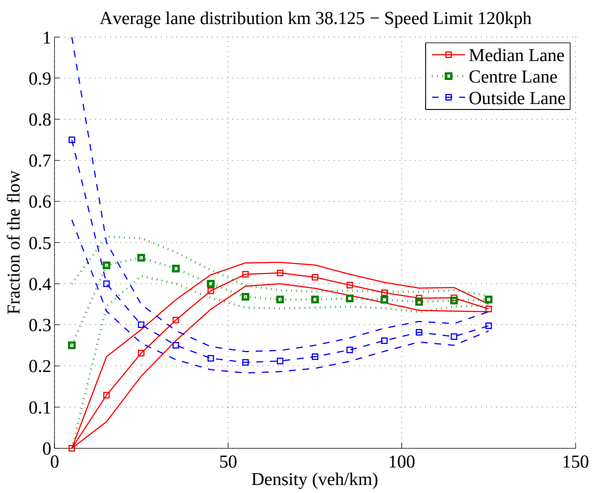
This section discusses the lane distributions. First, the regular distribution is discussed, both for the normal motorway and for the point upstream of the on-ramp and the differences between those. Section V-B does the same for the situation with VSL. Section V-C makes the comparison between the situation with VSL and without VSL.

A. Regular Situation

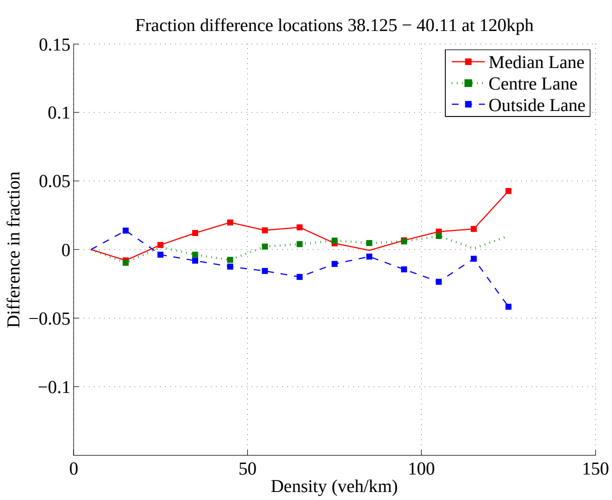
Figure 5 shows the lane distribution for the normal situation. Squares show the median of the fractions in the 10 veh/km wide bins, and the triangles the error margins (1 standard deviation). The general pattern is that for very low densities all traffic is using the rightmost lane. Once density increases more drivers will choose the middle lane. If the density increases further, drivers start using lane 3, the median lane. The outside lane, lane 1, is the lane where slower trucks drive. Drivers of passenger cars tend to avoid this lane in busier periods. Therefore, at densities from 30 veh/km and up, the flow in the left two lanes is more than in the right lane. Near capacity at around 75 veh/km, the speed decreases and many drivers want to go faster and overtake.



(a) No influence of ramp



(b) Just upstream of on-ramp



(c) The differences between the lane distributions; all differences between 10 and 130 veh/km are significant and hence indicated with a dot

Fig. 5: Lane distributions under normal speed limits

This means that a large part of the flow is now at the centre lane and the median lane. Once congestion has set in, the prohibition of overtaking at the left does not longer hold and the flow in the left two lanes will become equal. The flow in the right lane is still lower. Detailed data on the truck percentage lacks, but typical truck values for the site are 6-8%. However, regarding the difference between the use of the outside lane and the other two lanes, we conclude that the outside lane is not yet utilised at capacity. Namely, even in case there are only trucks on the outside lane with a passenger car equivalent of trucks is taken 2 [16], the flow in passenger car units is still lower than in the other two lanes.

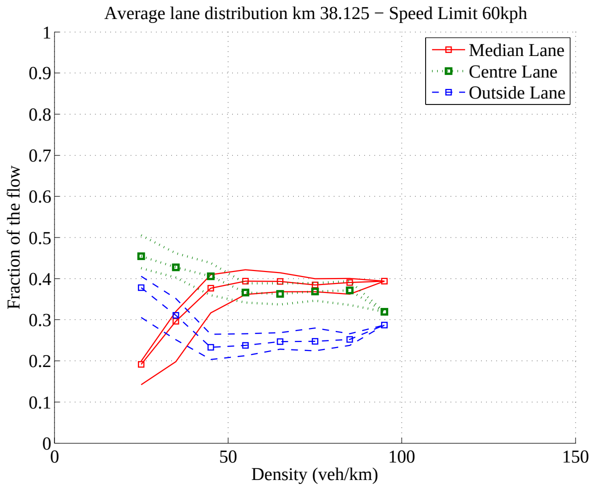
These are the similarities between the two locations. There are also differences between location 38.125 (figure 5a) and 40.11 (figure 5b). Figure 5c shows these differences graphically: the line indicates the value of the difference (the difference in fraction), and the squares mean that in that density bin, the difference between the two locations is significant. Most important is that the fraction of the flow in the outside lane is lower near the on-ramp. A t-test shows that all differences are significant for densities between 10 veh/km and 130 veh/km. That means that drivers make space for vehicles entering the motorway by the on-ramp (courtesy merging). The explanation for the lack of significant differences on a nearly empty road is that there is no need to make room for merging vehicles if the road is nearly empty.

Since the proportion of the flow on the outside lane is lower, on another lane the proportion of the flow must be higher. This is mainly on the median lane where over the same density regime the fraction of the flow is significantly higher. The fraction of the flow in the centre lane hardly changes: the fraction of the flow is shlightly lower for densities under capacity and slightly higher for densities higher than capacity.

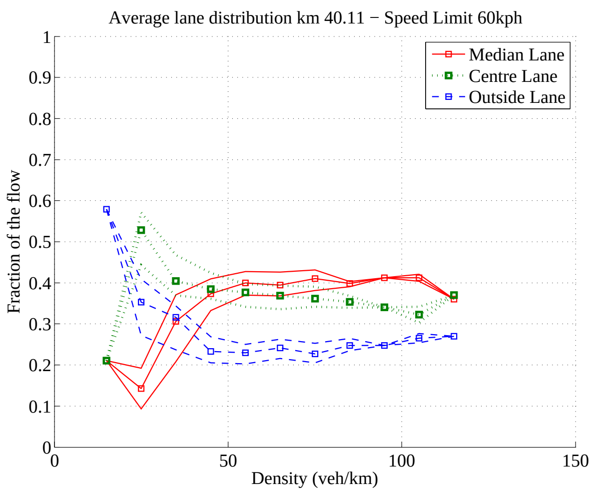
B. *Influence of merging under Variable Speed Limit*

In this section we focus on the differences in the lane distribution between detector 38.125 and 40.11 under a dynamic speed limit. Differences in the distributions on one location due to this speed limit are discussed in section V-C.

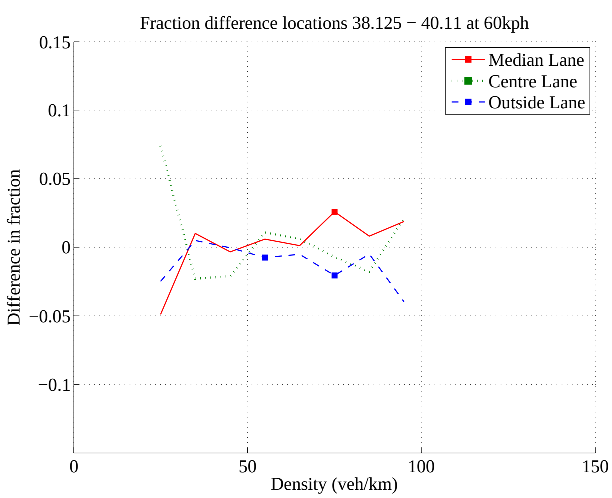
Figure 6 shows the lane distribution for the road under a 60 km/h dynamic speed limit. The VSL is only activated once a stop-and-go wave is detected. Since stop-and-go waves emerge in higher-density areas, there are no measurements with VSL active in low-density regions. Like in the case without VSL, we see that the outside lane is less occupied for densities near capacity. However, where in the situation without VSL there is a difference over (almost) the whole density range up to capacity, in case of the 60 km/h speed limit there are only significant differences in some density bins near capacity. This is possibly due to the limited working of the 60 km/h VSL, only near capacity. A wider application of VSL should show if the differences are also significant in other density bins.



(a) No influence of ramp

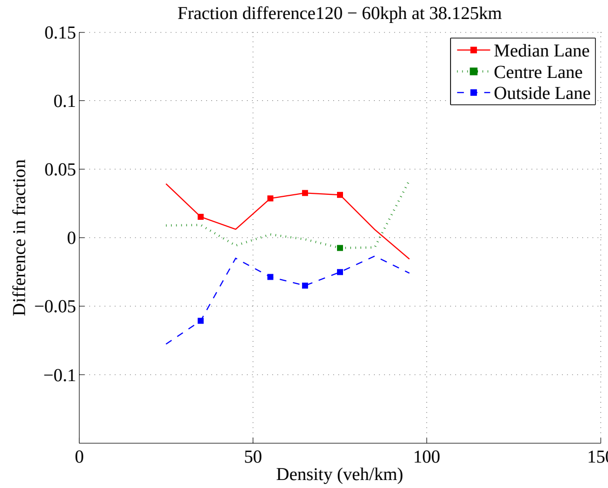


(b) Just upstream of on-ramp

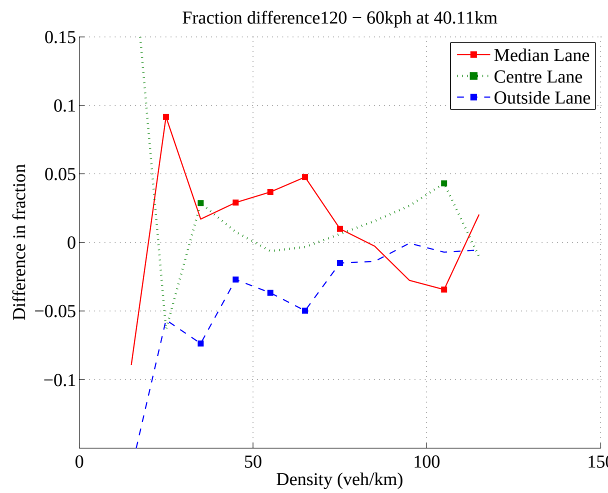


(c) Differences; significant differences are indicated with a dot

Fig. 6: Lane distribution under a 60 km/h dynamic speed limit



(a) No influence of on-ramp



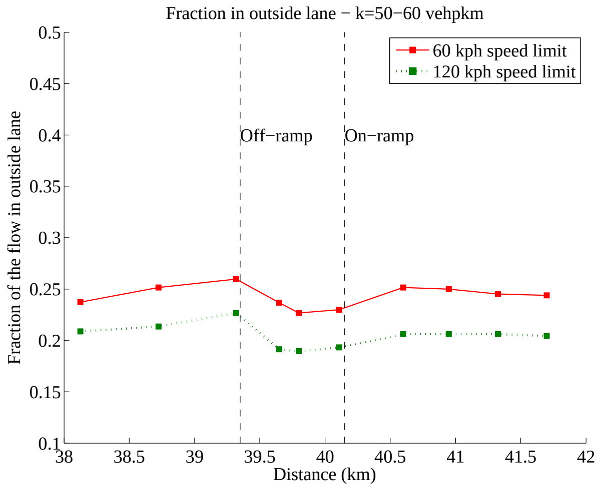
(b) Just upstream of on-ramp

Fig. 7: Differences in lane use due to variable speed limit: the measurements which are indicated with a dot are siginificant differences

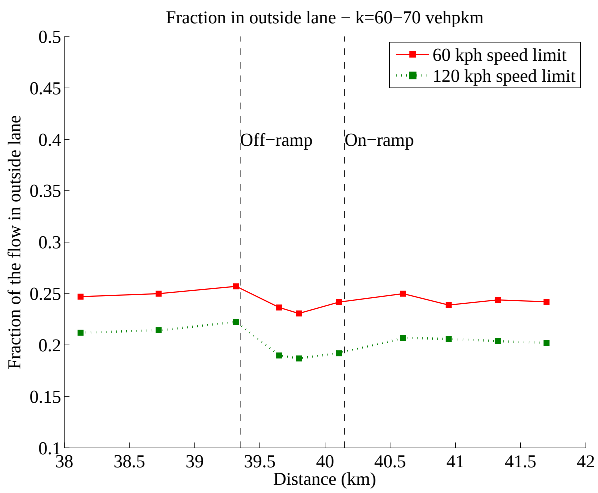
C. Differences due to Variable Speed Limit

This section discusses the differences in the lane distribution due to the VSL. Figure 7 shows significant differences due the speed limit. In fact, for densities just lower than capacity a significant larger part of the flow is in the outside lane in case the VSL is active, for both locations. This means that merging onto the motorway from the on-ramp will be more difficult once VSL is active.

Figure 8 shows how the fraction of the flow in the outside lane evolves over distance with and without the VSL. For the density bin 50-60 veh/km – as well as for most of the other density bins – the occupancy of the right lane is higher in case the VSL is active. Also in this figure, the squares mean that the difference is significant. In fact, at all detectors the difference between the two speed limits is significant.



(a) density 50-60 veh/km



(b) density 60-70 veh/km

Fig. 8: The change of the fraction of vehicles in the outside lane over distance

VI. CONCLUSIONS AND IMPLICATIONS

This paper studied the lane flow distribution under different speed limits and at different locations. It is shown that a Variable Speed Limit of 60 km/h significantly changes the lane distribution. In fact, under normal 120 km/h speed limit the outside lane is underutilised in conditions near capacity. A 60 km/h speed limit increases the flow on this initially underutilized lane. This gives opportunities to increase the road capacity.

The higher usage of the outside lane, at the other hand, will lead to smaller gaps in the traffic at the outside lane. This causes the merging process to be more difficult. The consequence is that some drivers might not be able to merge onto the main traffic flow smoothly and reduce speed. This will create congestion on the on-ramp. Then, there are two possible consequences which influence the traffic flow considerably. One possibility is that stopped drivers on the slip lane wait until there is a large gap, which considerably reduces the number of cars merging into the traffic stream, thereby influencing the merging ratio. Alternatively, they start merging with lower speeds which create large congestion on the main stream. What effect is stronger, and thus the effects on overall capacity, depends on the traffic demand from the ramp and at the main road. The main point argued here is that the effects of a variable speed limit on the lane distribution is large and that these effects therefore should be considered when implementing variable speed limits.

REFERENCES

[1] R. C. Carlson, I. Papamichail, M. Papageorgiou, and A. Messmer, "Optimal motorway traffic flow control involving variable speed limits and ramp metering," *Transportation Science*, vol. 44, no. 2, pp. 238–253, 2010.

[2] X.-Y. Wang and J.-S. Liu, "Research of the lane utilization with microsimulation," in *Proceedings of the Fourth International Conference on Machine Learning and Cybernetics*. IEEE, 18-21 August 2005 2005.

[3] C. F. Daganzo, "A behavioral theory of multi-lane traffic flow. part i: Long homogeneous freeway sections," *Transportation Research Part B: Methodological*, vol. 36, no. 2, pp. 131 – 158, 2002.

[4] ——, "A behavioral theory of multi-lane traffic flow. part ii: Merges and the onset of congestion," *Transportation Research Part B: Methodological*, vol. 36, no. 2, pp. 159 – 169, 2002.

[5] A. Kesting, M. Treiber, and D. Helbing, "General lane-changing model mobil for car-following models," *Transportation Research Record: Journal of the Transportation Research Board, No. 1999*, pp. 86–94, 2007.

[6] N. Wu, "Equilibrium of lane flow-distribution on motorways," *Transportation Research Records, Journal of the Transportation Research Board, No. 1965*, pp. 48–59, 2006.

[7] M. R. Amin and J. H. Banks, "Variation in freeway lane flow patterns with volume, time of day, and location," *Transportation Research Record: Journal of the Transportation Research Board, No. 1934*, pp. 132–139, 2005.

[8] W. Daamen, M. E. J. Loot, and S. P. Hoogendoorn, "Empirical analysis of merging behavior," in *Proceedings of the 89th Annual Meeting of the Transportation Research Board*, 2010.

[9] B. S. Kerner, *The Physics Of Traffic: Empirical Freeway Pattern Features, Engineering Applications, And Theory*. Springer, Berlin, 2004.

[10] A. Duret, J. Bouffier, and C. Buisson, "Onset of congestion due to low-speed merging maneuvers within a free-flow traffic stream: Analytical solution," *Transportation Research Record: Journal of the Transportation Research Board*, vol. Accepted for publication, 2010.

[11] S. Ahn and M. Cassidy, "Freeway traffic oscillations and vehicle lane-change maneuvers," in *Proceedigs of the International Symposium of Transportation and Traffic Theory*, R. E. Allsop, M. G. H. Bell, and B. G. Heydecker, Eds. Elsevier, Amsterdam, 2007, pp. 691–710.

[12] J. Lee and B. Park, "Lane flow distributions on basic segments of freeways under different traffic conditions," in *Proceedings of the 89th Annual Meeting of the Transportation Research Board*, 10-14 January 2010 2010.

[13] H. Rakha and W. Zhang, "Estimating Traffic Stream Space-Mean Speed and Reliability From Dual and Single Loop Detectors," *Transportation Research Record: Journal of the Transportation Research Board, No. 1925*, pp. 38–47, 2005.

[14] A. Hegyi, S. Hoogendoorn, M. Schreuder, H. Stoelhorst, and F. Viti, "Specialist: A dynamic speed limit control algorithm based on shock wave theory," in *Proceedings of the 11th International IEEE Conference on Intelligent Transportation Systems*, Beijing, China, Oct. 12–15 2008, pp. 827 – 832.

[15] A. Hegyi, S. Hoogendoorn, M. Schreuder, and H. Stoelhorst, "The expected effectivity of the dynamic speed limit algorithm specialist - a field data evaluation method," in *Proceedings of the European Control Conference 2009*, Budapest, Hungary, Aug. 2009, pp. 1770 – 1775.

[16] Transportation Research Board,, "Highway Capacity Manual," Tech. Rep., 2000.