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ABSTRACT

The paper presents the effects of Dynamic Speed Limit control (DSL) in a 3 lane section on the A13 freeway, in Rotterdam. The main objective is to contrast the latest empirical findings in Barcelona [1], where the mainline metering capability (i.e. gating, meaning mainline flow restriction) due to sub-critical speed limits (e.g. down to 40 km/h) was questioned. Moreover, according to the Barcelona results, the validity of the current fundamental diagram models accounting for DSL could be strongly compromised.

This investigation takes advantage of the huge empirical traffic database recorded by the Dutch government and of DSL strategies being present on most of their freeways. Data is treated in order to identify stationary periods of traffic. A method, reproducible elsewhere, and computerized into an algorithm has been developed to this end. The fundamental diagram is used as a graphical tool to assess the results.

The main findings do not contradict the Barcelona observations. Flows of 1850 veh/h per lane were steadily observed for the sub-critical speed limit of 50 km/h. The reactive nature of the DSL-control implemented in the Netherlands, implies that very low speed limits do not affect a wide range of traffic states. This hampered the possibility of extending this conclusion. Further research with less limiting DSL control strategies would be necessary to clarify the extent of the phenomenon considered.

Keywords: Dynamic speed limits; fundamental diagram; freeway traffic; empirical traffic data analysis; Rotterdam.

1. INTRODUCTION AND BACKGROUND

Around the 1970's a new freeway traffic control strategy known as Dynamic Speed Limits (DSL) appeared for first time in Germany [2]. During the last decades, DSL strategies have spread widely across Europe and America [3-6]. However, the possibilities behind DSL strategies to improve traffic conditions are still being investigated.

Since the 1970's, the Dutch freeways have been increasingly equipped with DSL systems and traffic data logging facilities. Nowadays, more than 2500 km length of freeway throughout the country is equipped with DSLs. The required surveillance equipment to manage these systems has given rise to a huge database over the decades, which is still increasing. Therefore, the Netherlands is one of the best places for the empirical analysis of DSL effects.

In international practice, two families of DSL strategies can be clearly differentiated. First, DSL control was applied in freeways near highly urbanized areas, mainly to increase traffic safety or to reduce pollution levels. Usually, this first family of strategies imply a reduction in the maximum speed limit (e.g. from 120 to 80 km/h) and the implementation of Automatic Incident Detection (AID) speed control. AID control consists in progressively lowering the speed limit when approaching a queue or any kind of incident (e.g. from the prevailing 80 km/h to 40 km/h, considering 20 km/h discrete speed jumps approximately every km). The reduction of severe traffic accidents and the improvement of the air quality in these areas have been consistently reported [7-10].

The second family of DSL strategies focuses on the possibility of improving traffic conditions through DSL control. Since its beginnings in the 1980's, these strategies have been based on the concept of traffic homogenization. The underlying idea is to reduce the speed limit to a value close to the critical speed (i.e. the average speed at capacity, generally between 70 and 90 km/h) or higher, aiming to develop a more uniform traffic speed. In the early days, the belief was that this pre-congestion DSL control could increase capacity and thus maintain the free flow conditions longer. However, hardly any of the applications has resulted in a statistically significant improvement of the flow or the capacity. Section 2 presents a detailed review of the DSL effects on traffic flow, together with the flow - occupancy models proposed to date.

More recently in the literature (the first reference goes back to 2004, [11]), a new type of Low Speed DSL control (LS-DSL) has been proposed. LS-DSL control aims to use the speed limit as a mainline flow restriction. The objective is to restrict vehicular flow upstream of critical bottlenecks by means of very low speed limits (i.e. clearly sub-critical <<70 km/h). This could avoid the activation of the bottleneck (or could even deactivate it, if already active) and eliminate the traffic breakdown followed by the capacity drop at the bottleneck location.

One of the very few empirically tested LS-DSL strategies (the only one to the authors knowledge) is found in the Netherlands, where the SPECIALIST algorithm was developed and successfully tested in the resolution of shock waves (i.e. jams produced by traffic instabilities) [12, 13]. The algorithm takes advantage of the fact that when the speed limit is instantaneously reduced on a freeway stretch, the flow reduces proportionally with the speed reduction, while the density remains the same. In practice, this was achieved by instantaneously lowering the speed limit using several speed limit gantries (with a spacing of 500-600m) over a longer stretch (several km). This flow reduction is enough to solve a traffic jam. The approach also stabilizes the traffic that approaches the speed-limited region by dynamically changing the head and tail of the speed-limited stretch. A similar approach could also be applied to an infrastructural bottleneck with a fixed location [14].

Other LS-DSL strategies have been proposed in the literature with the objective of creating the permanent mainline flow restriction necessary to resolve congestion at critical and severe bottlenecks. The concept behind all of them is the same, “mainline metering” by using very low speed limits, usually in coordination with ramp metering. This coordination makes it possible to regulate all the freeway inflows and distributing the queue length and the delay between both, the on-ramp and the main trunk, according to some predefined strategy. This allows the extension of the application of ramp metering strategies, usually limited by queue lengths at the on-ramps. Several control algorithms have been proposed. For instance, [15, 16] present model predictive control schemes based on simulation. Recently, [17-19] propose feedback control for the coordination of LS-DSL and ramp metering, always validated through simulation. All these contributions have in common the assumption that very low speed limits (often around 20 km/h) are capable of significantly restricting the mainline flow, and always their validation (or even the concept behind the strategy) is based on models (analytical or simulated) where the previous effect of low speed limits is incorporated. However, the empirical evidences proving that this permanent flow restriction can be achieved by imposing sub-critical speed limits are very limited. Results in [20] seem to suggest a slight capacity reduction due to a speed limit of 40 mph with respect to the no speed limit case, but this was not clearly quantified, as the authors were focusing on the capacity increase due to DSL, not on its reduction.

An important milestone regarding the empirical validation of the effects of sub-critical speed limits was set in 2013 with the Barcelona experiment [21]. This was the first DSL experiment devoted to understand the effects of low speed limits on freeways. During seven days, different configurations of speed limits were displayed along a 13 km stretch of freeway, with the main objective of answering some research questions. The preliminary results obtained proved that sub-critical speed limits are not able to restrict much the flow in gated sections. The minimum speed limit tested was 40 km/h, achieving a sustained capacity of approximately 1900 veh/h/lane [1]. The effects of even lower speed limits remain unexplored. Far from clarification, these results, which limit the effectiveness of DSL mainline flow metering strategies, brought more controversy to the field.

The present paper pursues to give further evidence, or to reject the Barcelona’s findings in a different test site on a Dutch freeway. The A13 freeway, connecting The Hague with Rotterdam and controlled by several DSL strategies, is selected. With respect to the Barcelona experiment, this test site has some limitations, which need to be taken into account. First, congested periods are due to queue spillbacks from downstream bottlenecks, so that there is no active bottleneck in the selected stretch. This makes difficult to assess capacity, because it is affected by a more restrictive bottleneck downstream. Second, for some of the DSL strategies the low speed limits are a result of low measured speeds in jams. This avoids the possibility of keeping low speed limits for long periods of time and for a wide range of traffic densities. This problem is recurrent and has been faced previously in other investigations, [20, 22]. In fact, this is the reason why the Barcelona experiment is unique in its nature. Regardless of the traffic conditions the speed limit was kept constant. This allows seeing the complete effects of very low speed limits for a wide range of traffic demands.

The available loop detector data from the Dutch site have been treated in order to estimate stationary periods of traffic. The technique developed by Cassidy (1997) [23] has been used. To some extent, this is a manual technique, and it is difficult to reproduce exactly the same results between different applications, even with the same data. To keep the objectivity in the analysis, the method has been translated into an algorithm and programmed. Results are visualized by means of the fundamental diagram (i.e. the flow-density diagram), to assess the range of possible traffic states under each speed limit.

The obtained results show that flows of the same order of the ones observed in the Barcelona experiment for the sub-critical speed limit of 50 km/h are possible, and also measured in the Dutch test site. However, this does not invalidate that more significant metering capabilities could exist for lower speed limits. Further research in more appropriate conditions is necessary to know to what extend the DSL metering capabilities in gated sections are possible.

The rest of the paper is structured as follows. In Section 2, a review of the reported effects of DSL on the fundamental diagram is presented. In Section 3, the methodology of the analysis will be explained. In Section 4, the details of the test site and available data are exposed. The results obtained on the A13 follow in Section 5. In Section 6, a critical comparison with previous results is made, and finally, in Section 7, some conclusions are outlined.

2. SPEED LIMITS AND THE FUNDAMENTAL DIAGRAM: A REVIEW

The fundamental diagram (i.e. the relationship between flow and density, or its proxy the occupancy) is an appropriate tool to assess the aggregate behavior of a traffic stream. It allows visualizing the critical parameters of a freeway section, like the capacity, the critical density and the critical speed. Several models have been proposed in the literature to reveal the impact of DSL on aggregate traffic flow behavior. Only a few found empirical support. In Table 1 and Figure 1 the most relevant are presented.

TABLE 1

FIGURE 1

From this review it follows that many aspects regarding DSL effects on aggregated traffic behavior are lacking consensus in the scientific community. More research is needed and this should be driven by the analysis of real data. Among the gaps in the current knowledge, the existence or not, or to what extent, of the flow restriction capabilities of sub-critical speed limits, stands out. Many control algorithms are being investigated based on this still unproved assumption. The answer to this question is therefore essential to drive the research for DSL control strategies towards a feasible direction.

3. METHODOLOGY

The fundamental diagram is clear and robust when it is constructed from stationary data points [23]. Simply plotting q-k minute aggregated data would result in a lot of scatter limiting the reliability of the results. Stationary periods of traffic can be defined as time intervals where all the macro traffic variables (q, k, v) are approximately constant. By constructing re-scaled curves of cumulative number of vehicles (N-curves) and cumulative density (T-curves) with respect to time, stationary traffic conditions can be identified by looking for intervals with approximately constant slopes and similar wiggles in both curves [23]. By averaging the slope of each curve in these periods, the flow and density values that represent the stationary traffic state are determined.

However, the determination of constant slopes by simple observation lacks of objectivity and reproducibility. Just consider the fact that the magnitude of the fluctuations in the slopes of these cumulative curves depends on the background “flow” subtracted in order to re-scale them

[30]. Therefore, slightly different periods would be found at each application, depending on the background flow selected and influenced by the subjectivity of the researcher. Also, the fulfillment of the "approximately constant" condition is vague and the limits of the obtained period blurred. Moreover, the procedure is time-consuming. In order to solve these problems, it is needed to systemize the method.

Two criteria should be fulfilled to define a stationary period: being longer than a minimum duration, and the variability of measurements being within an accepted tolerance. This "minimum duration" and "accepted tolerance" are the parameters of the method (see Table 2 for the values selected in the present application). A clear trade-off exists in the selection of these thresholds. On the one hand, if the duration is too long, it might be difficult to find periods within the admissible tolerance for the variability. If the tolerance is increased, different traffic states may be averaged out. On the other hand, short durations may accept smaller tolerances, but in this case random fluctuations will have a higher influence, compromising the stationary concept and producing scatter in the diagrams.

In general, because of the presence of instabilities, the variability during congested traffic is much bigger than during free-flowing periods. This is translated into the method with relaxed criteria for congested periods. So, the first step is to identify the time intervals in congestion. These periods are clearly identifiable by comparing T- with N-curves [31]. Opposite trends in these curves indicate congestion (i.e. flow rate is decreasing while density rate is increasing), despite of the background value used.

Second it is needed to eliminate extreme fluctuations due to detector malfunctioning. These fluctuations are detected by comparing the absolute difference of flow and speed between consecutive minutes to a maximum threshold. Only one minute can be eliminated without "breaking" the period. If two or more consecutive minutes need to be eliminated, the database is "cut", meaning that a unique stationary period cannot extend to both sides.

The third step is to apply the definition of the stationarity. A moving average of flow and speed is computed starting from the first data point after the last "cut". Whenever a new data point is included in the average the tolerance condition (as expressed in Equations 1 and 2 for flow and speed) is checked. If it is fulfilled the data point is added to the period. The process ends when one of the tolerances is not fulfilled. This last data point is excluded from the average, and the database "cut". Finally it is only needed to select as stationary the periods between "cuts" longer than the minimum duration required for each type of traffic (congested or not).

The tolerance condition is formalized in Equations 1 and 2.

$$\left|\bar{q} - q_i\right| \leq q_r \ \forall \ i \in T \tag{1}$$

$$\left|\bar{v} - v_i\right| \leq v_r \ \forall \ i \in T \tag{2}$$

Where,

- $\bar{q}$ and $\bar{v}$ refer to the average flow and speed of the period lasting "T" minutes.
- q_i and v_i refer to the flow and average speed measurements (for instance in a one minute aggregation in the present application).
- q_r and v_r are the thresholds for the maximum deviation accepted.

TABLE 2

4. TEST SITE AND AVAILABLE DATA

The test site is a 3.3 km stretch on the A13 freeway accessing the Rotterdam Ring (A20) and the city center from the north. A detailed layout of this site, including the surveillance and control equipment installed, is presented in Figure 2. Essentially, the system is composed of loop detectors about every 400m, with an associated Variable Message Signs (VMS) very close to its position. In April 2014, the static speed limit on the stretch was reduced from 100 km/h to 80 km/h with the objective of improving air quality and reducing the noise pollution. Point-to-point speed enforcement by camera surveillance aims to guarantee the compliance of this speed limit. In addition, the stretch is permanently under Automatic Incident Detection (AID) control, a national DSL algorithm implemented in the 80's. The AID system reduces the speed limit as soon as slow traffic is detected on the freeway. Today, it is clear that the AID system is not suitable for preventing or resolving jams, but it has a significant effect in the prevention of head-tail collisions [32].

The AID responds to a reactive algorithm, and the activation of the different speed limits is in essence as follows:

- First activation if v < 35 km/h (v is the average minute speed measured at the detector). Then show a limit of 50 km/h at the location and of 70 km/h at the next immediate upstream gantry.
- Change 50 to 70 km/h if v > 55 km/h (drivers actually have to violate the speed limit before it switches).
- Deactivate if v > 75 km/h.

FIGURE 2

Two days were carefully selected, with similar demand and weather conditions. Each one corresponds to a different period regarding the maximum speed limit (i.e. 100 km/h and 80 km/h). The morning and afternoon peak periods are analyzed (i.e. 6-9am and 3-6:30pm). The available data includes flow, average speed (arithmetic mean of individual speeds) and the speed limit displayed in each gantry, per lane and every minute. Unfortunately, no density or occupancy data was recorded. Therefore, the density needs to be estimated from flow and speed using the fundamental equation. Note that the average speed relating flow to density at a particular point in space is the harmonic average of individual speeds, according to Eddie's generalized definitions of traffic variables [33]. The consequences of not using the proper average speed in the density estimation are more relevant in dense traffic [34], and consequently, significant scatter appears in the congested branch of the fundamental diagram. This makes more difficult to extract strong conclusions from this part of the diagram.

4.1. Typical Demand Pattern and Bottleneck Activation

Figure 3 shows speed contour plots for Day#1 (September 23rd, 2014; limit 80 km/h) and Day#2 (March 12th, 2013; limit 100 km/h). Two main sources of congestion can be identified form the figures. The first one, at KP 19.1, appears sporadically and for short periods through the day. Longer congested periods happen during the morning rush (e.g. from 7:30 to 8:00am on Day#1). The second one, at KP 18.5, shows a more recurrent behavior, and it is congested for most of the afternoon rush. Shockwaves emanate at short time intervals, so that stop-and-go traffic occurs. During the recoveries (i.e. the "go" periods) the sub-critical speed limits of the AID system are active. Some free-flow stationary periods are going to be observed in this context.

Remarkably, none of these two locations are active bottlenecks. The analysis of these congested periods (using downstream detectors) shows that queues spillback to these points from downstream bottlenecks, at the merging of the A13 with the A20 (the Rotterdam ring). For instance, at KP 19.1, queues spill from the westbound merging, while at KP 18.5, from the two lanes of the eastbound merging.

Strictly speaking capacity could only be assessed where an active bottleneck is present [35]. Otherwise, there might not be enough demand to reach capacity, or alternatively queues might arise due to spillback from a more restrictive active bottleneck downstream. In such cases, only values close to capacity are obtained. Furthermore, in case of queue spillbacks, the capacity drop and posterior queue discharge observed, can be totally meaningless and does not represent any property of the section, but the comparison of two different sections: the measured one and the downstream active bottleneck [31]. In spite of this, the detector located at KP 17.8 was selected for the analysis. This is the downstream detector on a 3 lane homogeneous section of 1 km (between KP 17 till KP 18).

FIGURE 3

5. RESULTS ON A DUTCH FREEWAY

The methodology to estimate stationary periods (see Section 3) was applied to data from Day#1 and Day#2. The statistics of the results obtained in the process are summarized in Table 3.

The fundamental diagram extracted from the analysis at KP 17.8 is presented in Figure 4 and in Table 4. The maximum flows are in agreement with the capacities and queue discharge rates typically seen in Dutch freeways. This confirms that, despite not being an active bottleneck, the chosen location allows to see a wide range of flows reaching a value probably near capacity. The analysis of maximum flows when the lower speed limits are in force (i.e. 50 and 70 km/h) is more conflictive. These speed limits are due to the AID system, which activates as a consequence of downstream congestion. This congestion is due to a queue spillback, meaning that the flow is restricted by the capacity of the downstream bottleneck. It is possible that this hampered the possibility of observing higher flows under these sub-critical speed limits.

TABLE 3

FIGURE 4

FIGURE 5

TABLE 4

6. CRITICAL ANALYSIS AND COMPARISON TO PREVIOUS RESULTS

Clear differences are observed between the Barcelona and Rotterdam results regarding the maximum flows, critical speeds and critical densities achieved under different speed limits (compare Figures 4a and 5 and see Table 4). Before directly comparing these values, one should note that the motivations behind LS-DSL strategies in Rotterdam and Barcelona are different. In Rotterdam the low speed limits are due to the AID system devoted to warn drivers when downstream congestion occurs, while in Barcelona they are result of an ad-hoc experiment and low speed limits are posted for extended periods of time and for a wide range of traffic densities.

While these different contexts would add enormous difficulties in the comparison of traffic performance at the corridor level (e.g. different speed limit propagation affecting differently the generated shock waves), the effects on a sectional level comparison are much less severe. There is in both sites a section with the same number of lanes, under the same (or similar) speed limit, the same traffic demand, and the same traffic state (congested or not), so that the differences at the sectional level are limited to the short duration of the low speed limits periods in Rotterdam (i.e. only for the 70 and 50 km/h limits), because of the AID system. This will be taken into account in the comparison.

Capacity values in Barcelona are insensitive to the speed limit, while a flow reduction is observed in Rotterdam for 70 and 50 km/h sub-critical limits. The explanation of such differences must consider the following:

- 70 and 50 km/h sub-critical speed limits in Rotterdam are due to the AID system. This implies the existence of downstream congestion. It is possible that the capacity restriction downstream limits the discharge flows during the recovery phases at the analyzed location. To what extent this happens it is unknown. Comparing the measured flows under these speed limits with similar contexts in Barcelona (see Table 4), one can see that the differences are small. However the reduction in the maximum flow due to these sub-critical speed limits, with respect to the maximum flows under higher (i.e. critical) speed limits, is only around 5% in Barcelona while it is around 15% in Rotterdam. The analysis of such differences must consider that the actual maximum capacity at both sites is unknown as none of the sections represent an active bottleneck, and there is no reason to think neither that they should be equal, nor the contrary. In spite of this, note that in Rotterdam these flows are measured during short recovery phases between congested periods when the capacity drop has already taken place. In contrast, in Barcelona they are measured in pure free-flow, before traffic breakdown occurs. This explains why in Barcelona the maximum flow measured for the 40 km/h speed limit is significantly higher than the flows achieved for the same occupancies in congested regimes (see Figure 5).
- Maximum flows for critical speed limits (80 km/h or higher) in Rotterdam are significantly above those measured in Barcelona (80 km/h). This could suggest that in the Barcelona experiment capacity is not reached due to the lack of demand. It is accepted that this is the case, because the only proof for reaching capacity is that a breakdown occurs at the given location and this did not happen. However, the fact that the average speed is significantly reduced for the higher flows under the 80 km/h speed limit (see Figure 5) suggests that that the maximum flow measured is actually not far from capacity. Although in a different context, it has been empirically shown that the reduction of speed for increasing density only happens near capacity [23]. In any case, the Rotterdam data does not present this effect in the fundamental diagram for the higher speed limits (as it exists in Barcelona, meaning lower critical speeds and higher critical densities). The authors could not find any clear explanation for the phenomenon. Several factors such as driving skills, the type of vehicles, the geometry of the road, the enforcement strategy (punctual vs point-to-point) might have an influence.

What can be concluded from data observed in both locations is that a speed limit of 50 km/h is not capable of reducing the flow under 1850 veh/h. These empirical results discard modeling assumptions leading to significant lower flows as a result of speed limits around 50 km/h. The empirical effects of lower speed limits (e.g. 20 km/h) remain unexplored and should be treated in future investigations, if they are feasible in practice.

Finally, because in the Rotterdam test site the congested states are only measured with 50 km/h speed limit, and because the free-flowing periods under this speed limit only represent the "go" periods of stop-and-go instable traffic, when the capacity drop has already taken place, no conclusion can be reached regarding the effects of low speed limits on the shape of the fundamental diagram. Whether the free-flowing branch of the diagram when very low speed limits apply can be extended significantly above the maximum measured flows in congested regimes under the same speed limit (as conceptually and empirically shown in Figures 1e and 5 respectively, and implying a huge capacity drop due to traffic breakdown under these low speed limits), or not (as assumed in most of the current models [11, 16], see Figures 1b and 1d) remains as an open issue.

7. CONCLUSIONS AND FURTHER RESEARCH

This paper presents the analysis of the dynamic speed limit (DSL) effects in the fundamental diagram (flow – density) on the last stretch of the A13 freeway in Rotterdam. The huge traffic database available and a good level of DSL implementation in Dutch freeways has been determinant to obtain new findings.

For a clear representation of the fundamental diagram, a new methodology for the definition of stationary periods has been developed. It is objective, reproducible and automated, easing significantly the previous manual procedures. Nonetheless, the robustness of the method could be improved, particularly looking for an endogenous definition of the parameters used.

The most relevant conclusion of the research is that flows around 1850 veh/h per lane can be sustained when speed limits of 50 km/h are in force. Flows in this range were measured in both locations. However, in Barcelona there was no flow-reducing effect as a result of the low speed limit, but in the Netherlands there seems to be a flow reduction of 15%. To what extent this different behavior is a result of: i) a rarely low capacity in Barcelona; ii) because low speed limits in the Dutch AID system are associated with low flow anyways (due to decelerating or accelerating traffic) and not directly due to the speed limit, or iii) both; is unknown.

Results are therefore inconclusive on whether very low speed limits allow for extremely dense and stable high flows in free-flowing traffic as previously postulated the Barcelona experiment [1], or not. Unfortunately, this limits the possibility of relating further the findings in this paper with the current state of the art in traffic flow theory.

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TABLE 1 DSL Effects on the Fundamental Diagram: Literature Review[1]

Cremer (1979) [24] (See Fig. 1a)
Proposes a quantitative model for the flow-occupancy diagram, based on data extracted from Zackor (1972) [2]. It is claimed a 21% capacity increase due to DSL and a shift of the diagram towards higher densities.
Smulders (1990) [25]
Using data from Dutch freeways [26], it is found that the effects of speed signal control are far less dramatic than previously assumed. Capacity hardly increased with DSL control (1-2%). The author acknowledges a traffic homogenization in terms of a reduction of the variance of vehicle spacings and headways.
Hegyi (2004) [11] (see Fig. 1b)
Proposes a model for the flow-occupancy diagram with no capacity increase due to DSL. It is claimed that the most significant effect would be the change in the uncongested part of the diagram indicated by a straight line with the slope corresponding to the speed enforced by the DSL gantry. The congested branch of the diagram is assumed to be unaffected by DSL. The critical occupancy is defined by the cross point between the uncongested and congested branches.
Papageorgiou et al. (2008) [20] (see Fig. 1c)
Estimates the effects of a 60, 50 and 40 mph speed limit on the flow-occupancy diagram, in relation to the no speed limit case. Data is measured on an European freeway. The main findings are: • Slope decrease on the q-occ diagram for undercritical occupancies (i.e. lower speeds in the free flowing regimes) • Shift of the critical occupancy to higher values, particularly for the 50 mph limit • Inconclusive results regarding capacity
Carlson et al. (2010) [16] (see Fig. 1d)
Presents a model for the flow-occupancy diagram based on data from Papageorgiou et al. (2008) [20]. The lower the speed limit, the lower the capacity, and the more the diagram shifted to higher occupancies. This implies lower free flow speeds, higher critical occupancies and higher density in congested states. So, it is assumed that speed limits affect the congested branch of the diagram. The empirical data behind the model is neither rich enough to empirically validate the model for very low sub-critical speed limits presented nor for very high occupancy levels (>28%).
Soriguera et. al (2014) [1] (see Fig. 1e)
Analyzes the data of a DSL experiment on a freeway accessing Barcelona [21]. Different speed limits, ranging from 100 km/h to 40 km/h are maintained during one whole morning rush (from 7 to 10 am) The main results found are: • For the 80 km/h speed limit, flows near capacity can be achieved for a wide range of occupancies (18 to 26%) and speeds (70 – 50 km/h). This is visualized in the flow-occupancy diagram as a flattening of the top part of it. • The only effect of speed limits above 50 km/h is the reduction of the average free flowing speed according to the speed limit in force. This is visualized as a reduction in the slope of the free-flowing branch of the diagram, and thus limits critical occupancies to its higher range. • The sub-critical 40 km/h speed limit implies a significant increase of the critical occupancy to 33%, while capacity is merely reduced. Low speed limits imply very high stable occupancies, preventing traffic breakdown.

[1] Only the effects on the aggregated fundamental diagram (i.e. at the sectional level, for all lanes) are presented. Recently, per lane analysis has been proposed in order to obtain more clear insights [27-29]. With such analysis, DSL has been found to promote the inter-lane homogeneity increasing the utilization of the shoulder lane. Because the shoulder lane is underutilized in some situations (e.g. when there is a significant percentage of heavy vehicles), speed control can lead to a slight capacity increase in this lane.

TABLE 2 Parameters Used in the Estimation of Stationary Periods

	Criteria for Elimination		Stationarity Requirements		
	Flow Threshold	Speed Threshold	Minimum Duration[1]	Flow Tolerance (q_r)	Speed Tolerance (v_r)
Free Flow	20 veh/min	15 km/h	3 min	8 veh/min	7 km/h
Congestion	Not applicable		3 min	15 veh/min	15 km/h

[1] The selected minimum duration is rather short. This is because speed limits change rapidly in the selected test site. Longer periods with low speed limits are rare.

TABLE 3 Summary of the Stationary Periods Obtained at KP 17.8

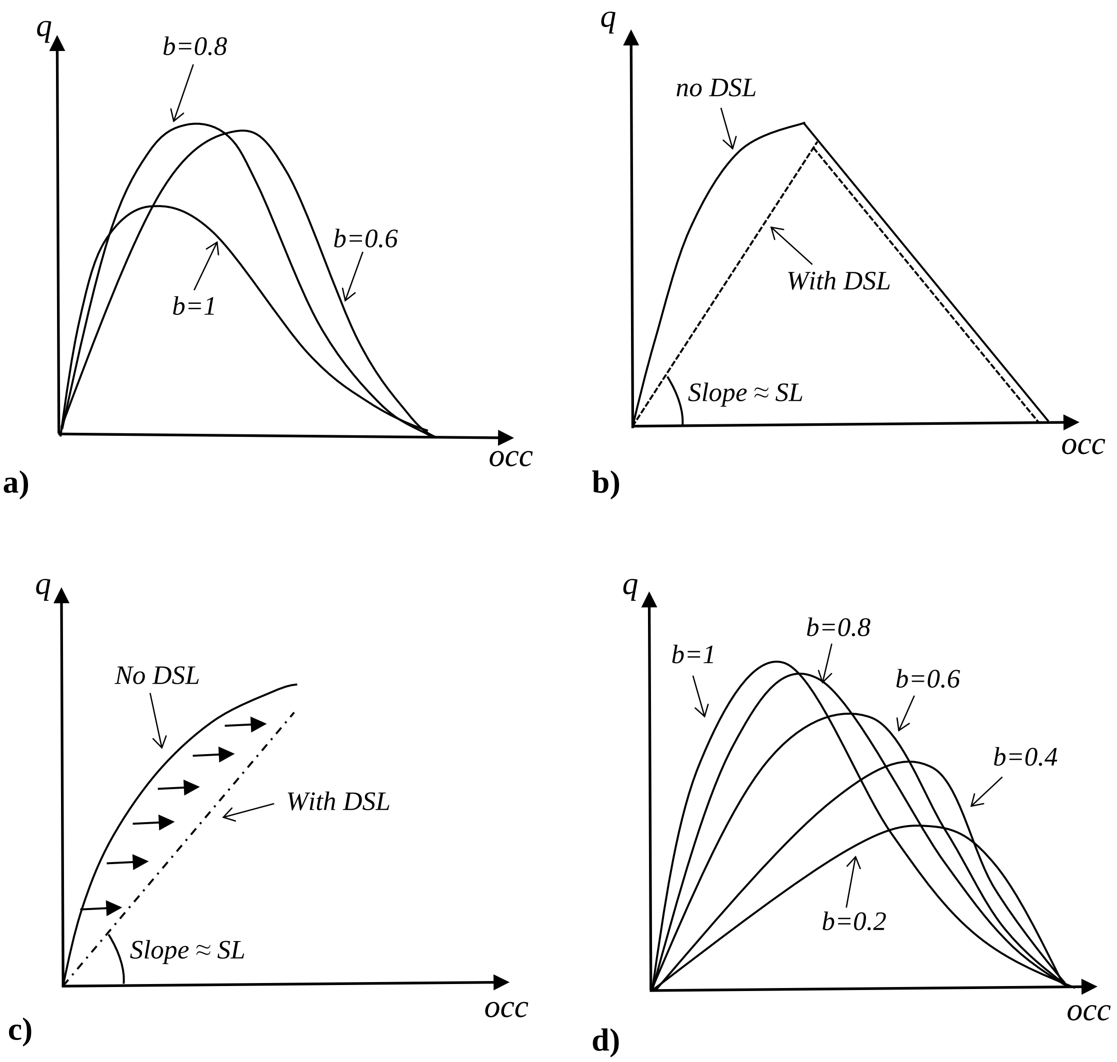
	Day#1				Day#2			
	Congested	**Free Flow**	**Non-Stationary**	**AID Active**	**Congested**	**Free Flow**	**Non-Stationary**	**AID Active**
Minutes	56	286	50	142	41	272	79	152
% of Time	14%	73%	13%	36%	10%	69%	21%	39%
Number of SP[1]s	8	49	NA[2]	22	8	57	NA	29
Shortest SP [min]	3	3	NA	2	3	3	NA	2
Longest SP [min]	22	15	NA	22	10	12	NA	10
Avg SP Duration [min]	7.0	5.8	NA	5.1	5.1	4.7	NA	4

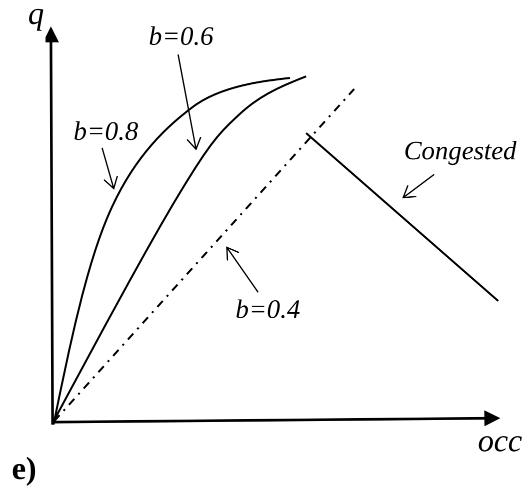
Note: [1] "SP" stands for Stationary Period. [2] "NA" stands for Not Applicable.

TABLE 4 Critical Values for Different Speed Limits (SL) at KP 17.8 and Comparison to the Barcelona Results

		Maximum Flow [veh/h per lane]	Critical Speed[1] [km/h]	Critical Density[1] [veh/km]	Duration[2] [min]
Rotterdam	SL=100 km/h	2225	84	80	19
	SL=80 km/h	2148	70	91	20
	SL=70 km/h	1872	61	92	18
	SL=50 km/h	1858	55	102	18
Barcelona	SL=80 km/h	1985	53	112	17
	SL=60 km/h	1960	50	118	11
	SL=40 km/h	1907	41	140	18

[1] It represents the average speed (or density) prevailing during the stationary period with maximum flow.
[2] Cumulative duration of the stationary periods considered in the estimation of the maximum flow.





Note: *b* is the ratio between the speed limit and the free flow speed without DSL-control.

a) Cremer (1979) [24] based on data from Zackor (1972) [2]
b) Hegyi (2004) [11]
c) Papageorgiou et al. (2008) [20]
d) Carlson et al. (2010) [16] based on data from Papageorgiou et al. (2008) [20]
e) Soriguera et al. (2014) [1]

FIGURE 1 Previous findings of the DSL effects on the fundamental diagram. Adapted from [20].

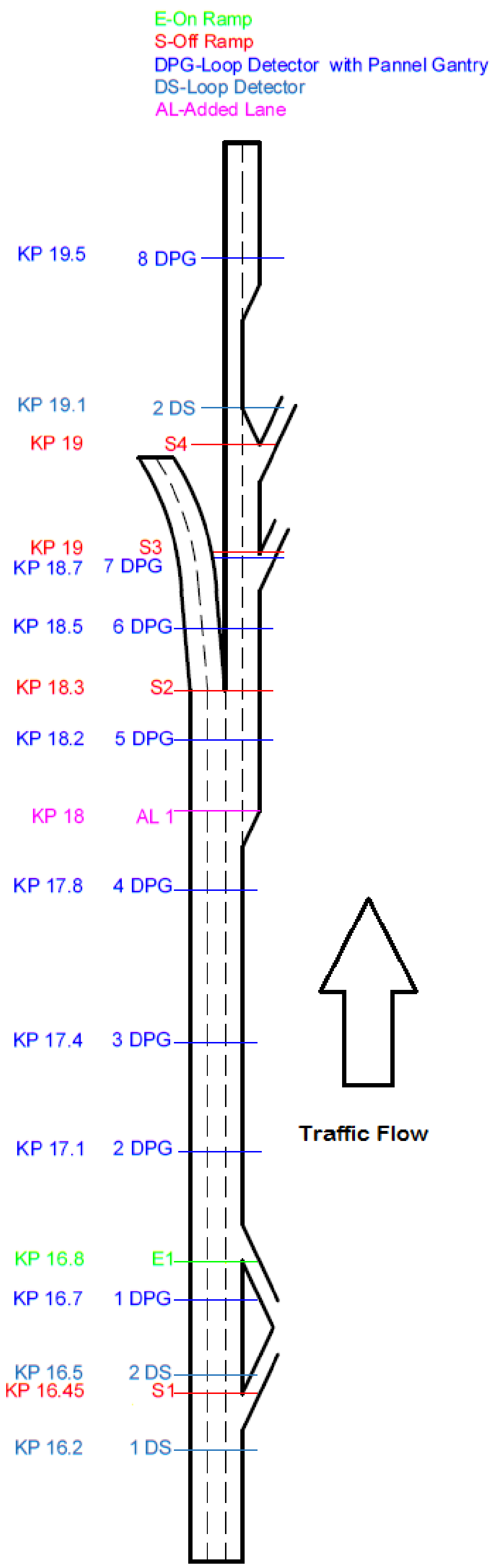
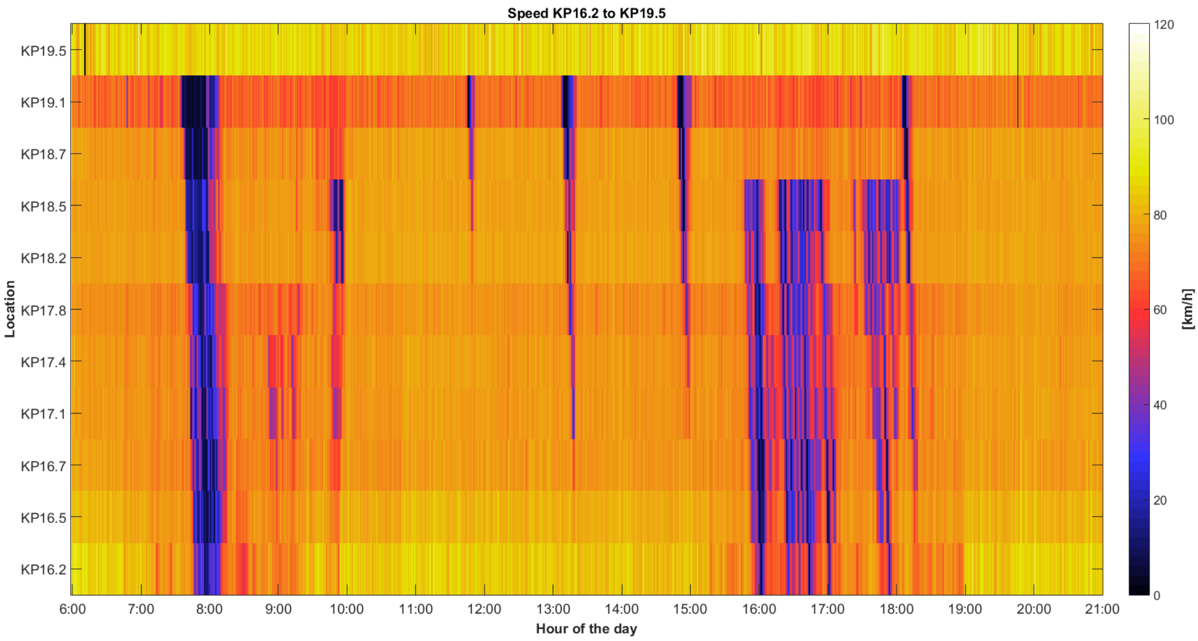
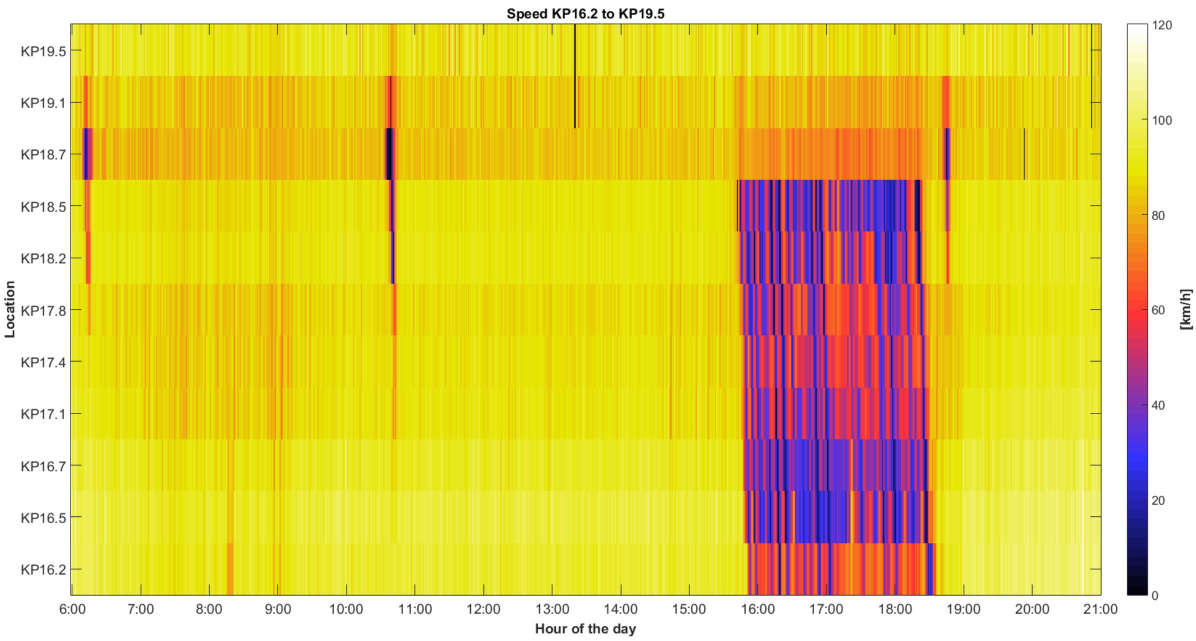


FIGURE 2 Test site layout: A13 between KP 16.2 till KP 19.5.

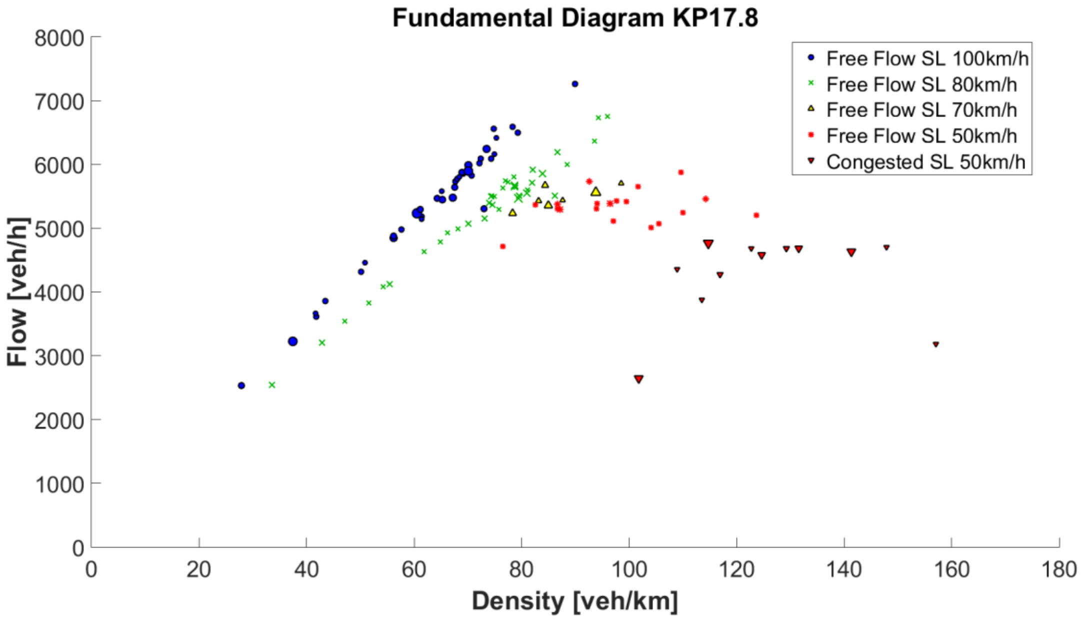


a)

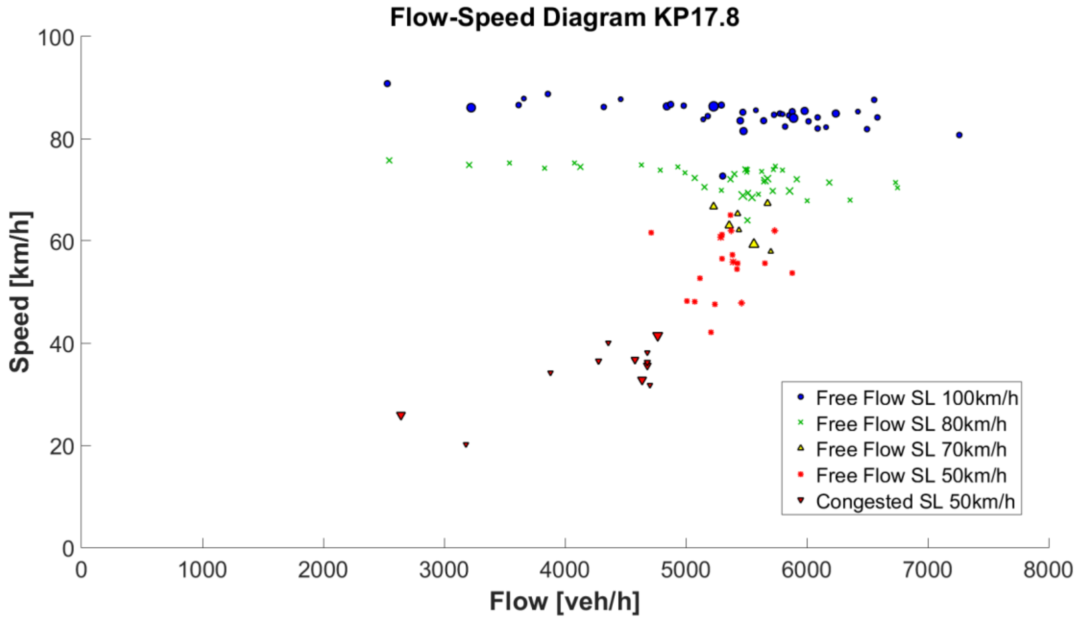


b)

FIGURE 3 Speed contour plots. a) Day#1 (September 23rd, 2014; limit 80 km/h); b) Day#2 (March 12th, 2013; limit 100 km/h).



a)



b)

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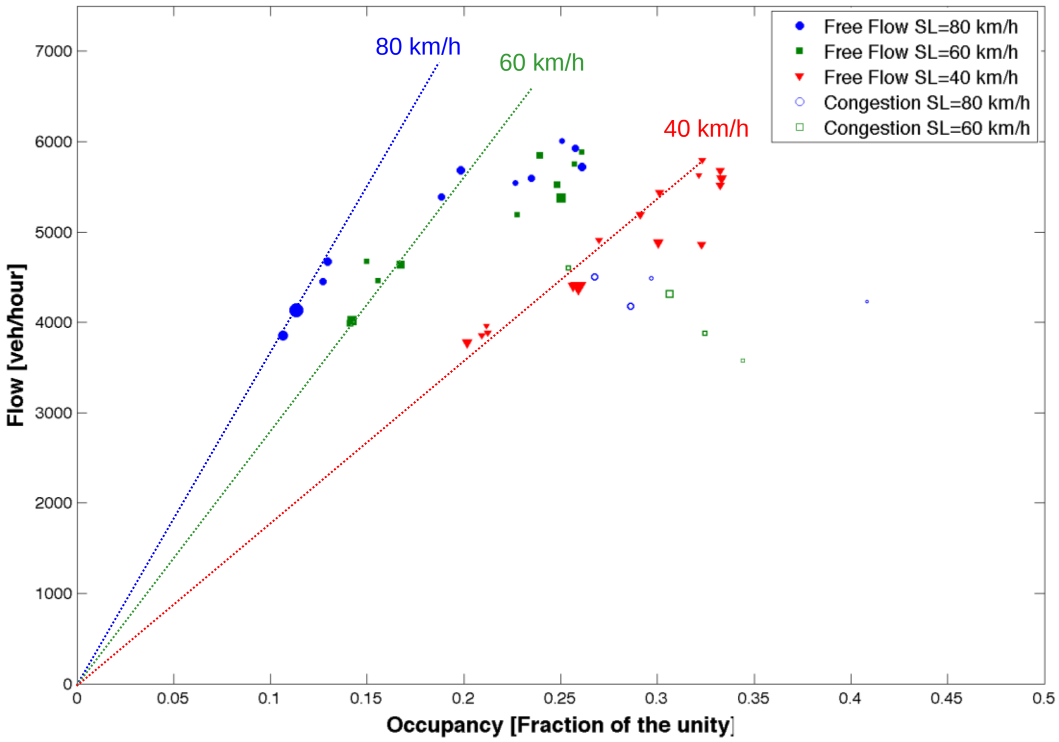

FIGURE 5 Fundamental diagram from the Barcelona experiment [1] for different speed limits (SL).