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ABSTRACT

Recent years have seen a renewed interest in Variable Speed Limit (VSL) strategies. New opportunities for VSL as a freeway metering mechanism or a homogenization scheme to reduce speed differences and lane changing maneuvers are being explored. This paper examines both the macroscopic and microscopic effects of different speed limits on a traffic stream, especially when adopting low speed limits. To that end, data from a VSL experiment carried out on a freeway in Spain are used. Data include vehicle counts, speeds and occupancy per lane, as well as lane changing rates for three days, each with a different fixed speed limit (80 km/h, 60 km/h, and 40 km/h). Results reveal some of the mechanisms through which VSL affects traffic performance, specifically the flow and speed distribution across lanes, as well as the ensuing lane changing maneuvers. It is confirmed that the lower the speed limit, the higher the occupancy to achieve a given flow. This result has been observed even for relatively high flows and low speed limits. For instance, a stable flow of 1942 veh/h/lane has been measured with the 40 km/h speed limit in force. The corresponding occupancy was 33%, doubling the typical occupancy for this flow in the absence of speed limits. This means that VSL strategies aiming to restrict the mainline flow on a freeway by using low speed limits will need to be applied carefully, avoiding conditions as the ones presented here, where speed limits have a reduced ability to limit flows. On the other hand, VSL strategies trying to get the most from the increased vehicle storage capacity of freeways under low speed limits might be rather promising. Additionally, results show that lower speed limits increase the speed differences across lanes for moderate demands. This, in turn, also increases the lane changing rate. This means that VSL strategies aiming to homogenize traffic and reduce lane changing activity might not be successful when adopting such low speed limits. In contrast, lower speed limits widen the range of flows under uniform lane flow distributions, so that, even for moderate to low demands, the under-utilization of any lane is avoided. These findings are useful for the development of better traffic models that are able to emulate these effects. Moreover, they are crucial for the implementation and assessment of VSL strategies and other traffic control algorithms.

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1. Introduction and background

Freeway traffic control by means of variable speed limits (VSL) was first introduced in the early 1970s in Germany (Zackor, 1972) and one decade after in the Netherlands (Remeijn, 1982). Nowadays, VSL is a popular advanced traffic management strategy, with many implementations around the world and much research interest (Lu and Shladover, 2014; Khondaker and Kattan, 2015). In spite of its expansion and international popularity, the effects of VSL on traffic are not fully understood yet. As a result, the vast majority of the implemented systems simply track the upstream propagation of measured low speeds (Haj Salem et al., 2013). With this logic, VSL acts as an incident warning system, with the objective of improving traffic safety. A global decrease in major accident rates of 20–30% after VSL implementation has been consistently reported (Sisiopiku, 2001; Lee et al., 2006; Soriguera et al., 2013). Furthermore, in locations where the implementation of VSL was tied to a strict enforcement of speed limits, and the average free flow speed declined, reductions in pollutant emissions and fuel consumption of 4–6% during free flowing periods have also been observed (Stoelhorst, 2008; Baldasano et al., 2010; Cascetta et al., 2010; Soriguera et al., 2013). However, traffic emissions peak during congested periods, so this reduction could be much larger if VSL systems prove to be also an effective measure for congestion relief.

Although many researchers have envisaged the potential of VSL to ease freeway traffic congestion, few strategies put into practice have succeeded in achieving this objective yet. Early research focused on the concept of "homogenization" (Smulders, 1990; Zackor, 1991; van den Hoogen and Smulders, 1994). These strategies were grounded on the early empirical findings suggesting that lower speed limits promote the reduction of fluctuations in traffic variables. Differences in speed, flow and occupancy, between lanes and within the lane (i.e. at vehicular level) could be reduced, and this would induce a capacity increase. Typically, homogenization strategies should be applied at volumes 15–20% below capacity, imposing speed limits around the critical speed (i.e. the speed observed at capacity; usually around 70–90 km/h) (Smulders, 1990). The effects seem to be maximized with speed limits around 80 km/h (Papageorgiou et al., 2008), although this value might be site specific.

Empirical evidence suggests (see Table 1), that indeed some homogenization happens as a result of VSL around critical speed limits. However, its effects on capacity raised much more controversy. Pioneer research (Zackor, 1972, 1991; Cremer, 1979) predicted a significant capacity increase as a result of VSL homogenization (up to 21%). Later (Smulders, 1990; van den Hoogen and Smulders, 1994; Papageorgiou et al., 2008), found these predictions too optimistic, concluding that no significant capacity increase could be systematically attributed to traffic homogenization. More recently, per lane analysis has been proposed in order to obtain more clear insights (Knoop et al., 2010; Heydecker and Addison, 2011; Duret et al., 2012). With such analysis, VSL homogenization has been found to increase the utilization of the shoulder lane. Notice that as 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 (Daganzo, 2001, 2002).

Table 1
Literature review: empirical VSL effects on a sectional basis.

Source	VSL range (km/h)	Compliance level	Free flow speed[a]	Critical density[b]	Capacity increase	Homogenization
Zackor (1972)	80	High	↓	–	↑ 5–10%[c]	↓ Speed differences[d]
Smulders (1990)	90–70	Low (advisory)	↓ Slight (0–5%)	↑ Slight	↑ 1–2%	↓ Spacing and headway variance[e]
Van den Hoogen and Smulders (1994)	90–70	High	↓	↑	No effect	↓ Flow, occupancy and speed differences[d]
Papageorgiou et al. (2008)	96–64	Advisory & mandatory periods	↓	↑	Inconclusive[f]	–
Knoop el al. (2010)[g]	100–60	Low[h]	–	–	↑ Shoulder lane	↓ Flow differences between lanes
Heydecker and Addison (2011)	96–80	High (radar enforced)	↑↓[i]	↓	↑ Central and shoulder lanes	–
Duret et al. (2012)[g]	110	High	–	–	↑ Shoulder lane[j]	↓ Flow and speed differences between lanes

[a] Meaning average speed at low occupancies, where an increase/decrease of the occupancy level does not modify the travelling speed. A reduction of free flow speed implies higher occupancy to serve the same flow.

[b] Meaning density measured at capacity (i.e. maximum flow).

[c] Cremer (1979) proposed a quantitative model for the flow-occupancy diagram based on these data achieving a 21% capacity increase.

[d] For individual vehicles as well as between freeway lanes (i.e. Intra and Inter-lane).

[e] No significant effect was found on speed differences and inter-lane distributions.

[f] Results in Papageorgiou et al. (2008) 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 VSL, not on its reduction.

[g] Only free flowing states are analyzed.

[h] The low compliance rate implied that actual measured speeds were 79 km/h for the 60 km/h speed limit case.

[i] Depending on the lane considered and on the speed limit in force. Inconclusive.

[j] Duret et al. (2012) observed that there exists a critical total flow (less than capacity) for which the flow on the shoulder lane reaches a maximum. In the absence of control there is an underutilization of the shoulder lane, because flow on the shoulder lane reduces while total flow is still increasing. This is called the U-Turn effect.

Despite the controversy about capacity increase as a result of VSL, scientific consensus exists regarding the reduction of the average free flow speed (see Table 1), this being the main effect of VSL strategies on aggregated traffic flow. This implies that the same flows are served with higher densities, and therefore the critical density (i.e. the traffic density at capacity) increases. These concepts are captured by all the aggregated traffic flow models aiming to reproduce the VSL effects (see Fig. 1).

In light of the very limited evidence of a capacity increase as a result of VSL homogenization, today, the expectations for VSL to become a control strategy with significant effects on freeway efficiency are based on its ability to restrict mainline flow (i.e. mainline metering or gating strategies). The idea behind this type of strategies is simple: to restrict the vehicular inputs using very low speed limits in order to prevent traffic breakdown and the subsequent ∼10–20% capacity drop (Cassidy and Rudjanakanoknad, 2005). Two different types of implementation approaches pursue this idea. The first one includes the SPECIALIST algorithm, developed and successfully tested in the Netherlands (Hegyi et al., 2008; Hegyi and Hoogendoorn, 2010). The algorithm is based on the fact that by instantaneously lowering the speed limit over an extended freeway stretch the flow is reduced proportionally while the density is kept constant. This reduction is temporary but enough in the SPECIA-LIST experiment to resolve shock-wave jams (i.e. traffic instabilities that arise in very dense traffic) and recover full capacity. A similar approach could also be applied to an infrastructural bottleneck with a fixed location (Chen et al., 2014).

The second type of implementation approaches (Hegyi et al., 2005a, 2005b; Carlson et al., 2010a, 2010b; Müller et al., 2015), assume that VSL can be used as a mainline metering mechanism by imposing very low speed limits upstream of bottleneck locations (i.e. down to 10 km/h in Müller et al. (2015) or around 20 km/h in Carlson et al. (2010a, 2010b). This, usually in coordination with ramp metering, would create the required permanent flow restriction to avoid the activation of the critical bottlenecks and the harmful capacity drop. The simulations of this strategy in test corridors result in reductions of 20% of the total travel time. However, the traffic flow models used to test these mainline metering algorithms (see Fig. 1b and d) have never been validated for this range of speed limits. Carlson et al. (2010a, 2010b) use the macroscopic second-order traffic flow model included in the METANET simulator (Papageorgiou et al., 1990; Kotsialos et al., 2002; Messmer and Papageorgiou, 1990), including the VSL impact by linearly modifying the parameters of the model according to the "$v_{control}/v_{free}$" ratio. This implies scaling down the flow – density diagram (see Fig. 1d). Hegyi et al. (2005a, 2005b) use
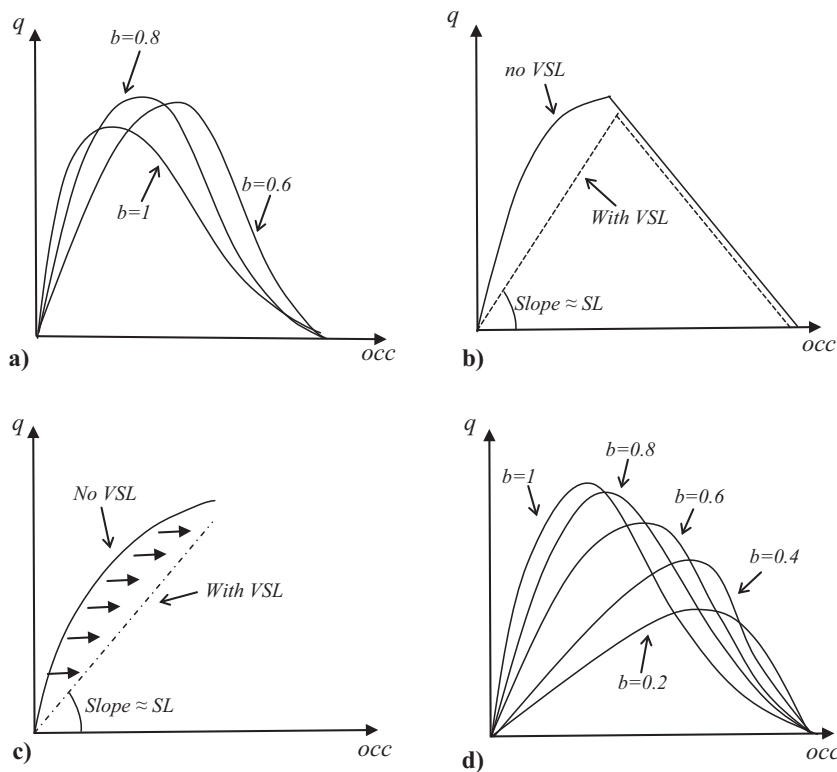
Fig. 1. Existing models regarding VSL effects on the flow-occupancy diagram. (a) Cremer (1979) based on data from Zackor (1972). Capacity increase was predicted as a result of homogenization. (b) Hegyi et al. (2005a, 2005b). The diagram under VSL is obtained as the intersection of a new free-flowing branch (according to the SL in force) and the previous diagram without control. This leads to capacity reductions for low speed limits. (c) Papageorgiou et al. (2008). A decrease in the free flow speed is observed as a result of VSL. Observations are inconclusive regarding capacity and congested states, for which no model is proposed. (d) Carlson et al. (2010) based on data from Papageorgiou et al. (2008), propose a model with capacity reductions for lower speed limits. *Note: b is the ratio between the speed limit and the free flow speed without VSL-control.*

the same second-order traffic flow model but VSL is included by assuming that the same flow – density relationship prevails and that the desired speed is the minimum between the one corresponding to the experienced density and the other caused by the displayed speed limit (see Fig. 1b). Müller et al. (2015) use the AIMSUN microscopic traffic simulator (TSS, 2012), which implements the Gipps' models for car following (Gipps, 1981) and lane changing (Gipps, 1986). All these models consider that a significant flow restriction can be achieved by imposing low speed limits (see Fig. 2). Such expectation comes from: (i) the reasoning based on traffic flow principles, assuming that drivers' behavior (i.e. the spacing-speed relationship) will not be modified by the existence of the speed limit, (ii) some empirical data in (Papageorgiou et al., 2008) where there seems to be a reduction in flow for the 40 mph (64 km/h) speed limit, although details regarding such reduction are limited, as the authors were focusing on the capacity increase due to VSL, not on its reduction, and (iii) engineering experience showing that bottlenecks are created in some roads that operate at high speed limits (80 km/h or higher) followed by sections with lower enforced speed limits. To the authors' best knowledge there are no detailed empirical experiments in connection with the mainline metering capabilities of speed limits. In fact, there are no published results on the empirical effects of low speed limits on freeway traffic flow, while there is common agreement that the capacity/speed limit relationship is a vital part of mainstream traffic flow control which should be further investigated (Müller et al., 2015).

This is not the only issue regarding VSL effects that still requires further research. For instance, evidence suggests that lane changes in dense traffic conditions can further disrupt traffic, and worsen the existing congestion problems. Previous empirical research has associated lane changes with some traffic phenomena such as the capacity drop (Laval and Daganzo, 2005, 2006; Laval et al., 2007) or traffic oscillations (Ahn and Cassidy, 2007; Duret et al., 2009). Similarly, the absence of lane changes has been associated with the smoothing effect (Menendez, 2006; Menendez and Daganzo, 2007). This was empirically proven in (Cassidy et al., 2010) by showing that the activation of high occupancy vehicle (HOV) lanes can indeed diminish lane changing maneuvers and smooth traffic, increasing the bottleneck discharge rates, even for the adjacent general purpose lanes. Given these findings, one would expect that any strategy that reduces the number of lane changes, could increase flow rates. Because none of these lane changing studies involve VSL, it is worth exploring in which circumstances the VSL homogenization effect ultimately reduces lane changing rates, allowing for increased flows.

These limitations and gaps in the literature are mostly due to the difficulties in obtaining a suitable traffic database. Data is generally obtained on a test corridor under specific VSL control algorithms, where different speed limits are displayed for different traffic conditions. This implies that data collected during a specific speed limit may not cover the whole range of possible traffic states. Results obtained are valid for testing the aggregated corridor performance with a specific VSL algorithm, but conclusions on the detailed drivers' behavior when facing different speed limits on the same infrastructure cannot be addressed in detail for all traffic conditions (Papageorgiou et al., 2008; Torné et al., 2014). Moreover, speed limits lower than 60 km/h are rarely implemented, hence empirical data on those cases is practically non-existent. These difficulties were addressed in the Barcelona VSL experiment on the B-23 freeway (Soriguera and Sala, 2014), which provided a suitable database for answering the previous research questions. The experiment consisted in posting clearly different and fixed speed limits (80, 60 and 40 km/h) during the whole morning rush on three different working days, and measuring in detail all the relevant traffic variables.

The objective of the present paper is to empirically assess the effects of different speed limits on traffic flow, based on the analysis of data collected with the Barcelona experiment. The analysis includes the evaluation of both, the macroscopic and the microscopic effects. The macroscopic effects (i.e. those effects on the aggregated traffic flow) can be seen as the final consequences of speed control. To analyze them we used traditional traffic theory tools (e.g. transformed curves of cumulative
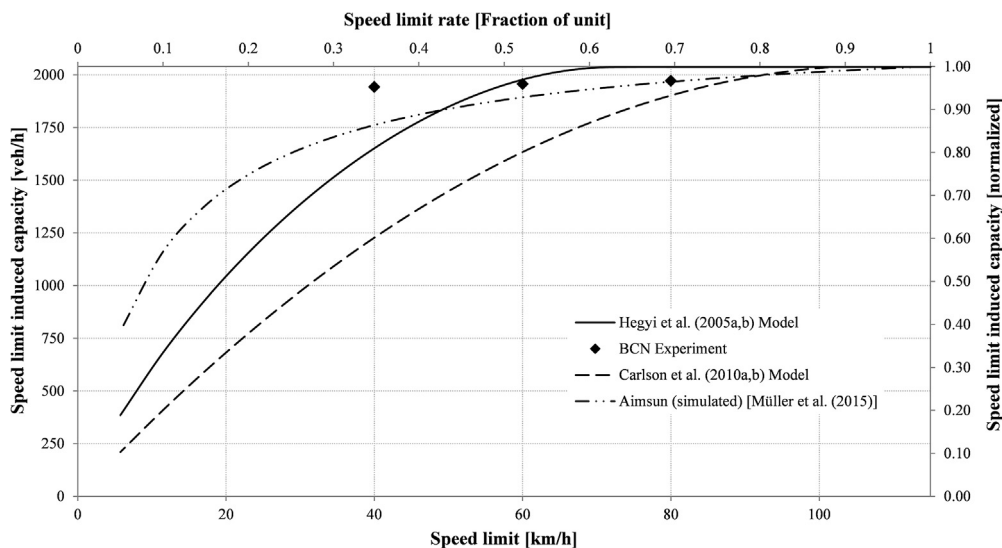

Fig. 2. Capacity – speed limit relationship according to different models. *Note:* "BCN experiment" stands for the empirical data presented herein.

vehicle count and cumulative occupancy) based mostly on loop detector data. These tools provide the required resolution to estimate, through careful analysis, robust periods of stationary traffic. The evaluation of these stationary traffic states revealed that the permanent flow restriction due to the application of low speed limits is not as significant as models assume, at least in the observed context, with speed limits as low as 40 km/h and punctual enforcement. This is relevant and needs to be taken into account for the achievement of adequate designs of speed control strategies aiming to restrict the mainline flow on freeways.

The microscopic effects, on the other hand, can be seen as the raw effects of VSL on individual vehicles, and the underlying cause of the macro consequences. Intra and inter lane speed homogeneity, vehicle distribution across lanes and lane changing probability, in the different speed limit scenarios, are compared. The underlying data includes both that from loop detectors, and additional radar and video recordings also collected at the site. Results reveal that the homogenization effect reported for speed limits between 110 and 70 km/h cannot be simply extended to lower speed limits. For instance, while the flow distribution across lanes is more uniform for lower speed limits, the relative speed difference between lanes increases. For moderate demands, this also implies an increase in the lane changing rate. Such findings are important for the design of speed harmonization schemes, and could inform more efficient future algorithms for controlling the speed and lane changes of autonomous vehicles.

The rest of the paper is organized as follows. In Section 2 the test site and the available data are presented. This includes the physical description of the site, the traffic demand pattern, and the experiment itself. Section 3 presents the methodology used for the data treatment. Section 4 presents the macroscopic results, meaning the effects of the different speed limits on the flow-occupancy diagram. Section 5 presents the microscopic results, including the effects on traffic homogeneity. Section 6 addresses congested states, and finally in Section 7 some conclusions are outlined.

2. Test site description and available data

The B-23 freeway provides access from the south to the city of Barcelona (Spain). Since 2012 a VSL control system is installed on the last 13 km of the freeway towards the city. The selected test site is located at kilometer post (KP) 4.73 on the inbound direction (see Fig. 3). This is a straight, slightly uphill, 3-lane section of a typical freeway with 3.5 m wide lanes, and 2.5 m wide hard shoulders.

Previous research on the B-23 VSL corridor (Soriguera and Sala, 2014) has shown that this section is in between two recurrent bottlenecks. Downstream, the capacity of the off-ramp at KP 3.57 is not enough to serve peak demands. Jammed traffic fills up the off-ramp and spills to the main highway trunk, creating a diverge bottleneck at this location. The queue generated from this bottleneck generally reaches past the section at KP 4.73. Upstream, the traffic weaving at the KP 6.20 junction, creates a slight merge bottleneck. Both bottlenecks activate recurrently during the morning rush.

The VSL experiment on the B-23 freeway corridor took place during the first three weeks of June 2013. The experiment consisted in switching off the default VSL algorithm and posting fixed speed limits on the overhead gantries for the whole morning rush, between 7 and 10 am. Section KP 4.73 is the location of an overhead VSL gantry with radar enforcement, which ensures a high level of speed limit compliance (Soriguera and Sala, 2014). Three different speed limits were posted on different working days: 80 km/h (identified herein as Day#5, measured on Thursday June 6th, 2013), 60 km/h (Day#6, measured on Thursday June 13th, 2013), and 40 km/h (Day#7, measured on Tuesday June 18th, 2013). The posted speed limit in the immediately upstream VSL gantry (i.e. Section KP 6.15) was 80 for days #5 and #6, and 60 km/h for Day#7. This implied a speed reduction at the analyzed location, even for Day#5 with uniform 80 km/h speed limit. This is because of the radar speed limit enforcement at Section KP 4.73. Notice that the average free flow speed measured at the upstream Section KP 6.15 (without enforcement) was approximately 15 km/h higher than the posted speed limits (Soriguera and Sala, 2014). For the downstream VSL gantry at KP 3.79, the speed limits of Section KP 4.73 were maintained.

During these periods, detailed measurements of all traffic variables were taken. At Section KP 4.73, these included:

- Vehicle count, time mean speed, and detector occupancy, per lane and in a one-minute aggregation (from the magnetic double loop detector at the site).
- Individual vehicle speed and detector occupancy, per lane (from a multiple technology non-intrusive sensor: radar, ultrasound and passive infrared).
- Lane changing count per every pair of adjacent lanes (from video recordings on a 115 m long segment upstream of the section of interest).

In summary, the test section has sufficiently detailed data for the analysis, presents a wide range of traffic states (congested and not congested), a high level of speed limit compliance, and it is far enough from on- off- ramps so that mandatory lane changing is minor. This makes Section KP 4.73 suitable for the study presented below.

3. Data treatment methodology: per lane stationary periods

The objective of traffic data analysis is to reveal properties of the traffic stream that are reproducible over time. Cassidy (1998) showed that these reproducible properties exist when the considered measurements are taken while the average
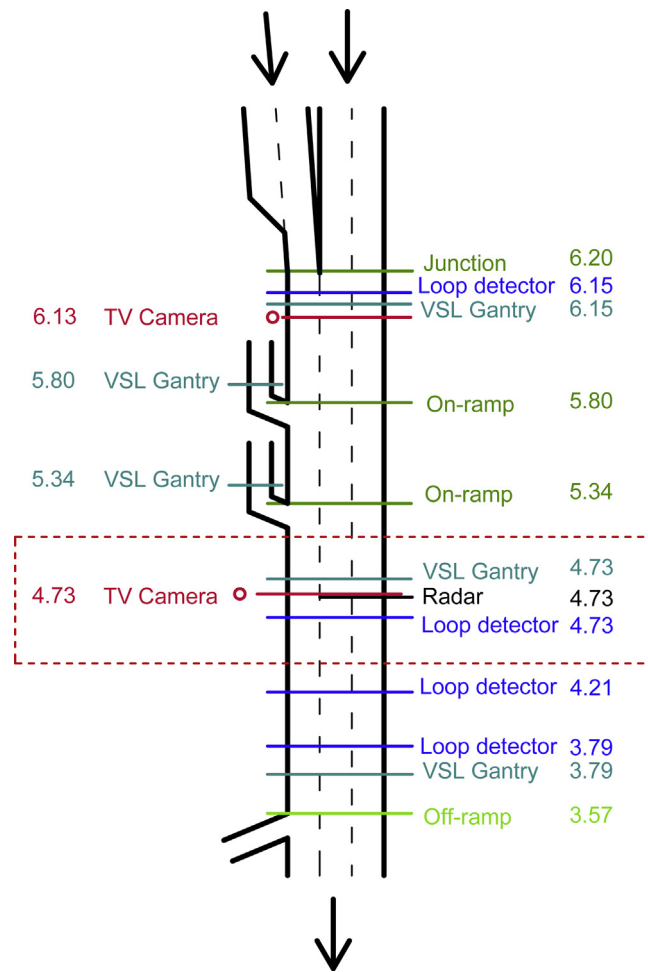
Fig. 3. Test site layout. *Note:* Analyzed data from kilometer post 4.73.

values of these data do not change (or change little) over time. Under these conditions, traffic is nearly time-stationary, and traffic stream properties represented by traffic diagrams (e.g. the flow – occupancy diagram), appear robust and with little scatter of data points.

Standard averaging or smoothing procedures are not always adequate to obtain stationary traffic periods. Smoothing out periods of time of an arbitrary length (even as short as a few minutes) may result in averaging two completely different traffic states, leading to an average traffic state that does not exist in reality. Working systematically with very short periods of time (e.g. 1 min) might result in data fluctuations, not fulfilling the reproducible properties of stationarity. Fortunately, there is a suitable and accurate method to diagnose the activation and deactivation times of bottlenecks, and to determine stationary periods of traffic. The procedure is based on a careful (i.e. manual and time consuming) analysis of transformed curves of cumulative vehicle count (N-Curves) and cumulative occupancy (T-Curves).

Congestion is defined as traffic regimes where an increase in the freeway occupancy is accompanied by a reduction of the through flow. In contrast, during free-flowing traffic an increase in the occupancy also implies an increase in the flow. Therefore, congestion is detected by a sudden increase in the slope of the T-Curve (i.e. occupancy increases) together with a reduction of the slope of the N-Curve (i.e. flow reduction). On the contrary, when both curves bend in the same direction with similar wiggles, free flow conditions prevail. A detailed description of the procedure is provided in several references (Cassidy and Windover, 1995; Cassidy, 1998; Cassidy and Bertini, 1999). Once free flowing and congested periods are identified, stationary traffic states are determined by imposing limited fluctuations of the measured minute flows and occupancies over an extended duration. The standard criteria are that fluctuations with respect to the average flow and occupancy of the period must be lower than 1.7 standard deviations, during a minimum duration of 10 min. In summary, the procedure consists in dividing free flowing and congested regimes into periods of maximum duration fulfilling the fluctuations restriction. Those with a duration longer or equal than 10 min are selected as stationary. The rest are discarded. To reduce the amount of information discarded, relaxed stationarity criteria are also used. This implies increasing the allowed fluctuations

Table 2
Summary of the per-lane stationary period estimation.

Speed limit	Lane	Number of periods Standard[b] (Relaxed)[c]		Cumulative SP[a] duration [%][d]		Average SP duration [min]	
		FF[a]	Cong[a]	FF	Cong	FF	Cong
Day#5 80 km/h	Shoulder	7 (2)	– (5)	64.4	14.1	12.8	5.2
	Central	5 (7)	– (4)	65.6	15.0	9.8	9.0
	Median	8 (2)	– (5)	64.4	12.8	11.6	5.8
	Whole section[e]	*11*	*3*	*46.7*	*12.8*	*7.6*	*5.2*
Day#6 60 km/h	Shoulder	6 (4)	– (3)	70.0	19.4	12.6	11.7
	Central	4 (5)	– (4)	70.6	17.8	14.1	8.0
	Median	5 (4)	– (3)	71.7	17.2	14.3	10.3
	Whole section[e]	*14*	*3*	*58.9*	*17.2*	*7.6*	*8.0*
Day#7 40 km/h	Shoulder	4 (8)	– (4)	63.6	7.2	9.5	4.3
	Central	6 (7)	– (3)	77.2	5.0	10.7	4.5
	Median	9 (5)	– (1)	78.9	3.3	10.1	6.0
	Whole section[e]	*15*	*2*	*44.4*	*3.3*	*5.3*	*3.5*

[a] "SP" stands for Stationary Period. "FF" stands for Free Flowing periods. "Cong" stands for Congested periods.
[b] Standard stationary period criteria: Minimum duration = 10 min. Maximum deviation from the mean = 1.7 std.
[c] Additional periods obtained using relaxed stationary period criteria: Minimum duration = 3 min. Maximum deviation from the mean = 2.0 std.
[d] Percentage of the 3 h duration of the experiment.
[e] Whole section stationarity is defined as the intersection of per lane stationary periods. Sectional traffic is stationary only if all lanes are simultaneously in a stationary traffic state.

to 2.0 standard deviations, and reducing the required duration to 3 min. Results shown in Table 2 are obtained from the application of the described procedure to data from Section KP 4.73.

While traditionally sectional aggregated traffic data (i.e. all lanes together) is used for the detection of stationary periods of traffic, here the procedure is applied to per lane data. Because different lanes have different behaviors and this has important implications in the analysis of VSL systems (Daganzo, 2002; Knoop et al., 2010; Duret et al., 2012), it is especially important to ensure per lane stationarity. Traffic will be stationary only if all lanes are simultaneously in a stationary, although potentially different, traffic state. Hence, this per lane stationarity is a subset of the traditional sectional stationarity, as per lane stationarity ensures sectional stationarity, but the reciprocal is not true.

## 4. Effects of low speed limits on the flow-occupancy diagram

Fig. 4a and b show the flow-occupancy diagrams (across all lanes) measured at Section KP 4.73 under different speed limit configurations. The analysis of the results will be based on the stationary traffic states illustrated in Fig. 4b. The raw minute data are shown in Fig. 4a only for illustrative purposes. Table 3 quantifies some of the metrics of the stationary traffic states associated with Fig. 4b. The obtained results empirically show the following:

- For an 80 km/h speed limit, maximum flows of an average of 1972 veh/h/lane can be reached for a wide range of occupancy levels (i.e. 17.6–25.8%) and speeds (i.e. 51–73 km/h).
- The 60 km/h speed limit implies a reduction of the free flow speed, in accordance with the new speed limit in force. The maximum measured flows remain practically unaffected (i.e. average of 1956 veh/h/lane). For lower travelling speeds, higher occupancies are necessary to serve the same flows. As a consequence, the occupancies measured during maximum flow periods are on its higher range (i.e. 24.4–25.8%).
- The 40 km/h speed limit implies a significant increase of the occupancy level measured during maximum flow periods (i.e. 32.0–34.7%). Maximum flows are merely reduced (i.e. 1942 veh/h/lane).
- Once a traffic breakdown has occurred (in this case at the downstream bottleneck at KP 3.57) and the queue spills back to the analyzed Section KP 4.73, the congested branch of the flow - occupancy diagram is not affected by different speed limits. Although there is a limited amount of data for congested regimes, this suggests that speed limits do not affect much the macroscopic dynamics of congested traffic.

Two main conclusions can be derived from the previous results. First, lower speed limits imply a significant extension to higher occupancy levels under free flowing conditions. So, low speed limits allow achieving very high stable occupancies, preventing the traffic breakdown, and thus avoiding the capacity drop and keeping a large accumulation of vehicles in the freeway. This result is in accordance with most of the previous findings (see Table 1).

Second, for speed limits as low as 40 km/h, average flows of 1942 veh/h/lane can be sustained for long periods (i.e. 17 min in the present case). This means that the permanent and significant flow restriction (i.e. metering capability) of low speed limits, assumed in a number of control strategies (Hegyi et al., 2005a, 2005b; Carlson et al., 2010a, 2010b; Müller et al., 2015, see Fig. 2) is limited, at least in the analyzed context (see Section 4.1). So, drivers' are able to "compress", maintaining stable and small headways while travelling at low speeds and very high occupancy levels.
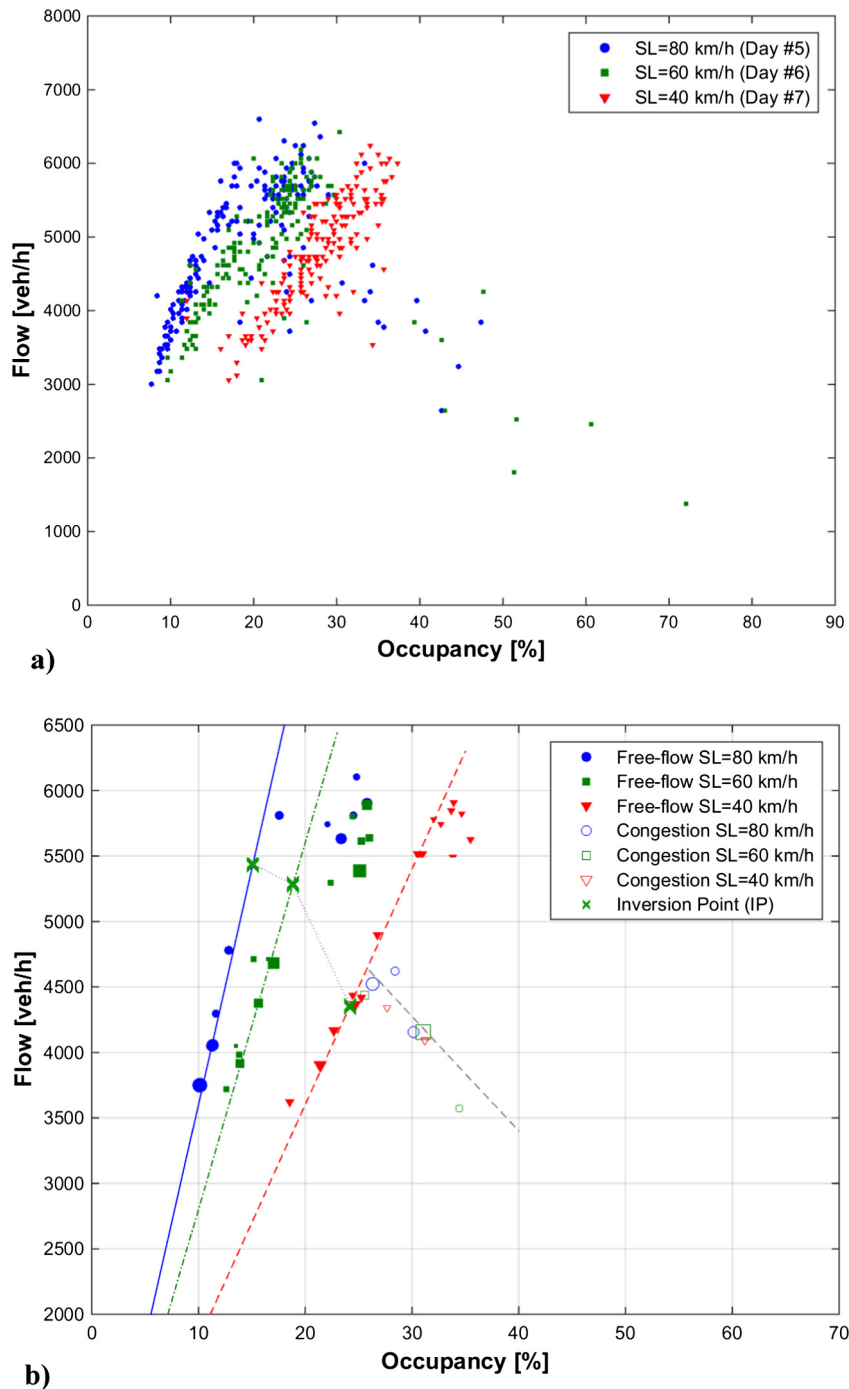
Fig. 4. Sectional (i.e. all lanes) Flow – Occupancy diagram for different speed limits. (a) Minute raw data, (b) Stationary periods. *Note 1*: The size of the stationary data marker indicates the relative duration of the stationary period. *Note 2*: Dashed lines result from linear least squares regression.

4.1. Limitations of the previous analysis and conclusions

   i. *On the capacity concept.* Strictly speaking, the capacity of a section can only be measured in an active bottleneck (i.e. traffic breakdown occurs at the given location). This is not the case for the analyzed Section KP 4.73. In the context of this experiment, demand could be starved from the slight upstream bottleneck (although there are two on-ramps in between). Therefore, it cannot be guaranteed that the maximum flow measured at the analyzed section corresponds to the capacity state. This invalidates the potential conclusions regarding the effects of low speed limits on capacity. In spite of this, the data does prove that high flows can be observed for low speed limits.

Table 3
Flow – occupancy diagram characterization (sectional level).

	Free-flow speed[a] [km/h]	Avg. veh. length[b] [m]	Max. flow[c] [veh/h]	Occupancy[d] (max. flow) [%]	Speed[d] (max. flow) [km/h]	Lane-Ch.[d,e] (max. flow) [Fr. unit]	Duration[f] (max. flow) [min]
Day#5 (80 km/h)	76.7 – 76.7	5.07	5915 (5810–6105)	23.0 (17.6–25.8)	59.2 (51.2–73.5)	0.1393 (0.11–0.17)	19
Day#6 (60 km/h)	69.0 – 65.3	5.15	5869 (5805–5890)	25.5 (24.4–25.8)	51.2 (50.2–54.1)	0.1389 (0.13–0.18)	16
Day#7 (40 km/h)	46.0 – 45.1	5.15	5827 (5740–5910)	33.4 (32.0–34.7)	41.5 (40.3–42.4)	0.1106 (0.03–0.15)	17

Note: Text in parentheses indicates range of values of stationary data points considered.
[a] Computed as the 95–85th percentile of the stationary average speed distribution during free-flow periods.
[b] Average vehicle length computed from least squares linear regression on minute detector data: $occ = \bar{l} \cdot \frac{q}{\bar{v}}$ where "occ" stands for the occupancy, "q" stands for the flow, "$\bar{v}$" stands for the average speed and "$\bar{l}$" stands for the average effective vehicle length. The average vehicle length is obtained from "$\bar{l}$" by subtracting the detector length, of 2 m.
[c] Average maximum flows measured for a cumulative stationary duration longer than 15 min.
[d] Computed from the same stationary periods considered in determining the max. flow.
[e] "Lane-Ch" stands for lane changing probability, defined as the total number of lane changing maneuvers per km over total flow.
[f] Total duration of the stationary periods considered for the max. flow computation.

ii. *On the range of tested speed limits.* The results presented here are valid for the range of speed limits observed (i.e. 80, 60 and 40 km/h) and show that the flow restriction is less significant than predicted by current models (see Fig. 2). How these results would extend to even lower speed limits (e.g. 10–20 km/h, typically used in VSL metering simulations) remains unknown. Regarding this issue, note that the sectional flow can be obtained as the average speed divided by the average vehicles' spacing (i.e. the fundamental equation of traffic). Because the reduction in the spacing is bounded by the average vehicle length, there will always exist a sufficiently low speed limit for any desired reduction of the flow level. Keeping this in mind, the relevant question would be whether these extremely low speed limits could be fulfilled by drivers, or whether they are, in practice, equivalent to a full stop (i.e. a periodic red traffic signal). This aspect is not addressed in the present paper. However, one should keep in mind that nowadays, implemented VSL strategies tend to be around 60–80 km/h.

iii. *On the dynamic effects over space and time.* The Barcelona VSL experiment consisted in posting fixed speed limits for the whole morning rush. The effects of some types of VSL strategies depend on how they are applied over space and time. For instance, this configuration excludes transitional states just after changing speed limits. Therefore, the temporary effect of a speed limit reduction/increase, used in the SPECIALIST like type of algorithms, is not present and cannot be analyzed here.

iv. *On the punctual speed limit enforcement.* Strict enforcement is strongly needed in order to ensure the drivers' compliance to low speed limits. Punctual radar enforcement was applied at the analyzed section. This opens-up the possibility of some sort of "dynamic effects". Drivers can be motivated to follow closely for short periods of time leading to very high flows. These temporary changes in driving psychology (i.e. the existence of "motivated" drivers) are reported and thoughtfully analyzed in (Muñoz and Daganzo, 2002; Daganzo, 2002) and have been proposed as explanations for several puzzling traffic phenomena, like the extremely high flows ("over capacity") observed in short weaving areas. It is plausible that the observed "compression" of the traffic stream under low speed limits at the analyzed section is stable just because drivers anticipate that they will only need to maintain a higher level of attention during the very short period while crossing the radar point. Afterwards, they will be able to speed up and increase the spacing again. This is supported by the fact that speed limits have very little effect on traffic behavior at the detector located approximately 500 m downstream (i.e. at KP 4.21). It is also possible (although not proved so far) that this "motivation" could be lost in case of extensive speed enforcement over longer sections (as assumed in (Hegyi et al., 2005a, 2005b; Carlson et al., 2010a, 2010b)). In such case, flow restriction could be more significant than observed here. In any case, an extended application area of very low speed limits would imply to increase vehicles' delay and to slow down the traffic reaction to VSL control algorithms (Müller et al., 2015).

5. Effects of low speed limits on inter- and intra-lane behavior

5.1. Effects of low speed limits on inter-lane traffic flow distribution

The main characteristics of the described sectional behavior are reproducible in a per lane basis (see Table 4). For the periods of maximum flow, the measured occupancy is similar across lanes. However, speed is higher in the median lane, especially for the higher speed limits. This implies that the maximum flow is significantly larger for the median lane in relation to the central and shoulder lanes.

For the 40 km/h speed limit, a maximum flow of 2053 veh/h can be sustained in the median lane. This represents a reduction of approximately 100 veh/h/lane with respect to the 80 km/h speed limit case. A similar reduction is observed for the central lane. This represents a 5% flow reduction on these lanes. In contrast, no significant reduction (or increase) in the maximum measured flow is observed for the shoulder lane. In addition, the U-turn effect (i.e. a reduction of the flow on the

Table 4
Flow – occupancy diagram characterization (per lane).

	Speed Limit Context	Median	Center	Shoulder
Free-flow speed [km/h]	Day#5 – 80 km/h	89.2 – 86.0	72.0 – 71.7	77.9 – 77.8
	Day#6 – 60 km/h	80.9 – 73.8	60.5 – 58.5	64.4 – 63.7
	Day#7 – 40 km/h	54.6 – 52.9	38.5 – 37.9	44.5 – 44.5
Avg. Vehicle Length [m]	Day#5 – 80 km/h	5.19	4.39	5.41
	Day#6 – 60 km/h	5.43	4.52	5.31
	Day#7 – 40 km/h	5.75	4.29	5.21
Maximum Flow [veh/h]	Day#5 – 80 km/h	2157	1987	1823
	Day#6 – 60 km/h	2076	1887	1892
	Day#7 – 40 km/h	2053	1888	1811
Occupancy (during max. flow) [%]	Day#5 – 80 km/h	25.8	24.2	26.5
	Day#6 – 60 km/h	25.5	24.4	25.2
	Day#7 – 40 km/h	33.9	32.4	32.4
Speed (during max. flow) [km/h]	Day#5 – 80 km/h	60.0	51.4	48.3
	Day#6 – 60 km/h	56.8	47.2	50.9
	Day#7 – 40 km/h	47.1[a]	36.2	40.8
Duration (max. flow) [min]	Day#5 – 80 km/h	21	25	16
	Day#6 – 60 km/h	22	18	19
	Day#7 – 40 km/h	23	19	17

Note: All variables as defined in Table 3.
[a] Some speeding happens on the median lane.

shoulder lane while total sectional flow still increases towards capacity, as reported in Duret et al. (2012)) is not observed either. Notice, however, that the shoulder lane maximum flows shown in Table 4 are significantly larger than those reported in Duret et al. (2012), which were below 1000 veh/h/lane. This may result from the different settings of the investigations. Data in Duret et al. (2012) were measured on an interurban French motorway with higher speed VSL control (i.e. 110–130 km/h) posted on long homogeneous sections far from junctions (i.e. >5 km), and with a higher percentage of trucks, leading to a lower capacity of the shoulder lane.

Previous research has also shown that the lane flow distribution (i.e. the fraction of flow travelling on each lane) exhibits linear trends against the total flow. The median lane increases its share of the flow as the total flow increases, and eventually takes the lead from the central lane as the lane with a highest throughput (Knoop et al., 2010; Duret et al., 2012). We call this the "Inversion Point". This linear behavior is confirmed in the present analysis, even for low speed limits (see Fig. 5). Some additional insights are revealed. First, the range of the lane flow distribution (i.e. the maximum difference between the flow fractions carried by two different lanes) significantly decreases for the 40 km/h speed limit (see Table 5 and Fig. 5). While for the 80 km/h speed limit this range reaches 13.5 percentage points (or 13.7 pps for the 60 km/h limit), it is as low as 5.0 percentage points for the 40 km/h speed limit. These maximum ranges are observed during the lower measured flows of around 3750 veh/h. This indicates a more homogeneous distribution of flow across lanes when low speed limits are applied to moderate demands. This is due to an increased use of the median lane, as a result of the increased lane occupancy induced by low speed limits. It is found that drivers just distribute themselves across lanes with the same preferences according to the lane occupancy, as lane flow distribution is almost insensitive to speed limits for a given occupancy level. Results show maximum differences of 2.6 percentage points in the fractions of flow carried on each lane for the same occupancy and different speed limits.

Further analysis of the lane flow distribution with respect to the sectional occupancy shows a strong homogenization trend across lanes as occupancy increases up to the Inversion Point (i.e. same flow fraction in the central and median lanes). After this point, the flow fractions remain more or less constant for any further occupancy increase (this result is in accordance with Knoop et al. (2010), where density is used instead of occupancy). This means that the Inversion Point could represent the critical lane flow distribution at which the transition from light traffic to heavy traffic happens. In other words, traffic evolves from a "multiple-pipe regime", as defined in (Daganzo, 2002) where different driver/vehicle types are segregated by lane implying different traffic performance between lanes, to a "1-pipe regime" where all drivers/vehicles use indistinctively all lanes leading to a more homogeneous behavior across lanes. This significance of the Inversion Point is further supported by its position on the flow – occupancy diagram (see Fig. 4b). There, it defines the extension of the congested branch (i.e. "1-pipe"). For lower speed limits, the Inversion Point is achieved earlier (in terms of total flow) and then, the critical lane flow distribution holds from moderate demands until the higher flows. Hence, the lower the speed limit, the wider the range of flows under "1-pipe" regime.

5.2. Effects of low speed limits on inter-lane speed differences

It has been consistently reported (see Table 1) that VSL around critical speeds imply a speed homogenization across lanes. This is not so evident for lower speed limits. The data analyzed here shows that the average speed difference between the
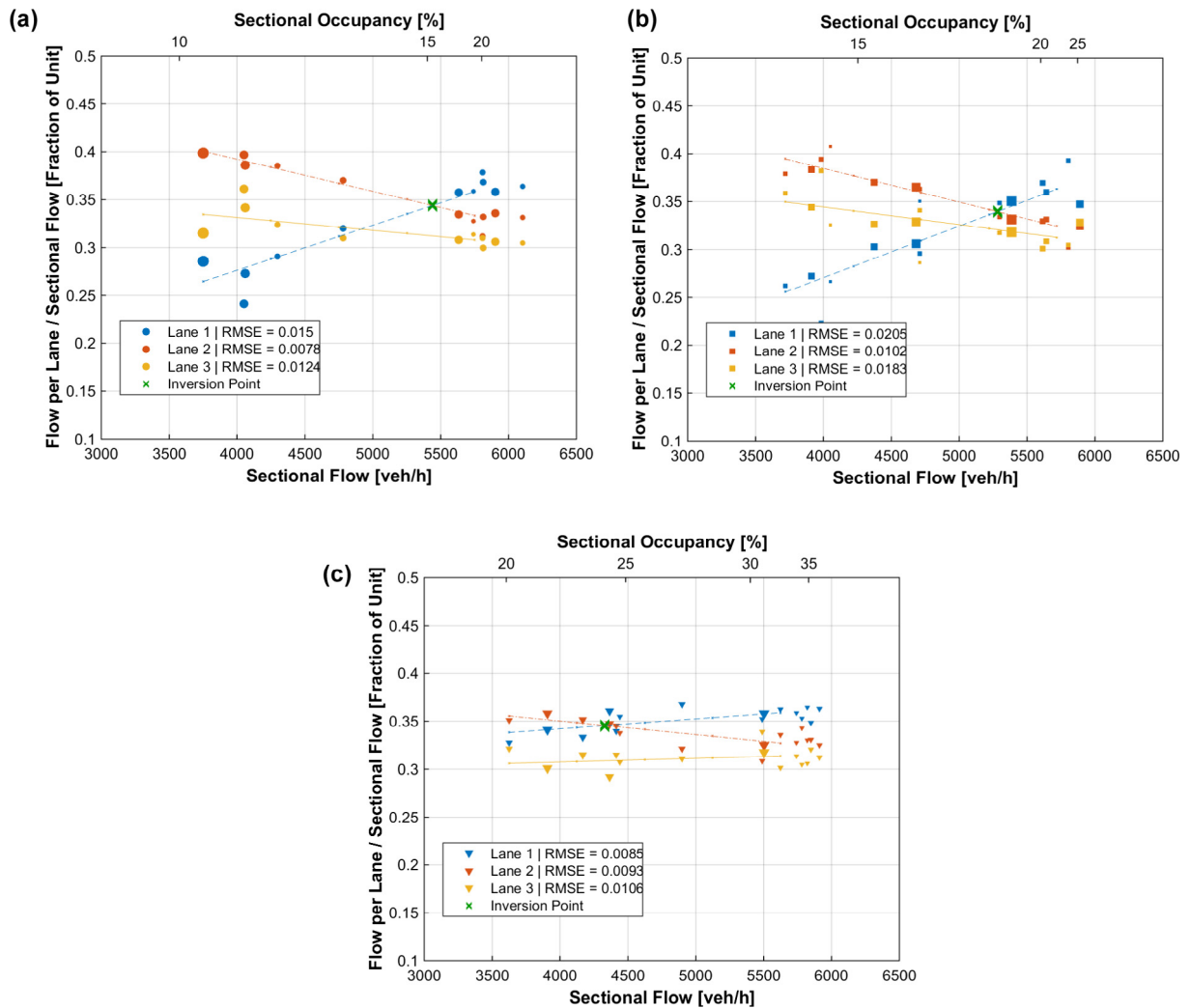
Fig. 5. Flow distribution across lanes. a) Day#5 (80 km/h), b) Day#6 (60 km/h), c) Day#7 (40 km/h). *Note:* (1) Lane 1 = Median lane; Lane 2 = Central lane; Lane 3 = Shoulder lane. (2) Only stationary free flowing periods are shown. The size of the stationary data marker indicates the relative duration of the stationary period. (3) Non-linear occupancy axes are represented above each figure. (4) Regression lines result from linear least squares.

Table 5
Lane flow distribution for different speed limits.

Speed limit	LFD[a] (during min. flow)	Inversion point		LFD[a] (during max. flow)
	Range[b] [ppts] M-C-S[c] [%]	Flow [veh/h]	Flow fraction [%]	Range[b] [ppts] M-C-S[c] [%]
80 km/h Day#5	13.5 26.5–40.0–33.5	5438	34.5	6.5 37.0–32.5–30.5
60 km/h Day#6	13.7 25.5–39.2–35.3	5283	34.2	7.1 37.8–31.5–30.7
40 km/h Day#7	5.0 33.8–35.6–30.6	4354	34.9	4.7 36.3–32.1–31.6

[a] LFD stands for Lane Flow Distribution, meaning the fraction of flow travelling on each lane.
[b] Max. difference between flow fractions (%) on different lanes. Difference expressed in percentage points [ppts].
[c] "M-C-S" stands for Median – Central – Shoulder lanes.

median and central lanes ranges from 8 to 18 km/h, and between the central and shoulder lanes from 0 to 8 km/h. The smaller differences are achieved for higher flows and occupancies, while they increase for the lower demands. These differences between adjacent lanes (in absolute terms, in units of km/h) are not significantly affected by the different speed limits. Lower

speed limits, however, do reduce the variability and fluctuations of these differences for the highest measured flows. The higher occupancies for lower speed limits might also be the cause of this homogenization.

In spite of this, because the travelling speed decreases for lower speed limits, the relative speed differences between lanes (in percentage, relative to the travelling speed) actually increase with the reduction of the speed limit (see Fig. 6). This effect is evident for moderate demands and is reduced for increasing flows. This is because the speed limit does not affect speeds in high occupancy regimes as much as free-flow speed, and because the absolute speed differences are smaller for higher occupancies, as previously stated.

### 5.3. Effects of low speed limits on lane changing

Speed difference between lanes has been associated with lane changing maneuvers (Laval and Daganzo, 2006; Menendez, 2006). Hence, assuming that drivers perceive clearly the relative speed difference between adjacent lanes, in light of the previous results one would expect an increase in the lane changing rates with the introduction of low speed limits. This behavior is confirmed by the empirical data on lane changing (see Fig. 7). Note that the lane changing probability is defined as the number of lane changes per unit distance over the vehicle count, for a given period of time, and represents the probability of changing lane of one vehicle in 1 km travel. The lane changing probability is a normalized version of the lane changing rate (i.e. lane change maneuvers per unit distance per unit time), accounting for the fact that higher flows imply more candidates to change lane per unit time. In order to obtain the lane changing rate from the lane changing probability, it is only needed to multiply it by the flow. The regression plot in Fig. 8 further illustrates the correlation between the lane changing probability and the relative speed difference between adjacent lanes. While correlation does not imply causality, the same tendencies in the behavior are observed. This correlation is stronger between median and central lanes. This might be due to the existence of some mandatory lane changing between central and shoulder lanes. In contrast to discretional lane changing, mandatory lane changes are not triggered by speed differences but by the need to use a specific lane for some purpose (e.g. exiting in a near off-ramp).

Previous results implicitly assume that different speed limits do not modify significantly the location of lane changing so that they could be moved out of the video camera observation range (which includes 115 m upstream of the analyzed section). This assumption is plausible because all the effects of the speed limits are concentrated around the enforcement point (i.e. the radar, located at the analyzed section) and diluted farther away.

In conclusion, low speed limits increase the relative speed difference between lanes, and this in turn, increases lane changing rates for moderate demands. Because lane changing has been postulated as one of the most disrupting factors in freeway traffic, this might be one of the causes of the slight increase in minor accidents reported after the implementation
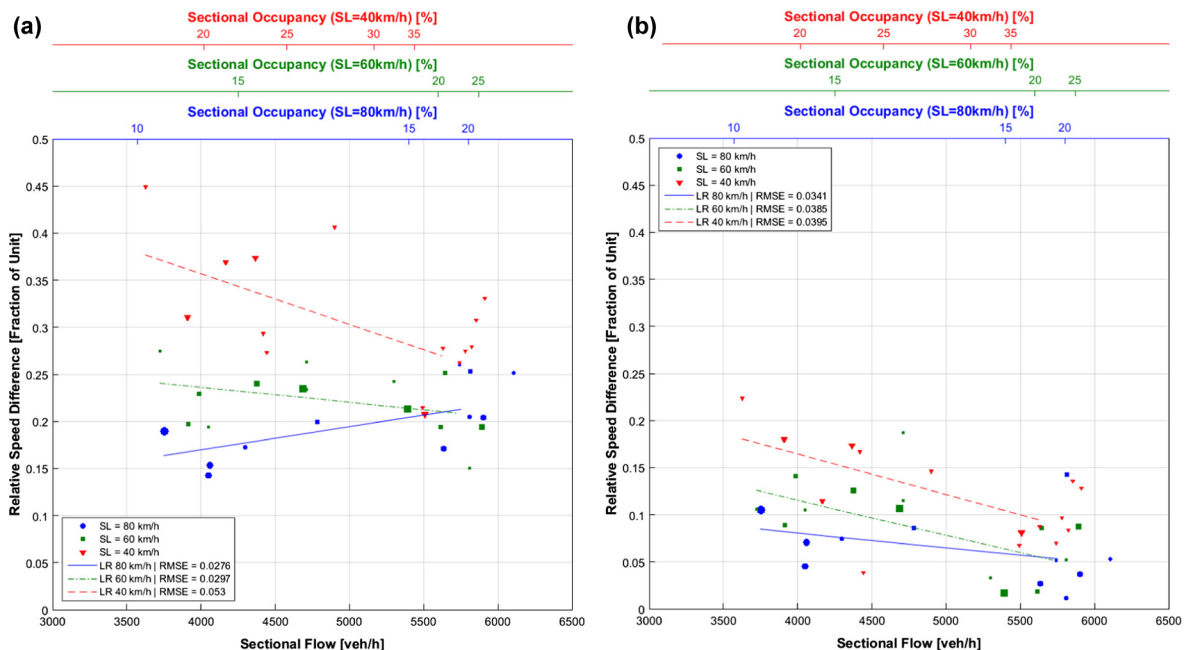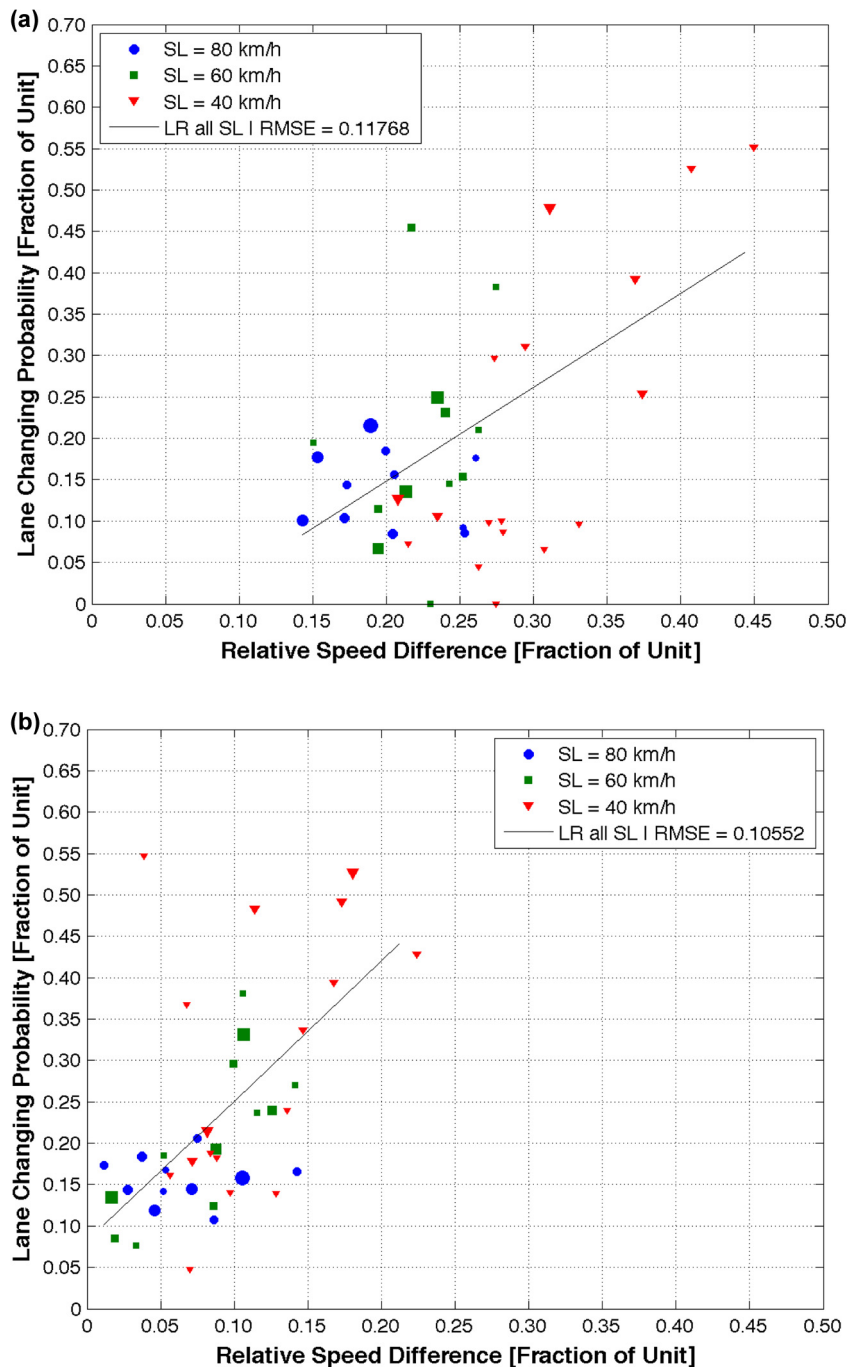

Fig. 6. Relative speed difference between adjacent lanes. (a) Between median and central lanes (b) Between central and shoulder lanes. *Note:* (1) Only stationary free flowing periods are shown. The size of the stationary data marker indicates the relative duration of the stationary period. (2) Relative speed difference is defined as the absolute speed difference over the minimum of the speeds in the considered lanes. (3) Non-linear occupancy axis are represented above each figure. (4) Regression lines result from linear least squares.
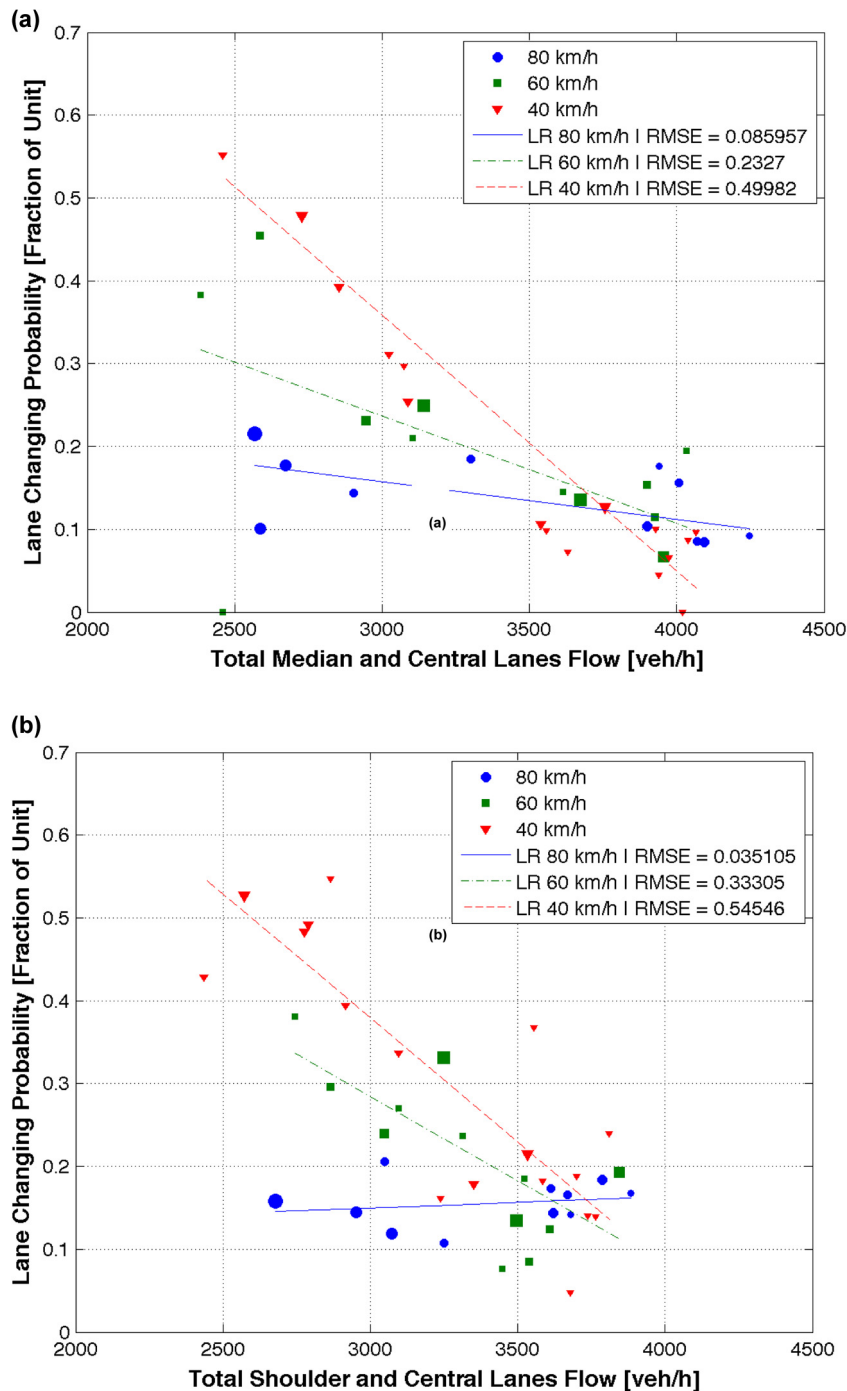
Fig. 7. Lane changing probability between adjacent lanes. (a) Between median and central lanes (b) Between central and shoulder lanes. *Note:* (1) Only stationary free flowing periods are shown. The size of the stationary data marker indicates the relative duration of the stationary period. (2) Lane changing probability is defined as the total number of lane changing maneuvers per km over the total vehicle count of the lanes considered. (3) Regression lines result from linear least squares.

of low speed VSL systems (Soriguera et al., 2013). This increase in lane changing is mitigated by the increase in occupancy, so that for higher flows lane changing probability is not affected by the speed limit (see Table 3) and therefore does not have any additional contribution to traffic oscillations or the triggering of the traffic breakdown. These findings caution against the use of traffic control strategies that employ low speed limits to reduce lane changing rates. Furthermore, the introduction in the next future of autonomous vehicles that might travel at lower speeds according to some kind of control will possibly increase lane changing rates of traditional vehicles. This implies that new freeway control algorithms in the context of mixed

Fig. 8. Lane changing probability versus relative speed difference between adjacent lanes. (a) Between median and central lanes. (b) Between central and shoulder lanes. *Note:* (1) Only stationary free flowing periods are shown. The size of the stationary data marker indicates the relative duration of the stationary period. (2) Lane changing probability is defined as the total number of lane changing maneuvers per km over the total vehicle count of the lanes considered. (3) Regression lines result from linear least squares.

traffic (i.e. automated and traditional vehicles) should aim at keeping low the relative speed differences between lanes. This could be achieved by wisely distributing automated vehicles across lanes forcing traditional vehicles to adapt.

### 5.4. Effects of low speed limits on intra-lane speed variability

In the previous sections, the homogenization effects of low speed limits have been analyzed by comparing the traffic dynamics on different lanes. An additional level of detail is addressed now, by analyzing the homogenization effects within

each lane. In dense traffic conditions, low speed variability within the lane might contribute to the elimination of traffic oscillations, while the opposite can be detrimental to traffic performance.

From data observation, it is postulated that the speed variability among vehicles in the lane is proportional to the difference between the desired and the actual (i.e. limited) travelling speeds. This could respond to the fact that different drivers exhibit different fulfillment thresholds when facing speed limitations. Regarding the desired speeds, two types of situations may exist: (i) The speed limit is "restrictive", meaning that it is below the average travelling speed that would prevail in the absence of the speed limitation. In such case, this unrestricted higher speed is desired. Or (ii) The speed limit is "not restrictive", because it is above the travelling speed. In this case, it is the occupancy level what restricts speed. Then, drivers wish to reach the speed limit. According to this model, the maximum homogenization happens when the speed limit follows closely the actual travelling speeds.

Fig. 9 compares the observed (Fig. 9a) versus the predicted (Fig. 9b) speed variability within the lane. The observed behavior qualitatively follows the predictions of the proposed model. Fig. 9b is only intended to show the qualitative behavior, and further research is needed in order to obtain robust calibration and numerical accuracy.

From the previous results, it can be concluded that for moderate demands low speed limits actually increase speed variability within the lane. Speed homogenization under the lower speed limits only happens when occupancy is high enough to
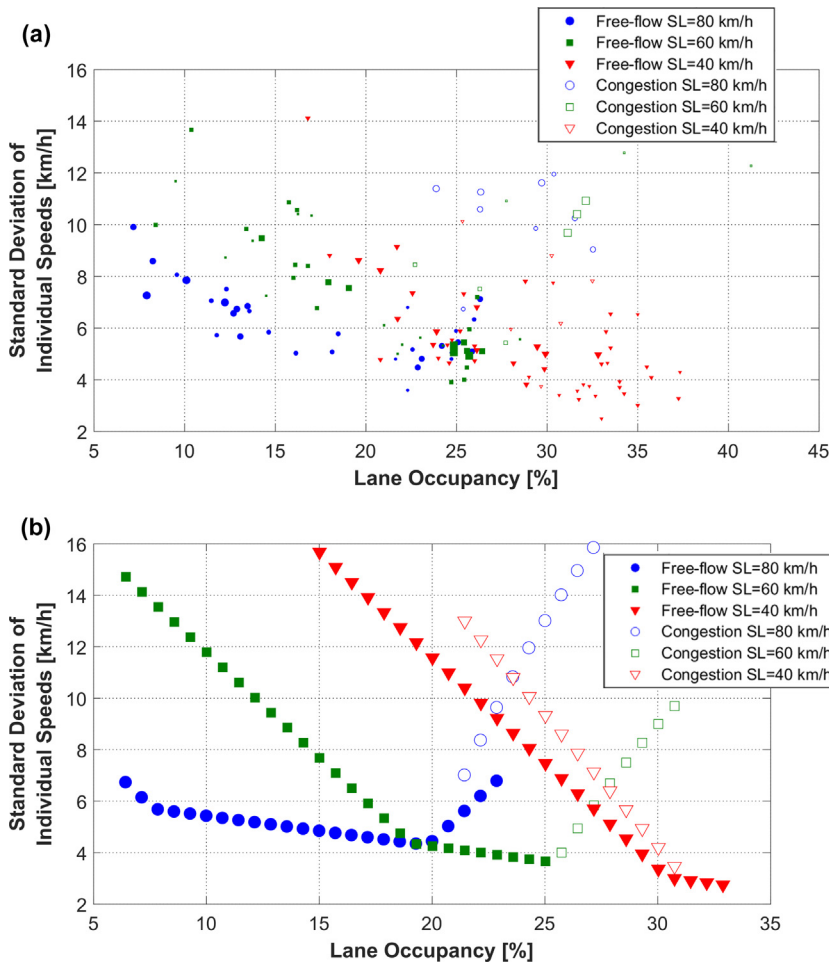
Fig. 9. Speed variability within the lane. (a) Observed. (b) Modeled. *Notes regarding Fig. 9a:* (1) Each data point corresponds to the standard deviation of vehicles' speed within one lane and stationary period. (2) The size of the data marker indicates the relative duration of the stationary period. *Notes regarding Fig. 9b:* (1) Desired speeds are modeled considering an inverse lambda shaped flow-density diagram, where: (i) For free-flowing regimes, speed is linearly reduced with density. (ii) A linear flow-density relationship holds for congested regimes. (2) Calibrated parameters are: $v_f = 110$ km/h; $v_c = 66$ km/h; $k_c = 30$ veh/km; $w = -18$ km/h; where v_f is the maximum speed, k_c is the critical density and v_c the corresponding speed, for which the free-flowing and the congested branches meet, and w is the speed of the characteristic congested wave (i.e. the slope of the congested branch of the flow-density diagram). (2) Maximum free-flowing occupancies for each speed limit are those reported in Table 3. (3) The average effective vehicle length (i.e. including the detector length of 2 m) is 7.15 m. (4) The proportionality parameters of the model are 0.4 and 0.5 for the free-flowing and congested regimes respectively. (5) A minimum standard deviation is assumed. This minimum is reduced with the occupancy level according to: $MinSTD = 6.6 - 11.7\ occ$ km/h.

imply a significant reduction of travelling speed, approaching the speed limit. These last situations include congested regimes, where low speed limits play a significant homogenization role, smoothing the stop-&-go behavior of congested traffic.

## 6. Some remarks regarding congested states

Congestion is defined as traffic regimes where an increase in occupancy is accompanied by a reduction in flow. With the exception of Fig. 9, results presented in previous Section 5 focus only on free-flowing stationary traffic states. This is because, from the macroscopic perspective, few significant differences have been observed between congested states for different speed limits (see Fig. 4). In spite of this, one can compare congested with free-flowing traffic states for the same occupancy levels. The existence of very high occupancy free-flowing regimes under low speed limits makes possible this comparison. Clearly, congested states imply lower flows and therefore lower average speeds (as the occupancy level is similar), but to what extent inter lane homogeneity properties are affected by the traffic breakdown, has not been addressed yet.

Fig. 10 presents such comparison. It is shown that there is no clear difference between free-flowing and congested states neither in the flow fractions carried by each lane nor in the speed differences between lanes. However, lane changing is significantly higher in congested regimes. To sum up, congestion implies an increase in the intra-lane speed variability associated with an increase in the lane changing activity. In order to establish whether these are the causes of traffic breakdown or its consequences, a more detailed analysis of the transitions between traffic states would be necessary.

7. Conclusions and further research

This paper uses empirical data collected during a VSL experiment on the B-23 freeway in Spain to study both the macroscopic and the microscopic effects of low speed limits on traffic performance. To that end, vehicle counts, speeds and occupancy per lane, as well as lane changing rates for three days, each with a different fixed speed limit (80 km/h, 60 km/h, and 40 km/h), were studied in detail. This is relevant, as the effects of VSL strategies especially on traffic operations are not fully understood yet. To the best of the authors' knowledge, this is the first empirical study evaluating the effects of a very low speed limit (e.g. 40 km/h) in a wide range of occupancy levels.

Results reveal some of the mechanisms through which speed limits affect traffic performance, specifically the flow and speed distribution across lanes, as well as the ensuing lane changing maneuvers. Lowering the speed limit extends the range of non-congested occupancies (e.g. up to 0.33 for the 40 km/h speed limit case) without reducing much the prevailing flows. In other words, drivers are able to travel at low speeds with small spacings, keeping a relatively high and stable throughput. As a consequence, even with very low speed limits (e.g. 40 km/h) a flow of 1942 veh/h/lane can be stably sustained. Such results are obtained within the specific context of the experiment, where speed limits are fixed and enforced by means of punctual radar. These settings do not allow to assess the effects of transitions between different speed limits. Also, the high stable flows measured under low speed limits might only be possible because of the "motivation" of drivers to cross the
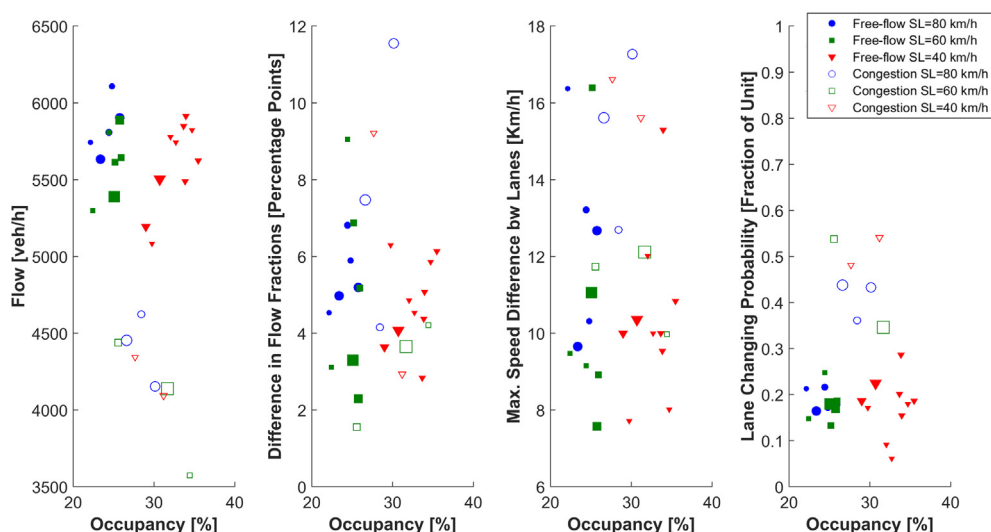
Fig. 10. Comparison between free-flowing and congested stationary states for similar occupancy levels. *Note:* (1) Congestion is defined as any stationary traffic state where an increase in occupancy leads to a reduction in flow. (2) Difference in Flow Fractions is defined as the difference between the max. and min. flow fractions in any lane. (3) Max. Speed Difference is defined as the maximum difference between the average speeds in any lane. (4) Lane changing probability includes median-central and central-shoulder movements.

radar point being highly attentive to keep very small spacings. It is possible that this "motivation" could not be maintained over longer enforced sections. This must be taken into account in the design of VSL strategies aiming to significantly restrict the mainline flow. Extended speed limit enforced sections will be necessary, implying longer transitions between speed limit changes and increased vehicle delays (Müller et al., 2015). Metering capabilities of even lower speed limits (10–20 km/h, as proposed in simulation experiments) remain unexplored, and should be addressed in future research, assuming they are indeed feasible in practice. In addition, new VSL strategies trying to get the most from the increased vehicle storage capacity of freeways under low speed limits, seem promising and should also be investigated (as also pointed out in Carlson et al. (2010a, 2010b)).

At a more microscopic level, results from this study confirm the importance of an Inversion Point, at which the flow distribution is homogeneous between the central and the median lanes. This point is achieved earlier (in terms of total flow) for lower speed limits. Therefore, low speed limits widen the range of flows under homogeneous (i.e. "1-pipe") lane flow distribution. For total flows below those corresponding to the inversion point, neither the flow distribution per lane, nor the speeds are homogeneous (i.e. "multiple-pipe" traffic regimes prevail). Moreover, for moderate demands, lower speed limits imply an increase in the lane changing probability. Such increase is not intuitive. In fact, it might be the opposite of the homogenization that is typically pursued with VSL strategies.

Notice that these findings are based on observations in controlled sections with high compliance rates. Lower compliance rates would most likely reduce the VSL effects described here. In addition, the analysis focuses on time-stationary traffic states. However, stationary traffic does not capture the full spatio-temporal traffic dynamics. For instance, lane changing activity has been observed to peak during transitions between free-flowing and congested states. Hence, the particular effect of different speed limits in these situations still needs to be investigated.

The findings presented in this paper are important because they reveal some limitations to take into account in the design of control strategies that aim to use VSL as a permanent and severe flow restriction mechanism (i.e. mainline metering), or homogenization scheme to reduce lane changing maneuvers. On the other hand, they provide the basis for new control strategies aiming to increase freeway vehicle storage without compromising throughput, or to use the autonomous vehicle distribution across lanes and within the lane in order to achieve traffic harmonization. Moreover, the results presented can also be used as the foundation for the development of better traffic models able to emulate the VSL effects. Most of the flow - density relationships used nowadays to model traffic do not capture the phenomena presented here for low speed limits.

Overall, the conclusions presented here are derived from a specific experiment at a single site in Spain. The obtained results do not prove the universality of the derived conclusions. However, they do prove that some of the preconceived ideas regarding the effects of low speed limits do not hold, at least in the analyzed context. Further empirical evidence might be needed to prove such a statement elsewhere and over extended freeway sections.

Acknowledgements

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