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Effects of low speed limits on freeway traffic flow

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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.