Dynamic Speed Limits

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Please note: The studies included in this synopsis were selected from those identified by a systematic literature search of specific databases (see supporting document). The main criterion for inclusion of studies in this synopsis and the DSS was that each study provides a *quantitative effect estimate*, preferably on the number or severity of crashes or otherwise on road user behaviour that is known to be related to the occurrence or severity of a crash. Therefore, key studies providing qualitative information might not be included in this synopsis.

1 Summary

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1.1 COLOUR CODE: GREEN

The available literature shows that dynamic speed limits (DSLs) have favourable effects on driving speeds and on the number of crashes. However, the number of empirical results is very limited and results should be confirmed by additional research.

1.2 KEY WORDS

Dynamic speed limit, DSL, variable speed limit, VSL, weather, speed, speed management, evaluation, effectiveness, crash, variable message sign.

1.3 ABSTRACT

Dynamic speed limits (DSL) are limits that change according to real-time traffic, road or weather conditions. In DSL schemes road users are typically informed of speed limit changes by electronic signs that are housed within gantries situated above the lanes. DSL systems are increasingly applied worldwide, usually on motorways. One of the objectives of DSLs is to improve traffic safety through reductions in mean speeds and in speed variations within and across lanes, and between upstream and downstream flows.

The number of studies on the safety effects of DSLs that have been published in peer-reviewed journals is limited. Moreover, they are sometimes difficult to compare with each other as multiple research designs were used, and not all studies evaluated DSLs that operate in comparable conditions. The reviewed studies report favourable road safety effects. The only available before and after study reports a significant reduction of 18% of injury crashes due to the presence of a DSL system. The observed reduction is mainly attributable to a reduction of rear-end crashes. Some other studies evaluated the effects of DSL on driving speeds, and reported decreases of mean speeds as well as reductions of speed variances.

Apart from affecting traffic safety, DSLs could also have effects on traffic flow, congestion and travel times, as well as on vehicle emissions and road noise. Nevertheless, no conclusive effects on any of these outcomes were found in previous implementations and experiments.

One cost-benefit analysis showed a benefits-to-costs ratio of approximately 0.7 for a DSL system, which means that the costs might exceed the benefits.

Little is actually known about possible conditions that could influence the effects of DSLs. It is likely that the impacts of DSLs are sensitive to the level of driver compliance. As the level of driver compliance tends to vary across jurisdictions, results of DSL schemes are not necessarily transferable from one jurisdiction to another.

1.4 BACKGROUND

1.41. What are Dynamic Speed Limits?

On the majority of the roads, fixed speed limits are set to represent the appropriate speed for average conditions. However, in order to take account of real time traffic, road and weather

conditions, dynamic speed limits (DSLs) can be applied (European Commission, 2017). DSL systems are activated at a given time, as a consequence of traffic volume or other environmental conditions (Islam et al., 2013; OECD, 2006).
Variable speed limits are often used as a synonym for DSLs. However, according to the OECD (2006) the term 'variable speed limits' refers to systems that are activated through general criteria (e.g. time of the day, season and certain weather conditions), which are usually set by generic legislation. In some countries the speed limit is reduced in case of rain, or speed limits nearby school zones are reduced at school start or end times. The focus of the present document is on DSLs, which are applied as a consequence of the real time situation.

1.4.2 How can Dynamic Speed Limits affect road safety?

Through DSL systems, speed limits can be adapted remotely, either automatically by an algorithm or manually by an operator. This makes it possible to show different speed limits at different times of the day and different days of the week (van Nes et al., 2010). DSLs are introduced to harmonize traffic flows which is often assumed to improve both throughput and traffic safety. The traffic safety improvement is targeted through reductions in speed variations within and across lanes and between upstream and downstream flows (Lee et al., 2004; Islam et al., 2013; Habtemichael & de Picado Santos; 2013).
The reduction of speed limits through electronic signs does not only serve the purpose of reducing driving speeds, but aims also at warning drivers for the presence of an incident downstream and therefore to raise attention.

1.4.3 Which other effects do Dynamic Speed Limits have?

Throughput improvement is expected due to the speed harmonization benefits (Fudala & Fontaine, 2010). DSLs are sometimes also used in order to reduce vehicle emissions and road noise (Papageorgiou et al., 2008). Lu & Shladover (2014) reviewed evidence from field studies that assessed effects on traffic flow in the UK, Germany, the Netherlands, France and the United States. The effects reported on traffic operations were mixed. Some authors reported a reduction of travel times (Chang et al., 2011; Hoogendoorn et al., 2013). Some studies found an improvement in throughput (Chang et al., 2011; Kwon et al., 2007), but others did not (DeGaspari et al., 2013). Papageorgiou et al. (2008) reported that effects on traffic flow are highly dependent on the saturation level of traffic with improved traffic flow at overcritical occupancies (dense traffic), but deteriorated traffic flow efficiency (lower average speeds) at undercritical traffic conditions. Hoogendoorn et al. (2013) evaluated effects of DSLs on emissions and noise. They reported a slight deterioration for both aspects.

1.4.4 How has the effects of Dynamic Speed Limits on road safety been studied?

The number of evaluation studies on the safety effects of DSL systems is limited. Five studies were eventually coded of which three studies contained empirically obtained estimates of effects on crashes. Two of these three studies (Rämä, 1999; Saha et al., 2015) dealt with weather-dependent DSL systems whereas De Pauw et al. (forthcoming) evaluated a DSL system that is mainly driven by data on speed and occupancy of the lanes and by processing information from incident detection cameras. Given the scarcity of empirical research results, this document discusses the results of different DSL systems together, regardless whether they are controlled by weather, traffic volume or incident-related parameters. Each of the coded studies was published in a peer-reviewed journal. Other studies analysed the effects of DSLs through simulation models and driving simulator studies. No meta-analyses have been made so far.

1.5 OVERVIEW OF RESULTS

1.5.1 Results of effect estimates

Al Ghamdi (2007) assessed the effectiveness of a fog detection and warning system on driver behaviour and found that mean speeds throughout the experimental sections reduced by about 6.5 km/h. Nevertheless the warning system was ineffective in reducing speed variability.

De Pauw et al. (forthcoming) did a before-after analysis on the effects of a dynamic speed limit system on the number of crashes. The results showed a significant (-18%) decrease of the number of injury crashes after the introduction of the system. A distinction according to crash type showed an almost significant decrease of 20% in the number of rear-end crashes whereas the number of single-vehicle crashes decreased by 15% (ns). No effect was found for side crashes.

Lee et al. (2006) used a microscopic traffic simulation model to simulate changes in traffic conditions as an effect of variable speed limits. The study results indicated that variable speed limits could reduce crash potential by 5 to 17%, by temporarily reducing speed limits during risky traffic conditions when crash potential exceeded the pre-specified threshold.

Rämä (1999) investigated the effects of weather-controlled dynamic speed limits. The results showed that in winter the change of the posted speed limit from 100 km/h to 80 km/h decreased the mean speed of cars traveling in free-flow traffic by 3.4 km/h, in addition to the average mean speed reduction of 6.3 km/h caused by adverse weather and road surface conditions. When poor road conditions were difficult to detect (e.g., there was no rain or snowfall or the rain was insignificant), the effect was 1.9 km/h higher (i.e., the reduction was 5.3 km/h). In addition to the effects on mean speed, lowering of the speed limit decreased the speed variance. There was no clear effect on headways. The signs decreased speeds also on the road section next to the equipped section.

Saha et al. (2015) examined the interaction between roadway geometric characteristics and adverse weather conditions and their impact on crash occurrence on rural variable speed limit freeway corridors through mountainous terrain in Wyoming, USA. From the model results, the VSL system was found to be significant in reducing crashes. The authors used winter data to fit their model.

1.5.2 Biases and transferability

The eventual traffic safety effects of DSL are likely to be dependent on the level of driver compliance (Habtemichael & de Picado Santos, 2013). As driver compliance is known to vary across jurisdictions, this means that variations of effects of DSL between jurisdictions are also possible. Moreover, the reviewed studies originate from different countries, but they also represent different conditions in which DSL systems are applied. Some studies apply to DSL systems in which speed limits vary according to weather conditions (fog, snow, ice…) (Al Ghamdi, 2006; Rämä, 1999; Saha, 2015) whereas other studies deal with DSL systems in which speed limits change according to changing traffic volume conditions (Lee et al., 2006; De Pauw et al., forthcoming). The specificity of the investigated schemes might affect the found results and therefore might render generalisation of the results less reliable.
It is likely that the impacts of DSL, in terms of safety and travel time, are quite sensitive to the level of driver compliance (Khondaker, B., & Kattan, 2015). As the level of driver compliance tends to vary across jurisdictions , results of DSL schemes are not necessarily transferable from one jurisdiction to another.

1.5.3 Cost-benefit analysis

In addition to the analysis of the effects, De Pauw et al. (forthcoming) also did a cost-benefit analysis. The cost-benefit analyses of the crash effects showed a benefits-to-costs ratio of approximately 0.7, which means that the costs tend to exceed the benefits. They concluded that no convincing evidence exists that the costs of the system currently outweigh the expected benefits in terms of crash prevention.

2 Scientific details

2.1 ANALYSIS OF STUDY DESIGNS AND METHODS

De Pauw et al. (forthcoming) discussed the results of simulations and field tests that were set up to assess the effects of DSLs.

Simulation models

Many authors developed simulation models to assess the effects of DSLs. Islam et al. (2013) studied the effects on mobility. In the best case scenario, DSL control with a 5-min speed limit update frequency and a 10-km/h maximum speed difference between two successive time steps, they reported a 33% reduction of total travel time. Fudala & Fontaine (2010) did this for work zones specifically. They found potential of DSLs to delay the onset of congestion and to help produce more rapid recovery from congestion when demand volumes are not too far above the zone capacity. When demand volumes are high, they found no benefit over static speed limits. The simulation also showed the importance of appropriate DSL sign location and effective algorithm design. Habtemichael and de Picado Santos (2013) analysed the operational benefits of DSLs under different traffic conditions. They studied the combination of different compliance rates and congestion levels and found that the operational benefits depended on these two factors. The system had the highest operational benefits during lightly congested traffic conditions, little benefit during uncongested conditions, and no benefit during heavily congested conditions.

Field studies

The effect of DSL systems was also analysed through empirical studies. Lu & Shladover (2014) reviewed evidence from field studies that assessed effects on traffic flow and traffic safety in the UK, Germany, the Netherlands, France and the United States. The effects reported on traffic operations were mixed. Some authors reported a reduction of travel times (Chang et al., 2011; Hoogendoorn et al., 2013). Some studies reported an improvement in throughput (Chang et al., 2011; Kwon et al., 2007), but others did not (DeGaspari et al., 2013). Papageorgiou et al. (2008) reported that effects on traffic flow are highly dependent on the saturation level of traffic with improved traffic flow at overcritical occupancies (dense traffic), but deteriorated traffic flow efficiency (lower average speeds) at undercritical traffic conditions. Multiple studies reported favourable effects on road safety for the implemented VSL strategies, but interestingly, none of the field studies that assessed effects on traffic safety has been published in peer reviewed journals and their methodological rigour is hard to assess (De Pauw et al., forthcoming). The road safety literature (Hauer, 1997; Elvik, 2002) has extensively reported that accident studies that don't take into account confounding factors such as trends and regression-to-the-mean tend to bias - usually to overstate - effects.

Based on the reviewed evidence, Lu & Shladover (2014) concluded that DSLs can significantly improve freeway traffic safety if the compliance rate is high enough, whereas the impact on traffic throughput is still controversial. The latter is explained by inherent difficulties in the observation of traffic flow status, by the large variations in driver behaviour and by the relative immaturity of DSL systems that often use algorithms that are unlikely to improve traffic flow.

Hoogendoorn et al. (2013) evaluated effects of DSLs on emissions and noise. They reported a slight deterioration for both aspects.

Table 1 provides a synoptic description of the background characteristics of the coded studies on dynamic speed limits.
The number of studies on the effects of DSLs that have been published in peer-reviewed journals is

limited. Moreover, multiple research designs were used and not all studies evaluate DSLs in similar conditions. Only one before-after study that assessed the number of crashes has been published (De Pauw et al., forthcoming). One other study (Saha et al., 2016) assessed the effect on the number of crashes by means of a cross-sectional risk model (a Safety Performance Function). The other studies assess the safety effect indirectly by measuring the effects on the distribution of speeds (Al Ghamdi, 2006; Rämä, 1999) or they use simulation techniques (Lee et al., 2006).

Table 1: Information on sample and design of coded studies (sorted by name of first author)

Author(s), year, country	Measure description and sample	Study design	Outcome indicators
Al-Ghamdi, A.S., 2007. Saudi Arabia	Fog detection and warning system at 2 study sites	Before-and-after study with comparison group	• Mean speed
De Pauw et al., 2017. Belgium	Dynamic speed limits at 5 motorway segments (59.5 km)	Empirical Bayes before-and-after study with comparison group	• Number of injury crashes • Number of rear-end crashes • Number of frontal and side crashes • Number of single-vehicle crashes • Number of crashes with killed or severely injured
Lee et al., 2006. Canada	Dynamic speed limits on a freeway section	Simulation	• Average total crash potential
Rämä, P., 1999. Finland	Weather-controlled dynamic speed limits on one test site.	Cross-sectional	• Mean speed • Speed variation
Saha, P. et al., 2015. Wyoming, USA	Weather-controlled dynamic speed limits on 4 segments of the I-80 corridor (152 mi)	Cross-sectional	• Percentage accident reduction

2.2 STUDY RESULTS

Al Ghamdi (2007) assessed the effectiveness of a fog detection and warning system on driver behaviour regarding speeds and headways. This warning system includes visibility sensors that automatically activate a variable message sign that posts an advisory speed when the presence of fog is detected. The system was installed on a 2 km section of a two-lane, rural highway. A data set of 36,013 observations from both experimental and control sections at two study sites was collected and analysed. The data included vehicle speed, volume, and classification; time headway, time of day, and visibility distance. Mean speeds throughout the experimental sections reduced by about 6.5

km/h. Nevertheless the warning system was ineffective in reducing speed variability.

De Pauw et al. (forthcoming) did an empirical evaluation of the effects of a dynamic speed limit system on motorways on traffic safety in Flanders, Belgium. The evaluation was done by means of a before-after analysis of crashes, completed with a cost-benefit analysis. Their results show that the number of injury crashes decreased significantly (-18%) after the introduction of the system. A separate analysis for serious and fatal injury crashes revealed a non-significant decrease of 6%. A distinction according to crash type showed an almost significant decrease of 20% in the number of rear-end crashes whereas the number of single-vehicle crashes decreased by 15% (ns). However, no effect was found for side crashes.

Lee et al. (2006) examined automated control strategies of dynamic speed limits. They developed a real-time crash prediction model to estimate crash potential based on short-term variation of traffic flow characteristics. They also used a microscopic traffic simulation model to simulate changes in traffic conditions as an effect of variable speed limits and combined this with the crash prediction model for the evaluation of control logics. Within this integrated evaluation framework, the study investigated the effect of strategy control factors on the crash potential reduction and total travel time. The study results indicated that variable speed limits could reduce crash potential by 5–17%, by temporarily reducing speed limits during risky traffic conditions when crash potential exceeded the pre-specified threshold.

Rämä (1999) investigated the effects of weather-controlled dynamic speed limits and signs for slippery road conditions on driver behaviour on a motorway in Finland. Local weather and road conditions were monitored from two unmanned road weather stations. The speed limits were lowered automatically during adverse road conditions, and in some cases signs for slippery road conditions were displayed as well. Speed and headway data were obtained from loop detectors. The results showed that in winter the change of the posted speed limit from 100 km/h to 80 km/h decreased the mean speed of cars traveling in free-flow traffic by 3.4 km/h, in addition to the average mean speed reduction of 6.3 km/h caused by adverse weather and road surface conditions. When poor road conditions were difficult to detect (e.g., there was no rain or snowfall or the rain was insignificant), the effect was 1.9 km/h higher (i.e., the reduction was 5.3 km/h). When road conditions were such that signs for slippery road conditions were also displayed, the variable speed limit system reduced the mean speed by 1.8 km/h, whereas the reduction caused by the weather was 9.3 km/h. In addition to the effects on mean speed, lowering of the speed limit decreased the speed variance. There was no clear effect on headways. The signs decreased speeds also on the road section next to the equipped section.

Saha et al. (2015) examined the interaction between roadway geometric characteristics and adverse weather conditions and their impact on crash occurrence on rural variable speed limit freeway corridors through mountainous terrain in Wyoming, USA. The authors developed a negative binomial model with a 7-day crash frequency as the response variable and weather, traffic, and geometric variables as the explanatory variables. From the model results, the VSL system was found to be significant in reducing crashes. The authors used winter data to fit their model.

In addition to the analysis of the effects, De Pauw et al. (forthcoming) also did a cost-benefit analysis. The cost-benefit analyses of the crash effects showed a benefits-to-costs ratio of approximately 0.7, which means that the costs tend to exceed the benefits. They concluded that no convincing evidence exists that the costs of the system currently outweigh the expected benefits in terms of crash prevention. However, DSL systems might bring about more favourable effects than what was included in the cost-benefit analysis. Next to crash effects, this measure could also have effects on traffic flows, congestion and travel times, and furthermore also on vehicle emissions and road noise. Nevertheless, no conclusive effects on any of these outcomes were found in previous implementations and experiments (Lu & Shladover, 2014).

2.3 DESCRIPTION OF ANALYSIS

Review-type analysis

Five key studies establishing the effects of DSLs have been identified, coded, analysed and summarized. Two studies directly assessed the effect on the number of crashes, of which one was a before-after study (De Pauw et al., forthcoming) and one was a cross-sectional study (Saha et al., 2015). One study simulated effects on crashes (Lee et al., 2006). Two studies assessed effects on speed behaviour and speed variability (Al-Ghamdi, 2007; Rämä, 1999). Given the small number of studies and the heterogeneity of applied research methods, a review-type analysis was conducted for the main effect of each of the coded studies. The reader is referred to Table 7 in the supporting document for more detailed information.

Conclusion

It appears that four out of five reviewed studies report favourable road safety effects. The fifth study, Lee et al. (2006), reported a 'potential' for crash reduction.

The number of studies is small, but the results appear to point in the same direction. This leads to a still limited though consistent overall picture which justifies a green colour code ("Results consistently show that the countermeasure reduces road safety risk"). However, it must be clear that caution has to be addressed as this conclusion is presently only based on limited evidence. In particular little is known about possible conditions that could influence the effects of DSLs.

3 Supporting document

This Supporting Document on dynamic speed limits (DSL) describes the literature search strategy (Section 3.1) and it presents references to the literature (Section 0).

Taxonomy	
Measure	Specific measure
Speed management and enforcement	*Dynamic speed limits* *Weather-variant dynamic speed limits*

3.1 LITERATURE SEARCH STRATEGY

A literature search for studies that assessed effects of DSL was carried out in three databases (ScienceDirect, TRID, Scopus) with combinations of search terms and operators. These studies were subsequently assessed and checked for their relevance. Tables 2, 3 and 4 below describe the search terms, the logical operators and the number of hits for the searches in the different databases.

Research terms and hits

Database: ScienceDirect **Date:** 03rd February 2017

Limitations/ Exclusions:

- Search field: TITLE-ABS-KEY
- Published: 1990 to current
- Document Type: ALL

Table 2: Search terms and hits in ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	TITLE-ABSTR-KEY("dynamic speed*" or "variable speed limit*") and TITLE-ABSTR-KEY((effectiveness or "road safety" or "efficiency" or "impact" or "effect"))	69
#2	TITLE-ABSTR-KEY(weather and "variable speed*") and TITLE-ABSTR-KEY(((effectiveness or "road safety" or "efficiency" or "impact" or "effect"))).	9
#3	TITLE-ABSTR-KEY(weather and "dynamic speed*") and TITLE-ABSTR-KEY(effectiveness or "road safety" or "efficiency" or "impact" or "effect").	2

Database: TRID **Date:** 06th February 2017

Limitations/ Exclusions:

- Published: 1990 to 2017
- Document source : ALL, Document Type: ALL, Subject area : ALL
- Language: English and French

Table 3: Search terms and hits in TRID

search no.	search terms / operators / combined queries	hits
#1	[Title] ("dynamic speed*" OR "variable speed limit*") AND (effectiveness OR "road safety" OR efficiency OR impact OR effect OR evaluation)	53
#2	[Title] ((weather AND "dynamic speed*") OR (weather AND "variable speed*") OR (weather and "message sign*")) AND (effectiveness OR "road safety" OR efficiency OR impact OR effect OR evaluation)	6

Database: Scopus **Date:** 06th February 2017

Limitations/ Exclusions:

- Search field: Abstract, title, keywords
- Published: 1990 to current
- Document Type: ALL
- Subject Area: ALL

Table 4: Search terms and hits in Scopus

search no.	search terms / operators / combined queries	hits
#1	(TITLE (("dynamic speed*" OR "variable speed limit*")) AND TITLE ((effectiveness OR "road safety" OR efficiency OR impact OR effect OR evaluation))) AND PUBYEAR > 1989	59
#2	(TITLE (((weather AND "dynamic speed*") OR (weather AND "variable speed*") OR (weather AND "message sign*"))) AND TITLE ((effectiveness OR "road safety" OR efficiency OR impact OR effect OR evaluation))) AND PUBYEAR > 1989	3

Principles

Papers and reports were excluded if they didn't study DSLs, just mentioned them rather indirectly or studied them from a perspective that was not meaningful for the purpose of the project. This was the case if they dealt mainly or completely with:

- Non-speed messages (warnings, information…) such as messages in work zones, messages related to railroads, congestion warning, warnings for animals, parking guidance
- In-vehicle messages
- Results on visibility/readability/legibility/viewing comfort/ text layout/display format
- Environmental effect/impact + impact on traffic flow
- Ex-ante evaluation / Evaluation of the impact/effectiveness through (micro-macro) modeling / model simulation / simulation-based evaluation; modelling of traffic flow under variable speed limit system
- Development of Variable Speed Limits control strategies for improving traffic efficiency; Search for the optimal VSL system/ Traffic Flow Control system; Impact on traffic performance

- Papers talking about traffic flow management and control systems (Intelligent Transportation Systems (ITS)) including several control measures (such as ramp metering, reversible lanes, high occupancy vehicle lanes, driver information, route guidance, etc.) and not focusing on variable speed limits

Interesting papers from the literature search

Applying the abovementioned principles to the preselected papers resulted in 42 promising references for Dynamic Speed Limits (DSL). Full paper versions of 32 of these references could be traced as shown in Table 5 below (papers indicated with 'V'). Subsequently the abstracts were checked and it was judged by the coders whether they were considered relevant or not for the purpose of the present synopsis. 17 abstracts were considered relevant.

Table 5: Preselection of studies based on title and abstract

Authors	Title	Year	Country	Available? (V= YES, X= No)	Scientific journal?	Relevant?	
Kuhn B., Balke K., Brydia R., Theiss L., Tsapakis I., Ruback L., Le M.	Evaluation of Variable Speed Limit Pilot Projects for Texas Department of Transportation	2016	USA	V	Yes - Transportation Research Procedia	Yes	• Impact on congestion • users' perceptions • safety impacts • violations • costs and benefits
Plana, Soriguera, Hegyi	Effects of Dynamic Speed Limits on a Dutch Freeway	2016	Netherlands	V	Yes - Transportation Research Record: Journal of the Transportation Research Board	No	Effects on traffic flows
De Pauw, Daniels, Franckx, Mayeres	Safety effects of dynamic speed limits on motorways	2017	Belgium	V	Yes – Accident Analysis and Prevention	Yes	• Safety effect (crashes) • Cost-benefit analysis
Soriguera, Sala	Freeway Lab: Testing Dynamic Speed Limits	2014	Spain	V	Yes - Procedia - Social and Behavioral Sciences	No, but " a preliminary analysis empirically proves that drivers' compliance with dynamic speed limits is very limited, unless speed enforcement devices are present."	The objective of the experiment was to construct a comprehensive database of traffic engineering variables on a freeway site when different speed limits apply. Detailed measurements of vehicle counts, speeds, occupancies, lane changing maneuvers and travel times were taken.
Garcia-Castro A., Monzon A.	Homogenization effects of variable speed limits	2014	Spain	V	Yes - Transport and Telecommunication	No, but Propose an useful classification of the different type of VSL	• review of some experiences, how their effects are evaluated and their results • presents a key indicator which measures the speed homogeneity • relation between this indicator and road performance and emissions values
Torné, Ramoneda, Soriguera	Empirical Evidences of Dynamic Speed Limit Impact on a Metropolitan Freeway	2014	Spain	V	Yes - Procedia - Social and Behavioral Sciences	No	• assessing the DSL drivers' compliance • detecting the causes which motivate drivers' behavior • effect on traffic performance
Geistefeldt J.	Impact of Variable Speed Limits on Motorway Level of Service	2013	Germany	V	Yes - International Journal of Intelligent Transportation Systems Research	No	Focused on impact on capacity/traffic performance
Weikl S., Bogenberger K., Bertini R.	Traffic management effects of variable speed limit system on a German autobahn	2013	Germany	V	Yes - Transportation Research Record: Journal of the Transportation Research Board	No	Traffic flow effects

Authors	Title	Year	Country	Available? (V= YES, X= No)	Scientific journal?	Relevant?	
Duan H., Liu P., Wan J., Li Z.	Evaluating the impacts of variable speed limits on freeway traffic operations and safety: A case study in hangzhou, China	2012	China	V	No - 12th COTA International Conference of Transportation Professionals, 2012	Yes	impacts of a VSL system on traffic operations and the safety Average speed, compliance rate,
Sevefelt B., Wessel P.	Variable speed limits in unprotected intersections implementation and evaluation of 12 sites in Sweden	2012	Sweden	V	No - 19th ITS World Congress, 2012	Yes	
Weikl S., Bogenberger K., Bertini R.L.	Empirical Assessment of Traffic Management Effects of a Variable Speed Limit System on a German Autobahn: Before and After	2012	Germany	V	Yes - Transportation Research Record: Journal of the Transportation Research Board	No	Impacts of a variable speed limit (VSL) system and driver information system on traffic flow characteristics.
Geistefeldt J.	Capacity effects of variable speed limits on German freeways	2011	Germany	V	Yes - Procedia Social and Behavioral Sciences	No	Impact on freeway capacity, traffic volumes, etc.
Lall K., Bham G.H.	Systematic evaluation of a variable speed limit system in St. Louis Missouri	2011	USA	V	No - First Congress of Transportation and Development Institute (TDI)	No	Impact on traffic flow parameters (speed, volume, occupancy, travel time, and congestion).
Layton E.C., Young R.K.	Effects on speeds of a rural variable speed limit system	2011		X			
Lucyshyn, Andy; Morrow, Rick; Russo, Christopher.	I-4 Variable Speed Limit Effectiveness Study.	2011		X			
Arezoumandi, M.	Estimation of Travel Time Reliability for Freeways Using Mean and Standard Deviation of Travel Time	2011	USA	V	Yes - Journal of Transportation Systems Engineering and Information Technology	No	Effects of the VSL system on travel time distribution and travel time reliability.
Nissan A., Koutsopoulosb H.N.	Evaluation of the impact of advisory variable speed limits on motorway capacity and level of service	2011	Sweden	V	Yes - Procedia Social and Behavioral Sciences	No	Impact of advisory VSL on traffic performance
Bham et al.	Evaluation of Variable Speed Limits on I-270/I-255	2010	USA	Only appendices found	No - Missouri Department of Transportation Research Report	No	VSL system and its potential impacts and benefits to the transportation users : mobility, safety, and public and police perceptions
van Nes, Brandenburg, Twisk	Improving homogeneity by dynamic speed limit systems	2010	Netherlands	V	Yes - Accident Analysis and Prevention	No	Investigates if the introduction of dynamic speed limit systems will contribute to an increase in homogeneity of driving speed and to what extent this can be explained by an increase in credibility of speed limits.

Authors	Title	Year	Country	Available? (V= YES, X= No)	Scientific journal?	Relevant?	
NISSAN, A.	Evaluation of variable speed limits: empirical evidence and simulation analysis of Stockholm's motorway control system	2010	Sweden	V	No - Doctoral Dissertation	No	design parameters and conditions under which VSL are most effective. Impact on traffic performance
Studer L., Cecchetto M., Marchionni G., Ponti M.	Evaluation of dynamic speed control on the Venice-Mestre beltway	2009	Italy	V	No - 16th World Congress on Intelligent Transport Systems and Services, ITS 2009	No	impact on mobility and of the effectiveness of the system. The analysis will follow the indication of the Evaluation Expert Group Guidelines and
Papageorgiou M., Kosmatopoulos E., Papamichail I.	Effects of variable speed limits on motorway traffic flow	2008	? (Europe)	V	Yes - Transportation Research Record: Journal of the Transportation Research Board	No	impact on aggregate traffic flow behavior
Towliat, Svensson, Lind	Safety effects of variable speed limits at rural intersections	2007		X			
Chris Lee, Bruce Hellinga, Frank Saccomanno + Lee, C., Hellinga, B. & F. Saccomanno.	Evaluation of variable speed limits to improve traffic safety + Assessing safety benefits of variable speed limits	2006 + 2007	USA	V	Yes - Transportation Research Part C + Yes - Transportation research record: journal of the transportation research board	Yes	examines automated control strategies of variable speed limits that aim at reducing crash potential on instrumented freeways. crash potential based on short-term variation of traffic flow characteristics
Lind G., Towliat M., Svensson H.	Effects of variable speed limits at intersections	2006		X			
Towliat, Svensson	Safety effects of variable speed limits at intersections	2006		X			
Chambers	Benefits of Advanced Traffic Management Solutions: Before and After Crash Analysis for Deployment of a Variable Advisory Speed Limit System	2016	USA	V	No - Thesis	Yes - Impact on crashes	Not sure (no detail on significance)
Downey et al.	Evaluation of a Traffic and Weather Responsive Variable Advisory Speed System in Portland, Oregon + Evaluating the Effects of a Congestion and Weather Responsive Advisory Variable Speed Limit System in Portland, Oregon	2015	USA	V	No -Transportation Research Board 94th Annual Meeting (monograph) No - Dissertation and Thesis	Yes – Impact on speeds, flows, travel times and crashes	Not sure (no detail on significance)

Authors	Title	Year	Country	Available? (V= YES, X= No)	Scientific journal?	Relevant?	
Li Z., Li Y., Liu P., Wang W., Xu C.,	Development of a variable speed limit strategy to reduce secondary collision risks during inclement weathers	2014	China	V	Yes - Accident Analysis and Prevention	Yes/No - Two surrogate safety measures, based on the time-to-collision notion, are used to evaluate the control effects of VSL.	
Ewan, Levi Austin	Weather responsive variable speed limit systems	2013	USA	V	No -Thesis	No	
Saha and Young	Weather-Based Safety Analysis for the Effectiveness of Rural VSL Corridors	2013	USA	V	No - Transportation Research Board 93rd Annual Meeting (monograph)	Yes - Impact on crashes	
Al-Kaisy, A.; Ewan, L.; Veneziano, D.	Evaluation of a Variable Speed Limit System for Wet and Extreme Weather Conditions: Phase 1 Report.	2012	USA	V	No - Oregon Department of Transportation Research Section and Federal Highway Administration, research report	No - Sensor use	
Al-Ghamdi A.S.	Experimental evaluation of fog warning system	2007	Saudi Arabia	V	Yes - Accident Analysis and Prevention	Yes - assess the effectiveness of fog detection and warning system on driver behavior regarding speed and headway	
Lind	Weather and traffic controlled variable speed limits in Sweden + Road weather controlled variable speed limits, Sweden + Variable speed limits: Evaluation of the road weather controlled section	2007	Sweden	V	No	Yes - Impact on speed	
Kolisetty V., Iryo T., Asakura Y., Kuroda K. + Kolisetty et al	Effect of variable message signs on driver speed behavior on a section of expressway under adverse fog conditions - A driving simulator approach + Effect of variable message signs on driver speed behaviour under fog conditions	2006 + ?	Japan	V	Yes - Journal of Advanced Transportation + No	Yes - Impact on speed	

Authors	Title	Year	Country	Available? (V= YES, X= No)	Scientific journal?	Relevant?	
Rämä P.	Effects of weather-controlled variable speed limits and warning signs on driver behavior	1999	Finland	V	Yes - Transportation Research Record	Yes - Impact on driver behaviour (speed, headway)	Yes
Hautala et Nygård	EFFECTS OF WEATHER-CONTROLLED VARIABLE MESSAGE SIGNING IN FINLAND – CASE HIGHWAY 1 (E18)	?	Finland	V	No	Yes - Impact on driver behaviour (speed, headway)	Not sure
Crean, A.	Innovative weather-activated variable speed sign trial: a first for road safety in New Zealand.	2016	New-Zealand	X (extended abstract only)			
Piao, J. & McDonald,	Safety Impacts of Variable Speed Limits – A Simulation Study	2008	UK	V	Yes - 11th International IEEE Conference on Intelligent Transportation Systems, (ITSC)	Yes	to assess the safety impacts : Speed differences between and within lanes, Time headways, Frequency of lane changes

Coding

The remaining 17 studies were checked, based on the full paper version. All checked studies are presented in Table 6. The table includes authors, title, year and source of the study. Studies highlighted in green were coded. The last column mentions the reason of exclusion for the not coded studies.

Table 6: Selection of studies to be coded

Authors	Title	Year	**Source**	Status	Reason of exclusion
Kuhn B., Balke K., Brydia R., Theiss L., Tsapakis I., Ruback L., Le M.	Evaluation of Variable Speed Limit Pilot Projects for Texas Department of Transportation	2016	Transportation Research Procedia	Not coded	No statistical details
De Pauw, Daniels, Franckx, Mayeres	Safety effects of dynamic speed limits on motorways	2017	Accident Analysis and Prevention	Coded	
Duan H., Liu P., Wan J., Li Z.	Evaluating the impacts of variable speed limits on freeway traffic operations and safety: A case study in hangzhou, China	2012	International Conference of Transportation Professionals, 2012	Not coded	Preference for journal papers
Chris Lee, Bruce Hellinga, Frank Saccomanno + **Lee, C., Hellinga, B. & F. Saccomanno.**	Evaluation of variable speed limits to improve traffic safety + Assessing safety benefits of variable speed limits	2006 + 2007	Transportation Research Part C TRR	Coded	2006: coded 2007: not coded, similar to 2006 study
Piao, J. & McDonald,	Safety Impacts of Variable Speed Limits – A Simulation Study	2008	11th International IEEE Conference on Intelligent Transportation Systems, (ITSC)	Not coded	Simulation, weaker ecological validity.
Chambers	Benefits of Advanced Traffic Management Solutions: Before and After Crash Analysis for Deployment of a Variable Advisory Speed Limit System	2016	MSc thesis	Not coded	Not published, no effects reported, graphs don't match tables .
Downey et al.	Evaluation of a Traffic and Weather Responsive Variable Advisory Speed System in Portland, Oregon + Evaluating the Effects of a Congestion and Weather Responsive Advisory Variable Speed Limit System in Portland, Oregon	2015	Transportation Research Board 94th Annual Meeting presentation Dissertation and Thesis	Not coded	Comparable to Chambers, but uses older data
Li Z., Li Y., Liu P., Wang W., Xu C.,	Development of a variable speed limit strategy to reduce secondary collision risks during inclement weathers	2014	Accident Analysis and Prevention	Not coded	Focus is not on evaluation but on development of control strategy
Saha P., Ahmed M., Young R.	Weather-Based Safety Analysis for the Effectiveness of Rural VSL Corridors	2015	Transportation Research Record	coded	
Al-Ghamdi A.S.	Experimental evaluation of fog warning system	2007	Accident Analysis and Prevention	Coded	

Authors	Title	Year	**Source**	Status	Reason of exclusion
Lind	Weather and traffic controlled variable speed limits in Sweden + Road weather controlled variable speed limits, Sweden + Variable speed limits: Evaluation of the road weather controlled section	Lind	Research report	Not coded	Preference for journal papers. No direct observations of effect on crashes
Kolisetty V., Iryo T., Asakura Y., Kuroda K. **+** **Kolisetty et al**	Effect of variable message signs on driver speed behavior on a section of expressway under adverse fog conditions - A driving simulator approach + Effect of variable message signs on driver speed behaviour under fog conditions	2006 + ?	Journal of Advanced Tarnsportation	Not coded	Simulator study
Rämä P.	Effects of weather-controlled variable speed limits and warning signs on driver behavior	1999	Transportation Research Record	coded	
Hautala et Nygård	EFFECTS OF WEATHER-CONTROLLED VARIABLE MESSAGE SIGNING IN FINLAND – CASE HIGHWAY 1 (E18)	?	Report	Not coded	Same motorway as Rämä

3.2 DETAILS OF ANALYSIS RESULTS

Table 7 provides information on the main outcomes of coded studies on DSLs.

Table 7: Summary of coded study results for dynamic speed display signs (DSLs) (sorted by surname of first author)

Author(s), year, country	Exposure variable	Dependant / outcome type	Effects on road safety		Main outcome – description
Al-Ghamdi, A.S., 2007. Saudi Arabia	Presence of an advisory speed limit in case of fog	• Mean speed	↗	Average speed decrease of 6.5 km/h	Mean speed throughout the experimental sections was reduced by about 6.5 km/h, but the warning system was ineffective in reducing speed variability.
De Pauw et al., 2017. Belgium	Presence of a DSL system	• Number of injury crashes • Number of rear-end crashes • Number of frontal and side crashes • Number of single-vehicle crashes • Number of crashes with killed or severely injured	↗	-18% injury crashes (95% CI [-30%; -4%])	The investigated DSLs have had a favourable effect on the number of injury crashes, with a significant decrease of 18%. Mainly the number of rear-end crashes (-20%) decreased, albeit just nearly significantly. The number of single-vehicle crashes showed a tendency to decrease, but this effect was not significant. No effect was found on the nuber of side crashes.
			-	-20% (ns) rear-end crashes (95% CI [-36%; +1%])	
			-	-0% (ns) of frontal or side crashes (95% CI [-36%; +56%])	
			-	-15% (ns) of single vehicle crashes (95% CI [-36%; +13%])	
			-	-6% (ns) severe crashes (95% CI[-32%; +29%])	
Lee et al., 2006. Canada	Presence of a DSL system	• Average total crash potential	-	-5% to -17% crash potential	The study demonstrated that real-time variable speed limits can reduce the overall crash potential by 5–17%.
Rämä, P., 1999. Finland	Presence of a weather-controlled DSL system	• Mean speed • Speed variation	↗	Mean speed -3.4 km/h (p<0.01) (winter+adverse weather)	The main results indicated that the weather-controlled system

Author(s), year, country	Exposure variable	Dependant / outcome type	Effects on road safety		Main outcome – description
			↗	Mean speed -5.3 km/h (p<0.01) (winter+adverse weather+no precipitation)	decreased both the mean speed and the standard deviation of speeds. The study controlled for the effects of the weather conditions by using a control location. On the control highway section (no VMS system) the mean speed was also decreased during adverse weather and road conditions, but less, and the variance of speeds increased.. In order to examine this effect, the data were divided into two parts according to the rain intensity. The results showed that when there was no considerable rain, the mean speed decreased more (1.9 km/ h) than it did on average. The system proved to be more effective when the adverse weather and road conditions were not easy to detect.
			↗	Mean speed -1.8 km (p<0.01) (winter+snow/ice)	
			↗	Standard deviation: -3.4 km/h	
Saha, P. et al., 2015. Wyoming, USA	Presence of a weather-controlled DSL system	• Percentage accident reduction	↗	Estimated 24.4% percentage crash reduction (p<0.01).	The authors developed a negative binomial model with a 7-day crash frequency as the response variable and weather, traffic, and geometric variables as the explanatory variables. From the model results,

Author(s), year, country	Exposure variable	Dependant / outcome type	Effects on road safety		Main outcome – description
					the VSL system was found to be significant in reducing crashes.

* Effects on road safety are coded as: positive (↗), negative (↘), non-significant (-) or no test for significance reported (/)

3.3 REFERENCES

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