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Transport and Telecommunication Institute, Lomonosova 1, LV-1019, Riga, Latvia

VARIABLE SPEED LIMITS. REVIEW AND DEVELOPMENT OF AN AGGREGATE INDICATOR BASED ON FLOATING CAR DATA

Alvaro Garcia-Castro, Andres Monzon

Transportation Research Centre (TRANSyT), Universidad Politecnica de Madrid
Escuela de Caminos, Canales y Puertos, Avda. Profesor Aranguren s/n. Madrid. Spain
Phone: +34 91 336 52 34; fax: +34 91 336 53 62; e-mail: alvaro.garcia.castro@upm.es

Changing factors (mainly traffic intensity and weather conditions) affecting road conditions require a suitable optimal speed at any time. To solve this problem, variable speed limit systems (VSL) – as opposed to fixed limits – have been developed in recent decades. This term has included a number of speed management systems, most notably dynamic speed limits (DSL).

In order to avoid the indiscriminate use of both terms in the literature, this paper proposes a simple classification and offers a review of some experiences, how their effects are evaluated and their results

This study also presents a key indicator, which measures the speed homogeneity and a methodology to obtain the data based on floating cars and GPS technology applying it to a case study on a section of the M30 urban motorway in Madrid (Spain).

Keywords: effectiveness indicator, variable speed limits, dynamic speed limits, GPS application, speed management, floating car data

1. Introduction

The main tool used by authorities to manage speed is the setting of speed limits, which tend to be fixed. However, the optimal speed cannot remain constant at all times, as the road conditions are affected by numerous factors, mainly traffic intensity and weather conditions [1].

Speed can be regarded as a key factor that directly affects certain aspects of the road such as traffic performance, road safety and environmental externalities.

1) *Traffic performance*

Together with intensity and density, speed is one of the key factors determining road capacity. At a critical speed and the corresponding critical intensity or density, the state of flow will change from stable to unstable and, speed differences and braking process can therefore lead to congestion and reduced road capacity [2].

2) *Road safety*

It is generally accepted that high speeds involve a high risk to road safety. This idea is supported by a large number of studies which highlight the relationship between speed and road safety. For instance, ref. [3] shows an extensive review of 98 studies containing 460 estimates of the relationship between changes in speed and changes in the number of accidents or accident victims, concluding "the relationship between speed and road safety is causal, not just statistical".

3) *Environmental externalities*

Apart from vehicle technologies, speed is a very important factor determining negative environmental effects such as CO2 emissions, pollutants [4] and noise [5].

The concern of traffic authorities to adapt traffic speed to changing road conditions has led in recent decades to the development of variable speed limits (VSL).

2. Variable Speed Limits. Classification

VSL is a broad term that includes many speed management systems with different motivations and control algorithms. VSL can be defined simply as speed limit management systems, which are time dependant. Some authors confine the term VSL to systems, which utilize traffic detectors to determine the appropriate speed [6]; however, this fails to take into account the existence of VSL that operate following prefixed calendars or timetables based on historical data. It is thus necessary to classify VSL as follows:

2.1 Scheduled Variable Speed Limits (SVSL)

These are VSL that depend on a pre-established calendar or timetable. Among these, the following types can be identified:

Seasonal Variable Speed Limits

These are applied to a specific type of road and set the speed limit during a particular season, with the most common being the winter/summer speed limits.

An example can be found in the Nordic countries due to their extreme weather conditions during the winter months. In Finland the reason for lowering winter speed limits is primarily the adverse road and driving conditions [7].

Experiments involving the setting of seasonal speed limits for safety reasons can be also found in the northern states of the U.S.A. For instance, the Wyoming Department of Transport first implemented the seasonal speed limit for six months beginning on October 15, 2008 [8].

In the Austrian region of Tyrol during the winter of 2006/2007, the speed limit was temporarily reduced on the Inn Valley Motorway from 130 km/h to 100 km/h, mainly due to high levels of air pollution during previous winter seasons [9].

Hourly Variable Speed Limits

These are mainly applied to prevent or reduce certain negative externalities in a specific road section or street at particular times.

Experiments of this type can be found in some German or American cities where authorities have implemented VSL in school areas in order to reduce speed when schools are open or at exactly the times children are arriving or leaving [10], [11].

There are also experiments related to noise reduction during night hours in residential areas or close to hospitals and other facilities. In the city of Berlin [10], speed is limited during the night hours to 30 km/h in residential or mixed areas.

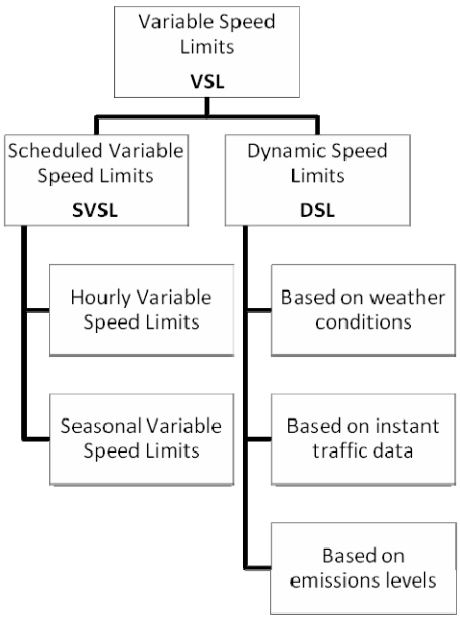

Figure 1. Proposed classification of Variable Speed Limits

2.2 Dynamic Speed Limits (DSL)

The term “dynamic” implies a force which produces a change in state or movement. In this case, the “forces” that produce changes in speed limits are the conditions in and around the road. Therefore, Dynamic Speed Limits can be defined as a type of Intelligent Transport System (ITS) which produces changes in speed limits in response to accurate information regarding road, driving, weather and/or environmental conditions [2].

In practice, the system consists of dynamic message signs (DMS) deployed along a roadway and connected via a communication system to a traffic management centre [12]. After data processing and speed limit calculation, the new speed limit information is displayed on these DMS.

Pure manual control methods are based simply on a protocol that the operators activate when one or more levels (traffic intensity, visibility, air pollution, etc.) exceed the pre-set thresholds.

The concept of automatic DSL is based on various approaches, ranging from basic protocols according to particular thresholds (similar to manual methods) to complex algorithms based on multi-objective optimization, game theory, predictive control and genetic algorithms [13]-[16].

3. Evaluation of Variable Speed Limits

DSL are being implemented worldwide; however their effects are not yet clearly defined, and in some cases their benefit is not fully proven.

Based on international experiments and research studies, we summarize the way in which DSL affect the parameters of traffic performance, road safety and environmental levels, and the variables that are used to assess their effectiveness.

3.1 Traffic Performance

With regard to traffic performance and traffic flow behaviour, there are several parameters which may be affected by the implementation of DSL, including particularly speed and capacity.

The reduction in average speed and speed variations depends largely on the type of speed limits imposed (mandatory or recommended) and their enforcement. Most DSL operate as mandatory limits, such as the M25 controlled motorway around London [17], although there are also some systems with recommended speed limits, such as the Motorway Control System (MCS) on the E4 in Stockholm [18].

These systems are based on the capacity increase that occurs when speed and speed variations are reduced by high flow levels. Moreover, speed homogenization reduces the number of acceleration and deceleration manoeuvres and therefore the oscillations in traffic flow [19]. Ref. [20] shows that under certain congestion conditions, speed determines density; based on this observation, the relationship between density and speed can be estimated depending on speed limits.

The reduction of speed limits has a considerable effect on the speed differential between lanes. In [2], the conclusions show that it can be said that dynamic speed limit systems do increase the homogeneity of the driving speed.

Based on computer simulators, some authors evaluate positively the effects of DSL on traffic performance. Reference [21] shows the simulation of a number of types of DSL scenarios, and the results indicate that the benefits of DSL are obvious when the traffic volume is equal to or greater than 2,800 veh. in a double-lane freeway. Ref. [13] simulates the effects of DSL on the prevention of congestion caused by shockwaves, obtaining a reduction in total travel time of 21.7%.

Germany has a long tradition of implementing VSL, and in particular DSL. The first experiment was implemented in 1965 on the A8 motorway between Munich and Salzburg, with good results in terms of harmonization and reduction of speed differences between lanes. These results and many others from German motorways can be found in [22]. Among these cases, we can highlight the report on the A5 motorway in Frankfurt. Based on data from video recording and induction loops, the authors found a significant increase in the empirical maximum traffic intensity in the southbound direction from 5,200 veh/h. to 5,900 veh/h. (about a 10% increase). However other studies in the Netherlands [23] estimate the capacity increase at around 2%.

The M25 in the U.K. can also be highlighted as a successful implementation of DSL. During the first year of operation, a section of this controlled motorway absorbed a 1.5% increase in throughput over 5-hour peak periods, without any detectable increase in congestion levels. Traffic conditions have improved as a result of the reduction in frequency and severity of shockwaves. The study [17] revealed a reduction of over 25% in the typical number of shockwaves during the morning peak period. It has also been observed that the traffic is now more evenly spread across all four lanes.

Reference [18] studied the application of DSL on the E4 motorway through Stockholm, revealing that lane changes were reduced by over 50%, and that lane distribution became more balanced after the implementation. However, this phenomenon can have negative effects in sections with a high density of on-ramps, as this will lead to smaller gaps in the traffic on the outside lane, making the merging process more difficult and therefore creating congestion on the on-ramp [24].

Experiments were conducted on the ASF (Autoroute du Sud de France) in France in the summer of 2004, with the implementation of an innovative traffic control system on the A7 motorway, which includes DSL. In the southbound corridor, the use of progressively slower speed limits depending on traffic volume has reduced congestion by between 16% and 40%, depending on the section [25].

3.2 Road Safety

The effects mentioned in the previous section can also have a positive impact on road safety, as decreases in the speed limits can lead to a reduction in the speed differences between successive vehicles, resulting in a decline in rear-end collisions.

Reference [26] presents a simulation-based study showing the potential safety benefits of DSL using a real-time crash prediction model integrated with a microscopic traffic simulation model. The study found that dynamic speed limits can reduce average total crash potential by approximately 25%, by temporarily reducing speed limits during hazardous traffic conditions. Positive effects of DSL have also been found in other simulation-based studies, such as [27].

Regarding the study of the DSL implemented, an analysis of crash data in Germany has shown that the use of dynamic speed limit and speed warning signs reduced the crash rate by 20 to 30% [28]. Other German studies cited by [22] estimate a reduction in the number of accidents of over 30% (A5 motorway, near Frankfurt), and a similar decline in fatalities by more than 60%. In Stuttgart, the reduction in accidents caused by fog conditions is as high as 86%.

In the U.K., [17] analysed data from the M25 in order to compare them with the trends. The impact of introducing the controlled motorway driving environment (mainly DSL and managed lanes) has been an estimated reduction in injury accidents of 10% during the period of operation, and a decrease in the ratio of damage of 20%.

The aforementioned programme in the South of France also had very positive road safety results, with crashes reduced by 10-20% [25].

Table 1. Summary of evaluation variables used in different research studies

Ref.	Case study	Variable	Effects
		Traffic Performance	
[5]	Simulation of 12 rural roads	Standard deviation of the average speed	Depending on scenarios
[21]	Simulation	Traffic volume, travel time, queue length, number of stops	Variable
[13]	Simulation	Total travel time	21% reduction
[31]	A5 Motorway, Germany	Intensity	10% increase
[23]	Simulation	Capacity	2%increase
[17]	M25, U.K.	Throughput	1.5%increase
[18]	E4 Stockholm	Lane changes	50%reduction
[25]	A7 France	Congestion	16-40%reduction
		Road Safety	
[26]	Simulation	Total crash potential	25% reduction
[27]	Simulation M6, U.K.	Time-to-collision Headway	Depending on scenarios
[28]	German motorways	Crash rate	20% reduction
[17]	M25, U.K.	Damage ratio	20% reduction
[25]	A7 France	Crash number	10-20% reduction
		Emissions	
[30]	Simulation	Total emissions	35% reduction
[17]	M25, U.K.	Emissions levels	Between 2-8%reduction
[17]	M25, U.K.	Noise levels	0.7-2.3 dB reduction
[9]	A12, Austria	NO_2 levels	3.6% reduction

3.3 Environmental effects

It is well-known that improved traffic flows can have a significant impact on emission levels [29]. There are very few approaches based on simulating emissions in DSL. Of particular note is the simulation of a case study based on model predictive control, where the total emissions are reduced by over 35% [30].

Returning to the case of the M25 motorway in the U.K., in [17] it was found that vehicle emissions have dropped as a result of reducing start-stop driving. Depending on the particular emissions measured, the decrease is between 2% and 8%. Fuel consumption has also been reduced. In parallel, there has been a favourable impact on noise as a result of the introduction of DSL systems between Junction 15 and 16.

The reduction in stop-start driving and the improved compliance with the speed limits have reduced the weekday traffic noise adjacent to the motorway by around 0.7 decibels, with reductions at some points of up to 2.3 dB.

Another example can be found in Inn Valley in Austria. The effects of the implementation of DSL were analysed on this motorway after one year of operation (November 2007 to November 2008). In a before/after evaluation the results show that NO2 emissions were reduced by 3.6%. Also, the NO2 limit value for short-term exposure (half-hour limit: 200 g/m³) was exceeded only twice during the first year of operation, while without the DSL in operation, it is estimated that it would have been exceeded nine times [9].

4. Methodology to Evaluate VSL Systems Using an Aggregate Effectiveness Indicator

4.1 Effectiveness indicator. Definition

Table 1 shows the large number of variables which are used in the scientific literature and other public reports to evaluate the effects of DSL. This fact highlights the need to find a single variable which makes possible to evaluate the system's effectiveness easily and concisely by aggregating the potential effects on traffic performance, road safety and emissions.

With regard to traffic performance, several of the aforementioned studies point out that the homogenization of speed (i.e., lower acceleration rates) contributes to a smooth traffic flow [19], an increase in capacity [20] and the attenuation of shockwaves [13].

Likewise, road safety has been proven to be related with traffic and speed homogeneity [2], [27], [32], [33]. It can therefore be concluded that there is a clear relation between speed variations and number of accidents.

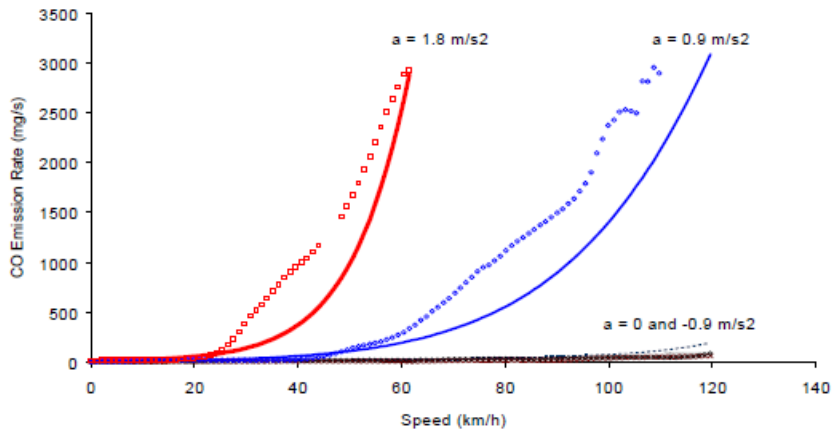

Figure 2. Regression fit for CO emissions as a function of speed and acceleration rates. Source [34]

Many research studies [34]-[37] also state that, apart from mean or average speed, positive acceleration rates also have a major impact on emissions, as shown on Figure 2 from [34].

It has thus been possible to pinpoint instant acceleration as a key factor by evaluating the effectiveness of implementing DSL, and then proposing an aggregate indicator as follows:

Positive Accumulated Acceleration (PAA) is defined as the sum of the speed variations on a particular road section.

Mathematically, it is the cumulative integral of the positive acceleration law (1).

$$\text{If } (v_i - v_{i-1}) > 0 \quad \text{then } \alpha = 1$$

$$\text{Otherwise} \quad \alpha = 0 \tag{1}$$

Graphically, PAA is the positive area of the region bounded by the acceleration law, as shown on Figure 3.

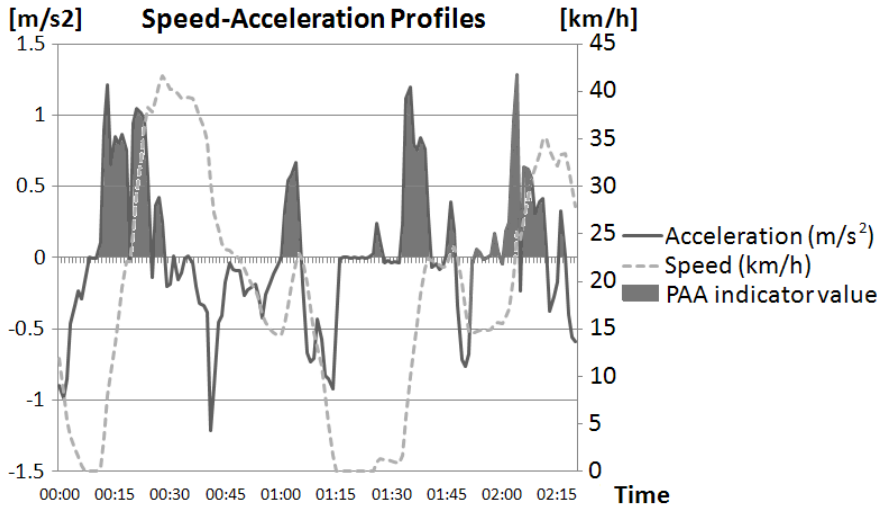

Figure 3. Graphic representation of PAA indicator from an acceleration function

The PAA indicator makes it possible to compare the same section before and after the implementation of DSL, thus evaluating its effectiveness.

4.2 Data collection and evaluation

As already mentioned, the PAA indicator is simply based on speed variations, and the data required to calculate it is relatively easy to obtain.

Speed data are often collected by induction loops located at certain points on the road, but this method makes it impossible to establish the speed evolution between two loops, and leads to the possibility of distorted results.

It is thus essential to obtain speed data at short time intervals, and the methodology proposed is therefore based on GPS technologies. With a small portable device it is very simple to collect and download speed data, position and so on every second, which allows a very accurate speed profile to be obtained along the road section analysed.

The methodology is based on a before & after evaluation, by observing the evolution of the PAA indicator. Ideally, the number of trip repetitions should be fairly high in order to limit variations caused by other factors such as meteorology, extraordinary events, incidents, etc. In any case, the trips must be made in the same time slot and on days with similar behaviour in terms of traffic. In the event of a limited sample, particular care must be taken to ensure that the conditions are almost the same. The traffic intensity upstream must be guaranteed to be substantially the same when performing the before & after trips.

Once the valid data has been processed and selected, the implementation of DSL can be valued positively if the indicator PAAa (activated) is lower than PAAd (deactivated).

5. Pilot Test Case: West Section of Madrid M30 Motorway

5.1 Description

Madrid is a city of about 3.5 million inhabitants, and up to 6 million in its metropolitan area. The city is surrounded by three motorway ring-roads, with the M30 the closest to the city centre.

In the afternoon peak hours on a normal working day, the M30 has high traffic levels southbound on its east and west sections. In an attempt to avoid this habitual congestion and its externalities, the Madrid Traffic Department is testing a DSL system based on recommended speed limits.

The tested section is a three-lane motorway (southbound) with traffic intensity in the afternoon peak hours of around 3,300 veh/h. (upstream), and a length of 5.8 km. Most of the section is limited to 90 km/h, except the last 100 m., where the limit is 70 km/h. (tunnel entrance). The congestion is usually caused by the bottleneck situated at the M500 junction, as around 2,800 vehicles merge into the M30.

The DSL system consists of three Variable Message Signs (VMS) situated before the M500 junction. These VMS display a recommended speed limit of 40, 60 or 80 km/h, depending on the control algorithm. This is based on instant speed and traffic intensity data recorded by induction loops situated along the section.

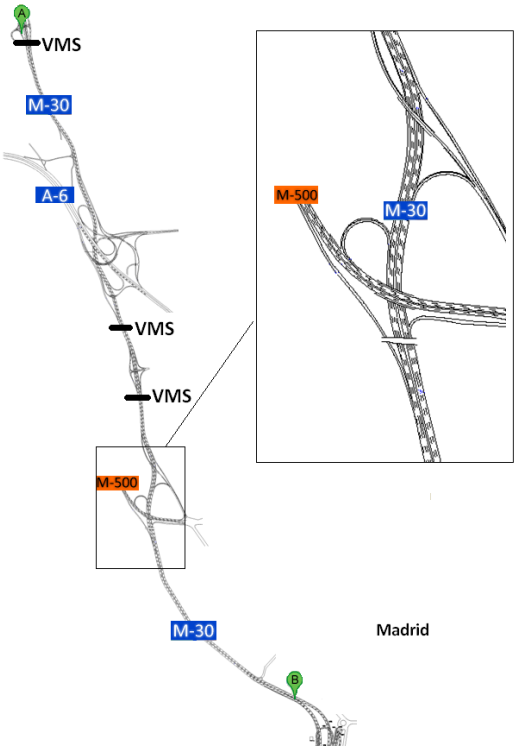

Figure 4. West Madrid motorway ring-road and the 5.8 km. test section (from A to B) with the location of the Variable Message Signs (VMS). The bottleneck junction where the congestion usually starts (M-500) is highlighted

A microscopic car study was undertaken in the afternoon peak traffic period between 18:00-20:00. A total of nine trips were made on 6 and 7 June (Tuesday and Wednesday) with the DSL system activated. One week later (12 and 13 June) another nine trips were performed at exactly the same times, this time with the DSL system deactivated. The intensity levels upstream for the test days were very similar, with a maximum deviation of 2.63% from the mean value (Table 2). The weather was sunny and there were no particular incidents or accidents during the test trips, except for unusual congestion on 6 June, which caused the system not to be automatically activated.

Table 2. Traffic flow intensities upstream (Measuring point PM 22421)

Time	Date				Mean	Max. mean deviation
	05-June	06-June	12-June	13-June		
18:00	3159	3196	3114	3324	3198	-2.63%
19:00	3501	3544	3506	3440	3498	-1.65%

The mobile study was carried out using an instrumented vehicle (Skoda Fabia TDI) equipped with a GPS data recorder (747+ GPS Trip Recorder), which was subsequently downloaded as an Excel Sheet (.csv) and georeferenced (.kml) documents.

The data collected included travel distance (m), position and speed (m/s), recorded every second, enabling the PAA to be obtained as defined in the previous section.

Likewise, seven trips (Figure 5) in free flow (southbound mornings) were performed in order to study the variability of the PAA in similar conditions and to isolate the effects of DSL from any other which may influence the results (small disturbances and changes in driving style).

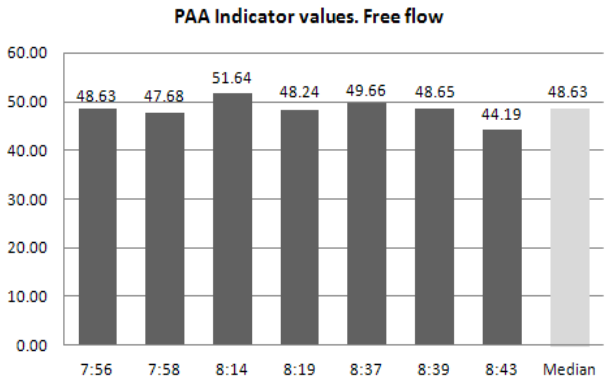

Figure 5. PAA indicator values in free flow. Obtained in the morning hours of 5 and 6 June

From this analysis, it can be concluded that in free flow and in similar conditions, 99% (confidence level= 0.99, ά=0.01) of the PAA results present a deviation from the median of less than 2.19 (confidence limits). Therefore any deviations greater than this value will be assigned to the effects of DSL.

5.1 Analysis of results

Table 3 shows the resulting values of the PAAa and PAAd from the trips performed on 5 and 12 June. The results on Wednesday 6 are considered invalid, as the system was automatically disconnected due to the unusual and extreme congestion (recorded speed under the operation thresholds).

Table 3. Values obtained for PAA Effectiveness indicator. Congested trips

Activated		Deactivated	
Tuesday 5 and 12. Afternoon peak			
Time	**PAA values**	**Time**	**PAA values**
18:30	91.68	18:29	92.04
18:52	88.20	18:52	88.89
19:11	72.23	19:10	90.99
19:32	59.62	19:32	105.88
19:51	63.54	19:55	69.36
Average	*75.05*	***Average***	*89.43*
Wednesday 6 and 13. Afternoon peak			
18:28	~~125.84~~	18:27	99.20
18:50	~~124.06~~	18:49	86.62
19:14	~~130.74~~	19:13	90.68
19:38	~~73.21~~	19:38	76.82
Average	~~*113.46*~~	***Average***	*88.33*

When the effects of DSL are isolated from any other effects, as described in the paragraphs above, the result shows that the PAAa falls by an average of 13.1%, compared to the PAAd.

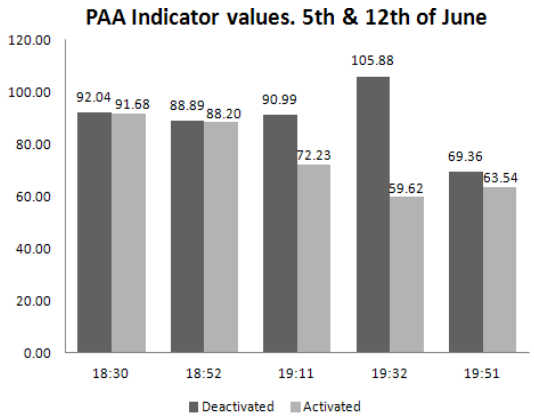

Figure 6. Comparison of the effectiveness indicator (PAA) on Tuesday 5 and 12 June

Figure 6 shows that PAAa and PAAd values are fairly similar, except for the trips that are highly affected by congestion. An analysis of the speed profiles on Figure 7 and the indicator values shows that in the 19:11 trip, the speed distribution is more homogeneous, although the congestion levels are similar. This fact causes the congestion on the following trip (19:32) to remain at similar levels (or even to decrease) while DSL is activated, and the queue length to increase while deactivated.

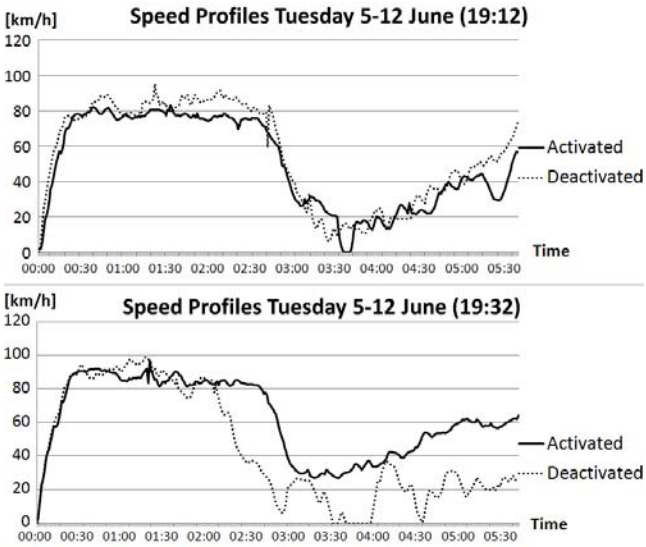

Figure 7. Comparison of speed profiles for trips with DSL activated and deactivated

6. Conclusions

After classifying Variable Speed Limits, the literature review has shown that in many cases VSL (and in particular VSL based on dynamic control) have been beneficial in terms of traffic performance, road safety and environmental effects. Based on the accumulated acceleration in a section (or instantaneous speed variations) the methodology described provides a single indicator (PAA) to evaluate whether the implementation of VSL is working properly and has the potential to produce the desired effects.

To evaluate the feasibility of the methodology on a practical level, a pilot study was carried out on a stretch of the M30 motorway ring-road in Madrid. This demonstrated the defined PAA effectiveness indicator to be specific, measurable, reliable and track-able.

Once the effects of driving variability have been statistically bounded by analyzing the trips in free flow, the variability in traffic intensities requires a greater number of routes. Future research in relation to this indicator could be directed towards establishing quantitative relationships between changes in the value of the PAA effectiveness indicator and the VSL effects (increase in capacity, accident rates, emission levels, etc.).

Acknowledgments

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