An Investigation on the Approaches and Methods used for Variable Speed Limit Control

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Abstract

In the light of increasing demand for further application of Variable Speed Limit Control Systems, it is essential to ensure that these systems are robust enough to produce the impacts required to meet the specific objectives set for their implementation. The extent of success of Variable Speed Control Systems largely depends on the underlying approaches and methods used in their algorithms logic. In this article, first a critical review of different approaches and methods for Variable Speed Control with emphasis on those currently implemented in real world is made. Then based on an assessment of the performance of existing systems especially the UK system (known as Controlled Motorways), a number of suggestions for further modifications to the existing rule-based practical systems is made. Considering the limitations inherited in the currently used practical systems, merits for the development and application of new network-oriented variable speed control systems based on robust theoretical control models and/or artificial intelligence techniques are highlighted.

Keywords: Variable Speed Control, Controlled Motorways, Congestion Management, Traffic Management, Intelligent Transport Systems

1. Introduction

The steady increase of traffic demand over the past decades has led to a high rate of congestion on many parts of road networks. This has created increasing demand for further application of existing and new traffic management systems on the road networks. Many Intelligent Transportation Systems (ITS) are being designed to reduce congestion and to ensure safer, quicker, less expensive, and more-energy-efficient travel. ITS measures such as ramp metering, mainline metering, incident detection and management, variable speed limit and strategic traffic management systems are used to prevent or reduce the chances of congestion, and to eliminate congestion in situations where it can not be prevented by traffic control.

The Motorway Variable Speed Limit (VSL) Control also known as Controlled Motorways in Europe is one of the ITS technologies that has been favoured by many highway authorities. These systems are adopted to provide appropriate speed on the

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basis of real-time traffic, environment and roadway conditions by means of signals and variable message signs.

In these systems, variable speed limits are established in a rapidly changing environment to encourage uniform driving behaviour and to meet specific objectives such as: safety improvement; congestion reduction (e.g. via improving travel times and/or maximizing throughput), emissions reduction and energy conservation.

The methodology to determine the appropriate speed limit in different conditions is by no means straightforward, and there is no single “right” answer for each situation. It requires trade-offs between user safety, travel time, throughput, practicality of enforcement, and other factors important to motorists and traffic managers.

This article is based on the findings of a study by the Atkins Consultants Ltd for the Highways Agency in England as the Work Package 1 of a project called “Monitoring of Innovative ITS Control Measures project”. The Work Package 1 entitled “A Critical Review of Controlled Motorways Algorithms and Parameter Setting” in which the author, formerly a senior ITS consultant for Atkins Consultants in the UK (2000-2006), was the task leader.

2. Problem definition and purpose of this research

In the light of increasing demand for further application of Variable Speed Control Systems, it is essential to ensure that these systems are robust enough to produce the impacts required to meet the specific objectives set for their implementation. The extent of success of Variable Speed Control Systems largely depends on the underlying approaches and methods used in their algorithms logic. On this basis the purpose of this research was to provide a critical review of the approaches and methods that have so far been introduced and especially those that have been implemented, to provide some indications on the current status of these systems and to highlight areas in which further progress are required. Structure of this article follows:

- Section 3 provides an overview of approaches that by far have been proposed for Variable Speed Control.
- Section 4 outlines possible methods for Variable Speed Control.
- Section 5 provides the summary of findings of a review on the methods currently used for Variable Speed Control worldwide. To provide an insight to the existing systems, the system currently used in the UK is introduced and assessed in more detail. An alternative method to set speed/flow thresholds is also proposed in this section.
- Section 6 outlines a number of proposals for fundamental enhancements to the Variable Speed Control Systems.

3. Different approaches proposed for Variable Speed Limits Control

A literature review of the approaches currently used for VSL control worldwide indicated that there are different views on the impact that VSL should have on traffic operation (1). This largely depends on the objectives of the system which would be
reflected in the way VSL algorithm is run and its parameters are set. As a result, different control systems are proposed each emphasising on specific objectives. In terms of approaches used by these control systems, they can broadly be classified into the following:

♦ Approaches mainly focused on the homogenisation effects of VSL (homogenisation means to create uniformity of speeds and volumes within and between lanes and thereby reduce the risk of shockwaves, crashes and congestion), and
♦ Approaches mainly focused on preventing traffic breakdown by reducing the excessive flow by means of speed limits.

3.1 Homogenisation Approach

The homogenisation approach \(^{(4)}\) intends to reduce the speed (and/or density) differences between vehicles in a traffic stream by which a more stable and safer flow can be achieved. This approach uses speed limits that are above the critical speed (critical speed is the speed corresponding to the maximum flow or capacity, i.e. Point C in Figure 9) so it does not limit traffic flow. In summary the impacts of homogenisation approach are:

♦ Slight reduction in the average speed and slight increase in density;
♦ Safer and more stable traffic flow;
♦ No significant improvement of traffic volume (throughput) is expected nor measured;
♦ In theory, it can delay the onset of flow breakdown but it cannot suppress or resolve shockwaves.

3.2 Breakdown Prevention Approach

The traffic breakdown prevention approach \(^{(4)}\) focuses more on preventing unstable traffic conditions. This is achieved by allowing speed limits that are lower than the critical speed in order to limit the inflow of traffic to the bottleneck areas. By preventing unstable traffic conditions, an overall higher throughput can be achieved in contrast to the homogenisation approach.

4. Possible Methods for Variable Speed Limit Control

Methods used for VSL Control can broadly be classified into the following categories:

♦ Theoretical methods based on advanced control methodologies;
♦ Practical methods based on simple rule-based heuristics;
♦ Knowledge Based methods that are based on the artificial intelligence techniques such as fuzzy logic and expert systems.

4.1 Theoretical Methods

The theoretical methods are usually based on macroscopic models of traffic flow on a road section. In these methods, traffic state for each site is estimated using traffic data
(e.g. speed and occupancy data) collected from the relevant sites. Based on this knowledge of traffic state for multiple sites and using a model of traffic flow, an optimal strategy for optimal signal setting may be designed \(^{19}\). Traffic models proposed by Cremer (based on observations made by Zackor) and Hegyi are two good examples of theoretical models \(^{4}\).

4.2 Practical Methods

Practical methods are usually based on a control logic where switching between the speed limit values is based on traffic flow, speed, or density. In some cases the switching between the speed limit values is also based on special circumstances such as weather and light conditions, or speed variance.

4.3 Knowledge-based Methods

Knowledge-based traffic control methods generate a solution (i.e. a control measure) given the traffic situation using reasoning mechanisms. Currently, Knowledge-based traffic control methods are mainly used in other areas of traffic control, e.g. Ramp Metering. However their application for VSL Control has recently been considered for traffic management especially at roadwork sites and adverse weather conditions (e.g. see references 13, 20 and 21).

5. A review of methods currently used for Variable Speed Control Worldwide

A review of VSL applications worldwide indicated that the methods currently used for VSL control are mainly based on the practical methods. Each practical method is usually designed to achieve specific objectives \(^{1}\).

The review also indicated that there is no specific practical method which is widely accepted nor implemented in several applications worldwide. As the current practical methods are not usually based on a sound theoretical basis, they are not frequently published in broadly available journals.

The review could not identify any evidence for the real world application of theoretical methods. So far, these methods have mainly been tested in simulation environments. Also there is no validation of their assumptions on the quantitative impact of VSL on traffic flow (e.g. on the fundamental diagram).

5.1 An example of real applications of VSL: UK Controlled Motorways

Variable Speed Control known as Controlled Motorways in the UK has been operational on the western quadrant of M25 motorway ring around London between Junction 10 and Junction 16 since 1995 (see Figure 1). It has also recently been deployed as part of the Active Traffic Management Pilot on the M42 motorway near Birmingham. It is based on an algorithm which displays mandatory signal settings in response to traffic conditions on the motorway. At calculated speed/flow thresholds, the system is switched ON and OFF, and the speed limit displayed to drivers is reduced and increased as required. The algorithm mainly relies on the Flow Thresholds but Speed Thresholds are also used to ensure that the signals remain set when flows drop into the stop and go traffic conditions.
The UK Controlled Motorways has the following key features (see Figure 2):

♦ Mandatory speed control, using variable speed limits displayed on special Controlled Motorway Indicators equipped with ‘Red Rings’, mounted above each lane on standard gantries (installed at nominal 1km intervals on M25 and 0.2km on M42);
♦ Automatic signal setting in response to traffic conditions, driven by a more advanced version of the Motorway Incident Detection and Automatic Signalling (MIDAS) system, with additional driver information on Enhanced Message Signs;
♦ The provision of speed enforcement using automatic camera technology.

The primary objective of the M25 Controlled Motorways scheme was to smooth vehicle speeds progressively to minimise the risk of flow breakdown, create a safer and ‘better’ environment for driving, and therefore maximise the motorway’s potential. Further objectives of the scheme were:

♦ smooth traffic flow;
♦ improve journey times and journey time reliability;
♦ improve lane utilisation;
♦ reduce the incidence of stop-start driving;
♦ improve safety;
♦ reduce the stress of driving.
5.1.1 A brief description of the algorithm

The current Controlled Motorways algorithm is based on a rule-based practical method designed to harmonise traffic speeds and to reduce the severity of congestion. The control system responds to minute by minute traffic speed/flow data continuously measured by the MIDAS loop detectors (see Figure 3). Speed limits are reduced if the measured flow goes above a pre-defined Rising Flow Threshold or the measured speed goes below a pre-defined Falling Speed Threshold. On light traffic conditions, the normal speed limit is 70 mph. On congested traffic conditions, the speed limit will be dropped to 60 and 50 mph as appropriate. Likewise speed limits are increased if the measured flow goes below a pre-defined Falling Flow Threshold and the measured speed goes above a pre-defined Rising Speed Threshold. The speed threshold is essentially used to ensure that the signals remain set when flow drop in stop & go driving conditions. Whether such a rule based practical algorithm would be successful in preventing traffic breakdown largely depends on the methodology used to determine Rising/Falling Speed and Flow Thresholds.

The algorithm is integrated within the MIDAS system which is designed to provide one or a combination of several traffic management functions including:

- Queue Protection via incident detection (see Figure 3),
- Congestion Management via variable speed control (see Figure 4), and
- Hard-shoulder Monitoring when hard shoulder is opened to traffic during peak periods.

Usually a combination of Queue Protection and Congestion Management functionalities of MIDAS are used in the Controlled Motorways areas.
The process used for signal/sign setting in a Controlled Motorways area is summarised in Figure 5.

Figure 3: An example of MIDAS signal/sign settings for Queue Protection

Figure 4: An example of signal/sign setting for Congestion Management in a Controlled Motorways area
5.1.2 An assessment of the system performance

The methodology originally used for the determination of speed/flow thresholds for the M25 Controlled Motorway was to apply lower speed limits at times when average traffic speeds were approaching these speeds anyway with a high likelihood of flow breakdown occurring. The methodology was based on the assumption that the reduction in actual traffic speeds due to the speed limits is likely to be small; hence if there is an increase in delay to drivers, this is also going to be small. On this basis, the initial algorithm was based on a homogenisation approach\(^{(2,7)}\).

It was anticipated that this gentle approach would still be able to smooth traffic flow and thereby a more stable and safer flow would be achieved. It was anticipated that the
capacity of the road would be increased, thereby increasing the peak throughputs. The onset of flow breakdown would also be delayed. The points on the speed/flow graph were not expected to change significantly, but there would be additional points at the right side of this graph.

However, despite continuous monitoring and fine tuning to the algorithm over the last 12 years, the evaluation results indicated that not all of these expectations were achieved. The capacity did not increase, so the peak throughputs and the time of flow breakdown were unchanged. The system has shown a benefit by aiding breakdown recovery. Whilst the system cannot suppress or resolve existing shockwaves, it can stop new ones forming. By smoothing traffic flows from off the front of existing shockwaves, the system reduces the probability of these vehicles triggering an additional shockwave at the seed point further downstream. In terms of the speed/flow graph, the curve is basically unchanged, but more time is spent in the upper part of the graph. The monitoring results also suggest that the system has produced positive impacts on journey time reliability, safety and air pollution but neutral or negative impacts on journey time and throughput.

The results also suggest that there has been some success in reducing the number of recurrent congestions (e.g. the number of shockwaves has been reduced from 7 in 1995 to 5 in 2002). With the evidence currently available from the monitoring results, it is not clear whether this should be attributed to the role of Queue Protection function or Congestion Management function of the MIDAS in the Controlled Motorways Areas or both, and if both, the extend of contribution of each functionality.

An analysis speed limits set by the system on M25 motorway in different traffic conditions using TRL’s Motorway Traffic Viewer software (MTV) indicated that, the system mainly reacts to congestions rather than trying to prevent it, e.g. the system activates when flow/speed breakdown is already in progress (e.g. see Figure 6).

Figure 6: A plot showing the relationship between signal settings and traffic conditions using Motorway Traffic Viewer (MTV) software
Based on an analysis of speed-flow relationships before and after Controlled Motorway implementation on M25 Junction 15 to 16, the following conclusions can be drawn:

- At low to medium-high traffic flows (e.g. for traffic flows up to 6400-7200 vehicle per hour per 4-lanes), traffic speeds in the Controlled Motorway scenario are generally lower than the No control scenario (e.g. Controlled Motorway produces negative impact, e.g. see Figures 6, 7 and 8 below);

- At high traffic flows (e.g. flows higher than 6400-7200 vehicle per hour per 4-lanes), the controlled motorway produces neutral or positive increase in traffic speed and longer the congestion period, the positive impacts of the Controlled Motorway in this respect are less pronounced (e.g. see Figures 6, 7 and 8 below). The positive impact of the Controlled Motorway is mainly pronounced during the recovery period (e.g. see Figure 8 below).

Figure 6: Speed/Flow relationship for the Morning Rising and Morning Congested Periods combined

Figure 7: Speed/Flow relationship for the Inter-Peak Morning Shoulder Period
Figure 8: Speed/Flow relationship for the Inter-Peak Middle Period

Overall, based on the available data reviewed by the author, the author is inclined to suggest that the current algorithm mainly produces the impacts of a homogenisation approach rather than a breakdown prevention approach.

Also a review of the approaches used in other countries indicated that they are also mainly based on the homogenisation approach\(^1\).

5.1.3 A review of parameter setting methods used in the UK Controlled Motorways Algorithm

As indicated before, the Congestion Management algorithm of the Controlled Motorways system uses both speed and flow thresholds to identify congestion level. It is necessary to include both parameters as more than one speed level may be associated to a flow level (i.e. traffic flow may have the same values for both light and congested traffic conditions, see Figure 9(c)). Currently, four different thresholds are associated with each speed limit (i.e. Rising Flow Threshold, Rising Speed Threshold, Falling Flow Threshold and Falling Speed Threshold). This would require considerable work to estimate all algorithm parameters in coordination with each other and at the end there would still be no guarantee that the optimal values are estimated. This problem will be more pronounced in the future if further speed limits (e.g. 40mph and lower) are going to be used. Additionally, because of the limitations inherited in the current algorithm, the estimated parameters would not be optimal values for all traffic conditions and they are also not transferable to the other sites.

Also the current UK CM algorithm need modification to allow for more flexible set of parameter values (e.g. for different times of day, days of week, different weather conditions etc).

These issues and also the overall performance of the algorithm may lead us to this conclusion that the current algorithm and the approaches used for its parameter setting are not sensible and robust enough to grant its suitability for application on new
schemes. Also its appropriateness for further use on the M25 Controlled Motorway is questionable. This may suggest that it would be worthwhile to look at more robust approaches to estimate traffic state (e.g. congestion level). Initial thoughts on potential options are presented in the following section.

5.2 An alternative method proposed for speed/flow thresholds setting

The Congestion Management algorithm is currently based on speed-flow relationship to identify traffic state at any time (e.g. see Figure 9 (c)). Due to the shape of speed-flow curve, both speed and flow levels are required to identify traffic state at any given time. On the other hand, the relationship between occupancy and speed is inversely proportional (e.g. see Figure 9 (a)). This would allow estimating a traffic state using occupancy data only. This would consequently reduce the number of parameters required by the algorithm to identify each traffic state.

It is therefore recommended to consider using the occupancy thresholds instead of currently used Flow and Speed Thresholds within the current algorithm structure.

There is currently little evidence available on the speed-occupancy relationship on the UK motorways and on motorways in other countries (14, 15, and 18). There is also little evidence available on the impact of environmental conditions on the speed-occupancy relationship (16). These issues should therefore be investigated further.

In a recent study, an alternative strategy for Variable Speed Control was proposed by Shi and Ziliaskopoulos (17). Their study was based on review of traffic behaviour on the UK (M25), Dutch and French motorways supported by microscopic traffic simulations. This study suggested that there is a critical density (occupancy) above which the speed variance becomes large and leads to more disturbances. To support this idea, they have referred to the data in Figure 10 which shows the relationship between speed and spacing headway (which is also an indicator of occupancy and density) taken from M25 motorway in the UK by the Transport Research Laboratory (TRL) (18).

Figure 9: The Fundamental diagrams of traffic behaviour
As at high occupancy, the increase in speed variance is usually resulted from the increase in the variance of time headway, they also suggested that there also exists a critical average time headway value, below which both the variance in speed and the variance in time headway become large. Therefore, when occupancy is above the critical value, all these factors contribute to traffic instability (i.e. small time headways, large speed variance, and frequent disturbances). It should be possible to identify this critical occupancy or headway value for each motorway using the collected loop detector data.

Ziliaskopoulos\textsuperscript{(17)} study confirms that there is a potential for using occupancy or time headway as a substitute for the combined speed and flow thresholds used by the current algorithms to identify different traffic states. If this proves right, it could simplify the process required to estimate the algorithm parameters, and their tuning when used on the live system. It is likely that the approaches based on the occupancy or headway data would be more robust leading to a better system performance. However, these ideas need to be investigated further.

6. Proposals for more essential changes to the VSL Control systems

Based on the information provided in the above sections, it is clear that there is not much room for improvement to the existing rule-based VSL Control systems. On this basis, it is proposed that the merits for a network-oriented traffic control model for the management of incidents and congestion on a motorway corridor or network are investigated. This method would allow using features such as coordination and prediction in the control system as previously has been proposed by Hegyi\textsuperscript{(4)} as well. For the following reasons, the coordination and prediction features can provide a more robust control system for incident/congestion management:

♦ In a congested network the effect of a local control measure could also influence the traffic flows in further upstream and downstream parts of the network. Hence the control measures should be coordinated such that they serve the same objectives;

♦ In order to determine the effects of control measures on further parts of the network, some form of prediction is required. This is due to the fact that the effect of the control measure has a delay that is at least the travel time between the two control measures in the downstream direction, and the propagation time of shockwaves in the upstream direction. On this basis it is recommended that future models should
use some form of prediction (anticipation). It could be in the form of simply using data from multiple downstream detectors (anticipation in space) up to more complicated forms which also predict near future traffic patterns based on the current traffic patterns and trends (anticipation in time).

♦ Network-oriented traffic control has several advantages compared to local control. For example, solving a local traffic jam only, can only result in the vehicles run faster into another (downstream) traffic jam, whereas still the same amount of vehicles have to pass the downstream bottleneck (with a given capacity). In such a case, the average travel time on the network level will still be the same. A network-oriented approach would take into account and, if possible, would resolve both congested areas.

♦ Using a network-oriented traffic control, it would be possible to link the control system to other motorway traffic management measures such as Ramp Metering, Mainline Metering, Strategic Traffic Management, etc. The synergistic effects of the integrated systems would increase the overall benefits of Traffic Management Systems.

♦ A network-oriented traffic control would also facilitate the application of the control system to achieve multiple objectives, e.g. for pollution and noise control as well as its normal use for incident and congestion management.

♦ A network-oriented traffic control approach would also allow limiting the inflow to the congested area to a level that is less than outflow of the area and still maintain the overall delays on the network below the non-controlled situation. This is a fast and effective approach to alleviate severe congestions, and to prevent secondary breakdowns.

A network-oriented traffic control may be based on robust theoretical control models and/or artificial intelligence techniques (e.g. expert systems, neural networks and/or genetic algorithms). It should be noted that complexity of the method does not necessarily mean that it would require significant expertise to use it as the complexity can be buried in the algorithm coding and to use the controller as a black box. Using Data Entry Packages and also User Manuals produced for this purpose, an ordinary operator would still be able to set the algorithm thresholds/parameters with minimal training.

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