THE ISRAELI SMART TRANSPORTATION RESEARCH CENTER

The Israeli Smart Transportation Research Center

Traffic Management and Control Committee

Knowledge Gap Research Report (DRAFT!)

Contents

1 Introduction

The major development in Transportation Technologies (automated driving, connectivity, power train technology, digitization, data intelligence, sharing economy) can improve the transportation safety and mobility, while enhancing the productivity through the integration of advanced communications technologies into the transportation infrastructure and within vehicles.

Traffic congestion in urban road and freeway networks leads to a strong degradation of the network infrastructure and accordingly reduces throughput, which can be countered via suitable control measures and strategies [1], where intersections are one of the major bottlenecks that contribute to urban traffic congestion [2].

The field of traffic management and control (TMaC) has a long history. One of the first review papers on this field was described in [3], where the review focuses on the elements of traffic engineering, describing consideration of the aspects of the transportation network user, the vehicle and traffic network, and the nature of the transportation planning mechanism, the relevant issues which guide its process, and the influence of this process on the pattern of urban land and network. The paper also describes the traffic assignment studies, transportation economy studies, travel time and delay studies, and spot speed and traffic flow studies. While the review in [4], existing Urban Traffic Control systems were described in details, where the traffic management objectives and capabilities are discussed.

In the review paper of [1], a comprehensive overview of proposed and implemented control strategies is provided for three areas: urban road networks, freeway networks, and route guidance. Selected application results, obtained from either simulation studies or field implementations, are briefly outlined to illustrate the impact of various control actions and strategies. The paper concludes with a brief discussion of future needs in this important technical area.

In the review paper of [5], a comprehensive overview of the state of the art in Traffic Management Systems (TMS) has been presented, where the three main TMS phases were described: information gathering, information process, and service delivery. The authors also proposed an in-depth classification and review of TMS services organized by their architecture and goals. Furthermore, a qualitative analysis was done based on TMS described. The review papers [1, 6, 7, 8, 9] are further described in the next section.

2 The scientific background and state-of-the-art

The field of traffic management and control is divided into five traffic “sectors" in this manuscript: (1) Urban, (2) Freeway, (3) Air, (4) Maritime, and (5) Mixed Systems. This manuscript does not cover all the literature and practice. However, the authors have reviewed the most relevant literature and tried to collect useful information on lessons learned and experience gained.

2.1 TMaC in Urban Traffic Systems

2.1.1 Isolated Intersection Control

1) Fixed-Time Strategies: Stage-based strategies under this class determine the optimal splits and cycle time so as to minimize the total delay or maximize the intersection capacity. Phase-based strategies determine not only optimal splits and cycle time but also the optimal staging, which may be an important feature for complex intersections [1]. Well-known examples of

stage-based strategies are SIGSET and SIGCAP proposed in [10] and [11], and for phase-based strategy see [12].

2) Traffic-Responsive Strategies: Isolated traffic-responsive strategies make use of real-time measurements provided by inductive loop detectors that are usually located some 40 m upstream of the stop line, to execute some more or less sophisticated vehicle-actuation logic. One of the simplest strategies under this class is the vehicle-interval method that is applicable to two-stage intersections. Minimum-green durations are assigned to both stages. If no vehicle passes the related detectors during the minimum green of a stage, the strategy proceeds to the next stage. If a vehicle is detected, a critical interval (CI) is created, during which any detected vehicle leads to a green prolongation that allows the vehicle to cross the intersection. If no vehicle is detected during CI, the strategy proceeds to the next stage, else a new CI is created, and so forth, until a prespecified maximum-green value is reached. An extension of the method also considers the traffic demand on the antagonistic approaches to decide whether to proceed to the next stage or not [1].

A more sophisticated version of this kind of strategies was proposed by Miller [13] and is included in the control tool MOVA [14].

2.1.2 Fixed-Time Coordinated Control

The most popular representatives of this class of strategies for urban networks are outlined below. By their nature, fixed-time strategies are only applicable to undersaturated traffic conditions [1].

1) MAXBAND: The first version of MAXBAND was developed by Little [15]; see also [16]. MAXBAND considers a two-way arterial with number of signals (intersections) and specifies the corresponding offsets so as to maximize the number of vehicles that can travel within a given speed range without stopping at any signal (green wave), [1].

2) TRANSYT: TRANSYT was first developed by Robertson [17] but was substantially extended and enhanced later. It is the most known and most frequently applied signal control strategy, and it is often used as a reference method to test improvements enabled by real-time strategies [1].

The main drawback of fixed-time strategies is that their settings are based on historical rather than real-time data. Traffic-responsive coordinated strategies, if suitably designed, are potentially more efficient, but also more costly, as they require the installation, operation, and maintenance of a real-time control system (sensors, communications, central control room, local controllers), [1].

2.1.3 Coordinated Traffic-Responsive Strategies

1) SCOOT: SCOOT was first developed by Robertson's team [18] and has been extended later in several respects. It is considered to be the traffic-responsive version of TRANSYT and has been applied to over 150 cities in the United Kingdom and elsewhere. SCOOT utilizes traffic volume and occupancy (similar to traffic density) measurements from the upstream end of the network links. It runs in a central control computer and employs a philosophy similar to TRANSYT. More precisely, SCOOT includes a network model that is fed with real measurements (instead of historical values) and is run repeatedly in real time to investigate the effect of incremental changes of splits, offsets, and cycle time at individual intersections

(functionally decentralized operation). If the changes turn out to be beneficial (in terms of a performance index), they are submitted to the local signal controllers, [1].

2) Model-Based Optimization Methods: A number of more rigorous model-based traffic-responsive strategies have been developed: OPAC [19], PRODYN [20], CRONOS [21], RHODES [22]. These strategies do not consider explicitly splits, offsets, or cycles. Based on prespecified staging, they calculate in real time the optimal values of the next few switching times over a future time horizon, starting from the current time and the currently applied stage. To obtain the optimal switching times, these methods solve in real time a dynamic optimization problem employing realistic dynamic traffic models with a sampling time of 2–5 s, fed with traffic measurements. The models include discrete variables to reflect the impact of red/green phases on traffic flow. Several constraints, e.g., for maximum and minimum splits, are included. The typical performance index to be minimized is the total time spent by all vehicles, [1].

3) Store-and-Forward Based Approaches: Store-and forward modeling of traffic networks was first suggested by Gazis and Potts [23], [24] and has since been used in various works notably for road traffic control [25, 26, 27, 28, 29, 30, 31, 32, 33, 34]. The main idea when using store-and-forward models for road traffic control is to introduce a model simplification that enables the mathematical description of the traffic flow process without use of discrete variables. This is of paramount importance because it opens the way to the application of a number of highly efficient optimization and control methods (such as linear programming, quadratic programming, nonlinear programming, and multivariable regulators) with polynomial complexity, which, on its turn, allows for coordinated control of large-scale networks in real time, even under saturated traffic conditions.

2.1.4 TMaC and the impact of CAV Systems

In the review paper of [6], the authors systematically review the potential solutions that take advantage of connected and automated vehicles (CAVs) to improve the control performances of urban signalized intersections.

Actuated signal control can dynamically adjust the timing parameters to respond to real-time traffic arrival changes. Since many existing studies considered prediction of traffic flow based on CAVs data, this kind of control is also called adaptive traffic signal control in the literature. This generally results in more efficient utilization of intersection capacity than fixed-time signal control in which signal phases and cycle lengths are pre-selected based on historical traffic patterns [35, 36]. Conventional actuated traffic signal control systems collect traffic information via inductive loop detectors that are usually installed tens of meters upstream to the stop lines. The obtained information is inaccurate and limited spatially. As a result, certain relatively rough models have been developed to describe traffic flow states which often fail to well present the variability in traffic demand and vehicular inter-arrival times [37, 38, 39]. CAVs provide a remedy for such problems [40, 41, 42, 43, 44, 45, 46]. Based on the accurate position information of the arriving vehicles, we can either extend/shorten the current phase or add an extra phase to make on-time changes, [6].

Actuated traffic control relies more on prevailing real-time traffic information and does not require too much future traffic conditions (i.e., traffic prediction). In contrast, traffic prediction is essential to platoon-based traffic signal control (and also planning based control). By identifying the platoons (or categorizing individual vehicles into pseudo platoons) and predicting their arrival time in advance, the platoon-based signal control aims to schedule the signal timing plans to allow the platoons to pass the intersections without severe interruptions, which can increase the overall traffic efficiency. Although the idea of platoon-based traffic signal control has been proposed for several decades [47], it became realistic only after V2X technique was introduced [48, 49, 50, 51]. This is because V2X makes it possible to properly identify platoons so that platoon-based optimal signal timing plans can be generated accordingly. [6]

Platoon-based methods categorize the incoming vehicles as platoons and ignore the inner dynamics and disturbances among vehicles in the same platoon. On the contrary, planning-based methods treat all vehicles at the same level, which can better describe the real traffic condition. Besides, platoon-based methods usually directly assume known arrival distributions (e.g., Poisson or uniform arrivals), or estimate the arrival time of the platoons and assume uniform arrivals within each platoon. Planning-based methods often estimate the actual arrival time of every vehicle and predict traffic conditions in a forward time horizon [6].

2.2 TMaC in Freeway Traffic Systems

As explained in [1], the rapid increase of traffic demand, however, led soon to increasingly severe congestion, both recurrent (occurring daily during rush hours) and non-recurrent (due to incidents). The increasingly congested freeways within and around metropolitan areas resemble the urban traffic networks before introduction of traffic lights: chaotic conditions at intersections, long queues, degraded infrastructure utilization, reduced safety.

The control measures that are typically employed in freeway networks are the following,

- Ramp metering,
- Variable speed limits,
- Driver information and guidance systems.

2.2.1 Ramp metering

In [1], ramp metering is explained, as it is the most direct and efficient way to control and upgrade freeway traffic. Various positive effects are achievable if ramp metering is appropriately applied:

- increase in mainline throughput due to avoidance or reduction of congestion;
- increase in the served volume due to avoidance of blocked off-ramps or freeway interchanges;
- utilization of possible reserve capacity on parallel arterial;
- efficient incident response;
- improved traffic safety due to reduced congestion and safer merging.

In the literature there are several models and advanced strategies related to ramp metering, the major strategies that are mentioned in [1] are briefly described as follows.

- Fixed-Time Ramp Metering Strategies, based on simple static models and constant historical demands, which operate offline. The goal is to minimize total time spent or maximize total travel distance. Another approach is to balance the ramp queues by minimizing the difference between the volume and the demand. Other formulations can be found in [52, 53, 54, 55, 56, 57, 58, 59, 60].

Fixed-time ramp metering may lead, due to the absence of real-time measurements, either to overload of the mainstream flow or to underutilize of the freeway. If the strategies are not accurate enough then congestion may not be prevented from forming or the mainstream capacity may be underutilized [1].

- Reactive Ramp Metering Strategies, are employed at a tactical level, i.e., in the aim of keeping the freeway traffic conditions close to prespecified set values, based on real-time measurements. The strategies can be locally, as stated in [61, 62], or multivariable regulator [63, 64]. While local ramp metering is performed independently for each ramp, based on local measurements, multivariable regulators make use of all available mainstream measurements on a freeway stretch, to calculate simultaneously the ramp volume values for all controllable ramps included in the same stretch.
  For urban freeways with high density of on-ramps, both strategies have a similar performance under recurrent congestion, while in the case of non recurrent congestion, multivariable regulator performs better than a local one due to more comprehensive measurement information (design based on advanced control-theoretic methods) [1].

- Nonlinear Optimal Ramp Metering Strategies, reactive ramp metering strategies need appropriate set values, and appropriate freeway networks need a superior coordination level that calculates in real time optimal set values from a proactive, strategic point of view. Such optimal control strategy should take into account: (1) the current traffic state both on the freeway and on the on-ramps; (2) demand predictions over a sufficiently long time horizon; (3) the limited storage capacity of the on-ramps; (4) the ramp metering constraints; (5) the nonlinear traffic flow dynamics, including the infrastructure's limited capacity; (6) any incidents currently present in the freeway. Based on this comprehensive information, the control strategy should deliver set values for the overall freeway network over a future time horizon so as to: (1) respect all present constraints; (2) minimize an objective criterion such as the total time spent in the whole network including the on-ramps; (3) consider equity aspects for users of different ramps in the network. Such a comprehensive dynamic optimal control problem may be formulated and solved with moderate computation time by use of suitable numerical algorithms [1].

In [7], a wide review for the ramp metering was done. Over a period spanning more than 30 years, several ramp metering algorithms have been developed to improve the operation of freeways. Many of these algorithms were deployed in several regions of the world, and field evaluations have shown their significance to improve traffic conditions on freeways and ramps, the algorithms are listed in Table 1.

In summary by [7], Asservissement Linéaire d'Entrée Autoroutière (ALINEA) was found to be the most widely deployed local ramp metering strategy. The algorithm is simple and implementation costs less than other strategies. It also guarantees the targeted performance goals provided that the on-ramp has sufficient storage. Several extensions were proposed in the literature to fine-tune its performance. Among the coordinated metering strategies, zone based metering is simple to implement and easy to re-configure. System-wide adaptive ramp metering (SWARM) algorithm is more sensitive to calibrate for accurate prediction of traffic states. Heuristic ramp metering coordination (HERO) algorithm can be useful if both

	Type	Algorithm	Evaluations
Asservissement Linéaire d'Entrée Autoroutière (ALINEA)	Local or Feedback	[62, 63, 65, 66, 67, 68, 69]	[62, 67, 68, 70, 71]
METALINE	Coordinated or Feedback	[63, 72, 73]	[63, 72, 73]
Bottleneck	Coordinated	[74]	[74]
Zone	Local or Coordinated	[75, 76, 77, 78, 79]	[76]
HELPER	Coordinated	[80, 81, 82, 83]	[81, 82]
System-Wide Adaptive Ramp Metering (SWARM)	Coordinated (Prediction)	[84, 85]	[85]
Fuzzy Logic	Coordinated	[86, 87, 88, 89]	[89]
Linear Programming	Coordinated	[90, 91]	[90]
Dynamic Ramp Metering	Coordinated	[92]	[92]
Advanced Real Time Metering System (ARMS)	Coordinated	[93, 94, 95]	[95]
COMPASS	Coordinated	[96, 97]	[96, 97]
Linked	Coordinated Feedback	[98, 99, 100, 101]	[99, 100]
Heuristic Ramp-Metering Coordination (HERO)	Local and Coordinated	[102, 103]	[102, 103]
Proportional Integral ALINEA (PI-ALINEA)	Local or Feedback	[104, 105, 106]	[104, 105, 106]
ALINEA with Speed Discovery	Local	[107]	[107]
Zippered Control Strategy (ZCS)	Local	[108]	[108]
Genetic Fuzzy Logic Control (GFLC)	Local or Coordinated	[109, 110, 111]	[109, 110, 111]
Dual Heuristic Programming Control (DHPC)	Coordinated	[112]	[112]
Iterative Local Control (ILC)	Coordinated	[113]	[113]
Additive Increase Multiplicative Decrease (AIMD)	Coordinated or Feedback	[114]	[114]

Table 1: Ramp metering algorithms

local and coordinated control are desired particularly if the local control is using ALINEA. Fuzzy logic based algorithms are gaining popularity because of the simplicity and the fast reconfiguration capability. Advanced real time metering system (ARMS) seems theoretically promising because of its proactive nature to prevent congestion; however, its performance is highly dependent upon accurate predictions.

In [7], some guidelines are proposed for future research either to develop new proposals or to extend the existing algorithms for guaranteed performance solutions:

a. The feedback based algorithms (e.g. ALINEA) eliminate downstream congestion if properly configured despite the distance from the on-ramp. However, it cannot detect upstream initiated congestion. The UPALINEA can detect upstream congestion only to a certain level. Future research should consider more fine tuning of ALINEA. Some useful guidelines for configuring ALINEA can be found in [115].

b. The success of achieving local ramp metering goals depends on the sufficient length of the on-ramp to store vehicles in the time of congestion on the freeway. If the ramp has limited storage, the queues on ramps will extend to the arterial upstream. One possible approach to avoid this is the coordination of upstream traffic signal and ramp meter [116]. However, many ramp metering algorithms have not addressed this phenomenon.

c. Online simulation based metering can provide more realistic results, but the operational cost and acquisition of real-time traffic data in this method are a barrier for such implementations.

d. The genetic fuzzy logic metering algorithms have the potential to be the future choice for ramp metering. However, these algorithms usually require more inputs than any other method. The probe vehicle approach [117] based on cellular phones' data (e.g. speed, location) of road users should be considered to reduce the cost of traffic data acquisition in real time.

2.2.2 Variable speed limits

Variable speed limits (VSLs) have been used in the United Kingdom since the 1960s for safety purposes. In the past decade, some VSL algorithms were developed through simulation for improvement of both safety and mobility. VSLs have been widely practiced in Europe in the past 5 years, especially in Germany, the Netherlands, France, and Sweden. In recent years, several states in the United States have field-tested some simple VSL algorithms, beginning with Washington State in 2009. The main objective of using VSLs in the United States was to improve safety and traffic flow, primarily safety [8].

VSLs could be enforced or advisory, locally applied or along a freeway corridor, or at work zones or other types of recurrent bottlenecks. VSLs displayed on roadside variable message signs (VMSs) have emerged as a widespread traffic control measure on motorways in many countries and have led to substantial traffic safety benefits. Some works in this aspect have also been reviewed in [8].

The following description about *VSL Simulations for Algorithm Development and Evaluation*, *VSL Practices and Evaluations* and *Looking Into the Future* is taken from [8].

VSL Simulations for Algorithm Development and Evaluation

Algorithm development and evaluation with simulation before field testing is always a good practice because field testing could be costly and could produce unexpected and negative results to public traffic if it is not done properly. Chen et al. used VGrid, a VII-based networked computer system developed from simulation for real-time operation purposes [118]. It was intended to achieve information broadcasting, safety alert, traffic parameter estimation, or VSL information. The approach tried to maximize throughput and reduce latency without an optimization process. Instead, each vehicle calculates the speed limit by itself. There is a problem here: no coordination occurs unless all the vehicles calculate with the same algorithm and with the same set of data. If the use of the same algorithm and data set cannot be achieved, each vehicle may have a different speed limit value. Different values cannot help to reduce speed variance and shock waves.

Work by Lin et al. presents two VSL algorithms, combined with ramp metering, for traffic improvement [119]. It is believed that VSLs not only can improve safety and emissions, but also can improve traffic performance by increasing throughput and reducing delay, primarily for work zones. Two control algorithms were presented. VSL-1 was for reducing time delay by minimizing the queue upstream of the work zone, and VSL-2 was for reducing total time spent by maximizing throughput over the entire work zone area. Simulation results showed that VSL-1 may even outperform VSL-2 in speed variance reduction. Alessandri et al. designed VSLs using the second-order METANET model [120]. The model assumed that the on-ramp and offramp flows were stochastic variables with known probability density function in an optimal control approach. An extended Kalman filter was used for traffic state estimation. Then a VSL strategy was designed by minimizing an objective function. Several objective functions were proposed, including total travel time and throughput.

In the work of Juan et al., freeway congestion was classified in two types: (a) demand driven, as a result of the increase of traffic volume; and (b) supply driven, due to the road geometric condition, weather, or traffic incident or accident [121]. Simulation was conducted in view of the cause of congestion and several factors that led to the instability of freeway traffic flow, including (a) Small time headway, (b) Large speed variance, and (c) Frequent disturbances.

Many scenarios of VSLs were simulated. The results indicated that the VSL benefits were obvious when the traffic volume was equal to or greater than 2,800 vehicles per hour (vph) (double lane). It was suggested that VSLs needed to be combined with ramp metering to control the traffic when the traffic volume was higher than 2,800 vph for a two-lane freeway.

Hegyi et al. suggested using VSLs to suppress shock waves at the end of queues in freeway traffic [122]. Hegyi et al. further identified two functions of VSLs: speed homogenization and prevention of traffic breakdown [123]. Prevention of traffic breakdown avoided high density, which achieved density distribution control through VSLs. As an example, a VSL strategy was used to suppress shock waves while considering the whole traffic network as a system.

Wang et al. used an empirical approach to investigate the effectiveness of reducing congestion at a recurrent bottleneck and improving driver safety by using feedback to the driver with advisory VMSs on an 18-km highway stretch [124]. The feedback includes (a) speed limit (piecewise constant in 12-km/h increments) and (b) warning information (attention, congestion, and slippery). The VSL strategy was based on the traffic situation upstream and downstream of the bottleneck. Data analysis showed that driver response to the speed limit and messages on the VMSs was reasonable, speed was regulated to some extent, and safety was improved by a reduction in the frequency of incidents or accidents of 20 % to 30 %; this improvement was more significant than the mobility improvements.

A simple real-time merging traffic control concept was proposed for efficient toll plaza management in cases where the total flow exiting from the toll booths exceeded the capacity of the downstream highway, bridge, or tunnel; without efficient toll plaza management, this flow would lead to congestion and reduced efficiency because of a drop in capacity [125]. The merging control strategy for toll plazas was similar to the mainline ALINEA ramp-metering algorithm, which is different from VSLs because VSLs do not completely stop the vehicles. Ramp metering with traffic signals decoupled the platoons into individual vehicles, while VSLs were intended to keep the platoons intact. Because the vehicles are completely stopped, lane dispatch flow is usually limited to 900 vph, whereas VSLs could achieve much higher lane flow.

For reducing shock waves or damping shock waves faster, Breton et al. incorporated several techniques, such as coordination, adaptive control, model based predictive control, and minimized travel time [126]. The work assumed that dynamic origin–destination information was available, although this assumption was impractical. It also incorporated the fundamental diagram into the model. As a consequence of damping the shock wave more quickly, the model claimed to have reduced the total travel time. Because of measurement delay and the effect of hysteresis, it was necessary to predict the traffic and uncertainty over the network. The following two approaches were adopted for VSLs: (a) Homogenization (to reduce speed variance) through the use of a reference speed close to the critical speed corresponding to the maximum flow [127] and (b) Prevention of traffic breakdown (to avoid or delay high density at the bottleneck and its immediate upstream), achieved with upstream speed control, thus assuming critical density at the capacity flow.

This work used an online optimization approach to adapt to traffic condition changes. The objective was to determine the preferred reference speed trajectory. A second-order model was adopted in this work. Simulations showed some positive potential.

Waller et al. reviewed VSLs and hard shoulder use practices up to the year 2009 [128]. They investigated the effect of VSLs and hard shoulder use on traffic improvement and safety with a microscopic simulation. They concluded that VSLs can improve safety but not throughput. Yang et al. proposed VSL algorithms based on traffic prediction to relieve traffic at a recurrent bottleneck [129]. The proposed model uses embedded traffic flow relations to predict the evolution of congestion patterns over the projected time horizon and computes the optimal speed limit. The results of a calibrated VISSIM simulation showed some positive improvement of the model over the status quo, as measured in travel time reduction and the number of vehicle stop times (stop-and-go traffic).

The Wyoming Department of Transportation implemented a VSL system in 2009 for traffic safety improvement. The system uses a manual protocol to determine appropriate speed limits to be posted on roadside VSL signs. The posted speed is initiated by either highway patrol or maintenance personnel who request a change on the basis of visual perception of road conditions. To support an automatic VSL operation, Sabawat and Young proposed a methodology for the determination of VSLs according to real-time traffic speeds and weather variables [130]. Simulation results indicated that there could be a significant increase in speed compliance and reduced speed variations with this strategy over the manual protocol.

Habtemichael and de Picado Santos studied the combination of different compliance rates and congestion levels and found that the safety and operational benefits varied with these two factors [131]. Yang et al. found that the accuracy of the predicted traffic state may significantly affect the performance of VSLs (e.g., VSLs with bad prediction may deteriorate traffic flow) [129]. Islam et al. focused on the VSL update frequency and safety constraints to improve VSL performance [132]. Li and Ranjitkar examined the combination of ramp metering and VSLs and found that both strategies could lead to improvement, but the improvement would be best with a combination of the two strategies [133]. Li and Ranjitkar [133] adopted the flow-based VSL algorithm for M25 in England, but the VSL algorithms in other work [131, 134] were not fully introduced. The algorithm adopted by Yang et al. [129] and by Islam et al. [132] is implicit because the VSLs were generated with an optimization function.

Talebpour and Mahmassani developed a speed harmonization approach that assumed early detection of shock waves and traffic breakdowns through vehicle-to-vehicle communication [135]. The advantage of vehicle-to-vehicle communication is that vehicles upstream gain information about the traffic situation downstream; the availability of information reduces time delays in the feedback loop. A microscopic simulation was used to evaluate the impact of the speed harmonization on traffic characteristics and improvements in safety. The speed harmonization approach included two parts: (a) shock wave detection using a wavelet transform algorithm (basically, pattern recognition in a nonstationary situation) and (b) VSL determination based on the traffic situation. Simulation results showed significant improvements in traffic flow and safety. The work also found through fundamental diagram analysis the optimal location and time for the VSL transition according to traffic phases.

Work by Dong and Mahmassani proposed a simulation to create a traffic breakdown scenario that is a macroscopic traffic characteristic; in the simulation, driver behavior was changed at the microscopic level [136]. The results could help researchers understand how traffic breakdown at the macroscopic level is caused by microscopic vehicle following and stochastic characteristics of differences in driver behavior.

VSL Practices and Evaluations

The use of VSLs on the motorways M25 and M4 in England is well known [137, 138]. The objectives were to improve traffic throughput (reduced delay), safety, and emissions. VSLs are activated, modified, and deactivated when flow or speed measurements cross preset thresholds between 35 mph and 65 mph. Evaluation showed positive results in many aspects, including reduction in incidents, increased flow, less lane changing, reduced breakdown times, improved throughput, decreased injury accidents by 10% and property damage–only accidents by 30%, overall decreased emissions between 2% and 8%, improved lane use and headway distribution, reduced driver stress, increased driver acceptance (two-thirds of drivers would like VSLs to be extended to other motorways), and higher critical occupancy values in the fundamental diagram [137, 138].

Preliminary VSL strategies were used in Germany and the Netherlands to improve traffic flow [139, 140, 141]. Bertini et al. used an empirical approach to investigate the effectiveness of the German approach in reducing congestion at a recurrent bottleneck and to improve driver safety by using feedback to the driver with advisory VMSs at certain locations along a stretch of highway (18 km long) [139]. The feedback included (a) speed limit (piecewise constant with 12 km/h increment) and start and end time and location and (b) warning information (attention, congestion, slippery road). The suggested speed was based on the traffic situation upstream and downstream of the bottleneck. Data analysis showed that driver responses to the speed limits and messages on the VMSs were reasonable, speed was regulated to some extent, and the improvements in safety were more significant than those in traffic throughput (up to 20% to 30%).

The Dutch experiment intended to smooth or homogenize the traffic flow along a stretch of highway by using VSLs with enforcement when volume approached capacity, and volume was kept constant along a section of the freeway [141]. Two speed limits were used: 70 km/h and 90 km/h; the speed limits were updated every 1 min. Traffic volume and average speed were measured in each section. Tests were conducted on multiple stretches totaling 200 km. Analysis showed that speed control was effective to some extent in reducing speed and speed variation and the number of shock waves, especially when vehicles maintained smaller driving headways. However, there was no significantly positive effect on capacity [141]. Besides, the overall performance of the freeway was not significantly enhanced. This result may suggest combining the variable speed recommendation with other methods, such as ramp metering.

Several traffic management and driver information data sources along an 18-km (11.2-mi) section of Autobahn 9 near Munich, Germany, have been used to analyze traffic dynamics and driver behavior before, during, and after bottleneck activation [139]. The main focus was on the effect on driver behavior and traffic (bottleneck formation) of VSLs displayed on overhead gantries. VSLs and traffic information did cause drivers to slow down, a result that delayed bottleneck activation; traffic density increased, but the traffic was still moving at 35 to 40 km/h. The algorithms for the VSLs were based on the fundamental relationships of speed, flow, and density between detector stations. Transformed curves of cumulative count and time-averaged velocity versus time were used to diagnose bottleneck activation. However, the shock wave back-propagation speed when VSLs were on was still 18 km/h.

In France, use of VSLs started in 2007 on the A7/E15 motorways south of Lyon [142]. As of 2011, VSLs were used on overhead gantries on several highways, covering 650 km. The main objectives are for traffic throughput and safety improvement. The VSL algorithms used included a maximum VSL of 110 km/h. The VSL control is triggered when the total flow exceeds 3,000 vph. Truck access is banned for some areas in peak hours. Observed results include increased lane utilization, improved safety, and positive impact on lane flow distribution. The evaluation on the A13 motorway with a similar VSL strategy showed more positive results [143]: average speed increased by 4% to 10%; the number of bottlenecks (jams) was reduced by 50%; average travel time was reduced by 30 s; lane capacity was unchanged; level of service was improved; crashes were reduced by 17%; time gaps were unchanged; and the compliance rate was still low.

Hoogendoorn et al. systematically evaluated performance of enforced VSLs on the A20 highway near Rotterdam, Netherlands, with several types of before-and-after data, including driver behavior change, traffic mobility and safety improvement, emissions, and noise reduction [144]. The comparison approach used was reasonably objective because data affected by external factors such as bad weather, special events, incidents or accidents, and road work were eliminated. The previously applied fixed-VSL strategy significantly reduced the flow of the overall system, worsened traffic congestion, and changed driver behavior in changing lanes and merging. Therefore, a dynamic speed limit was used; VSLs were between 80 km/h and 100 km/h and were changed according to the traffic situation. Evaluation results showed (a) a driver response delay, which was different for increases and decreases in VSLs; (b) response difference between lanes; (c) higher compliance with higher VSLs; (d) less of an effect on central lanes than on other lanes; (e) improvement in mobility of about 4%, with a decrease of 7% to 18% in queue duration; and (f) no observed improvement in emissions.

Weikl et al. systematically analyzed the effect of VSLs on German Autobahn A99 (16.3 km) near Munich with loop detector data [145]. The control means were enforced VSLs and traveler information about weather, incidents, and traffic congestion downstream. The VSL algorithms were based on the fundamental relationship between speed, density, and flow, but the objective of the algorithm was not stated clearly. Traffic aspects analyzed included speed, spatial–temporal extent of the queue (congestion), flow changes caused by identified bottlenecks, distribution of flow across lanes, percentage of trucks per lane, and flow homogeneity between lanes. Bottlenecks were first identified with oblique accumulated flow. The lane flow distribution was much better balanced when VSLs were in operation. Associated with smaller differences in lane flow, the incident rate was expected to be lower. However, the impacts of VSLs on bottleneck capacity varied in the field tests. The capacity drop when congestion happened with VSLs on was slightly larger than with VSLs off (from 4% to 3%, respectively). Several factors may affect the capacity observed. First, the bottleneck location was changed as a result of the VSLs; therefore, two bottlenecks were compared. Second, drivers did not know where VSLs were enforced and likely assumed that VSLs were enforced downstream of the bottleneck. Third, traffic conditions were different when VSLs were on versus when they were off. The former condition was dominated by wide jams (characterized by low speeds with small variations), whereas the latter was dominated by stop-and-go traffic (characterized by large variations in speed). Fourth, the driver compliance rate was unknown. With these factors, the VSL performance on capacity is not very solid either.

VSAs and enforced VSLs could generate different driver compliance rates. The focus of the work done by Nissan was to examine the impacts of VSAs and VSLs by analyzing the driver compliance effect using microscopic simulation with a case study on the E4 motorway in Stockholm, Sweden [134]. Simulation results showed that the effect of VSLs increases as the compliance rate increases. Simulations indicated that higher compliance rates resulted in delayed onset of the congestion and associated speed breakdowns and higher overall speeds. Simulations also showed that, with a compliance rate of 25% or less, the VSLs have almost no effect on traffic. Two generations of weather-related VSLs have also been evaluated [146].

Several empirical studies have been conducted in the United States since the 1960s in several states with varying levels of development, primarily for safety improvement and secondary for traffic flow improvement [147]. The outcomes were diverse; there were some positive results, but most were negative. The most impressive positive outcome was the work conducted in New Jersey, which was similar to the approach in Germany, but with the speed enforced instead of advised. Some experiments on individual vehicle speed advisory and enforcement were also successfully conducted for trucks traveling downhill [147].

On April 27, 2009, the Washington State Department of Transportation began operation of VSLs on westbound I-90 between I-5 and I-405 as part of the I-90 two-way transit project, aimed to relieve congestion and increase throughput and to reduce rear-end collisions. Later, the VSL strategy was further developed into an active traffic management system. At the beginning, the VSL algorithm was ad hoc and the VSL signs were controlled by engineers. Recently, automatic algorithms have been implemented. An extensive study has been conducted for the performance of the system with VSLs [148]. Researchers have observed some interesting traffic speed thresholds at which traffic flow may change significantly.

DeGaspari et al. focused on travel time reliability through analysis of 5-min data over 19 detector stations on I-5 in Washington State, where the VSLs were enforced [149]. Two reliability indices, the planning time index and buffer index, have been used. The results showed significant improvements in travel time reliability in most cases except during the morning peak between 6:00 and 8:00 a.m. The results also found a 5% to 10% flow drop, which may be a result of the impact of VSLs on driver route choice. However, traffic throughput may have been sacrificed.

VSLs have been deployed on Interstate 270 in Missouri. The performance has been evaluated recently [150]. The effect of VSLs on traffic performance was investigated at eight heavily congested locations. Traffic sensor data were used to determine speed limits, ranging from 40 to 60 mph, in 5-mph increments, to reduce vehicle speed before vehicles reached a congested area (congestion from a bottleneck, crash, or work zone). The before and after field data indicated that differences in the changes in two-dimensional flow–occupancy and speed diagrams (two forms of the fundamental diagram) were statistically significant at seven of eight locations. The slopes of the flow–occupancy plots for over critical occupancies were found to be steeper after VSLs. Slight changes in critical occupancy were observed. The changes in maximum flows before and after traffic breakdown were inconsistent; they increased in some locations but decreased in other locations.

Papageorgiou used data analysis to evaluate VSL strategies [151]. The paper summarizes available information on the VSL impact on fundamental diagram–aggregate traffic flow behavior as follows: (a) decrease the slope of the flow–occupancy diagram at under critical conditions, (b) shift the critical occupancy to higher values, and (c) enable higher flows at the same occupancy values in overcritical conditions.

The authors concluded that there was no clear evidence of improved traffic flow efficiency in operational VSL systems for the implemented VSL strategies.

Chang et al. focused on the evaluation of a field test [152]. The speed drop was significant in the evening peak around 5:00 p.m., dropping from 60 mph to 20 mph in 5 min. The algorithm used can be described as reducing approaching traffic speed to smooth the transition between the free-flow and congested-flow states and taking into account the responses of drivers in dynamically setting the appropriate control speed for each transition location. Test results showed that the proposed VSA strategy was effective at this location in the following aspects: higher average speed and throughput, shorter travel time, and smoothing the transition between the free-flow speed and stop-and-go traffic.

Hegyi et al. developed an algorithm to remove or reduce moving jams (shock waves) at recurrent or nonrecurrent bottlenecks using the second-order METANET model with model predictive control [123]. The basic idea is to reduce the feeding flow into the moving bottleneck and coordinate the traffic flow along a corridor. This idea can be explained in detail with space–time trajectories [153]. The algorithm is further refined as the SPECIALIST, which was tested in the field, with results presented elsewhere [153]. This approach is basically a feed-forward (open-loop) approach. The implementation requires the detection of shock wave fronts for both congestion and discharge waves, which requires high-density road sensors or significant market penetration of vehicle-to-infrastructure communication. Field experiments showed some effectiveness of the algorithm. However, care needs to be taken in that if the VSLs are too restrictive, they will cause new shock waves and bottlenecks upstream.

VSLs and VSAs were implemented at a recurrent bottleneck at a work zone on I-494 in Minneapolis–Saint Paul, Minnesota, and tested for a 3-week period in 2006 [154]. The algorithm adopted a two-stage speed reduction scheme by reducing the traffic flow into the end of the queue upstream of the bottleneck. Two VSL displays were used: one in the work zone and one upstream. Field test data showed a 25% to 35% reduction in speed variation in the morning peak and a 7% increase in total throughput in the evening peak. The driver compliance rate had a 20% to 60% statistical correlation with VSLs in the morning peak.

The Minnesota Department of Transportation also tested VSLs on I-35W in the Mn-BYPASS section of Minneapolis–Saint Paul [155]. The algorithm used detection of traffic downstream to determine VSL display 1.5 mi upstream. It gradually reduced the speed of the incoming traffic to the end of the queue at the bottleneck. The VSL values depended on current speed upstream (measured), speed near the end of the queue (measured), travel distance, constant deceleration, and so forth. The upper bound of VSL is 5 mph less than the fixed roadside speed limit. The VSL display update rate is 30 s. Evaluation of the effectiveness is not yet available.

Looking Into the Future

This section briefly summarizes some lessons learned and experience gained from previous works that could benefit future research, in particular how VSL and VSA research and practice should be conducted:

1. Most safety-oriented VSL and VSA approaches used an ad hoc algorithm that was unlikely to improve traffic flow. For throughput, the objective needs to be quantified and scientifically incorporated into the algorithm and implementation.

2. VSL strategies and algorithms for traffic flow improvements need extensive development. They need to take into account traffic demands, sensor locations, traffic speed estimation, ramp metering, feedback to the driver, public outreach, and so forth.

3. VSL and VSA algorithms for freeway corridors need traffic predictions. Because VSLs and VSAs will affect the traffic stream, which is speed dependent, and the link travel time depends on traffic behavior, a proper dynamic model is necessary for traffic prediction. The model needs to include speed dynamics, either flow-speed or density-speed dynamics. Although traffic density is difficult to measure directly, vehicle-to-infrastructure information could be fused with road sensor data for real-time density estimation [156].

4. Speed harmonization is a special case of VSLs and VSAs. It intends to control traffic streams to a speed corresponding to a static traffic state between free flow and saturated. However, practical traffic may change rapidly as a result of a variety of factors, including high peak hour demands, flow into off-ramps, and, most important, driver behavior. An ad hoc speed harmonization approach is unlikely to improve throughput significantly, as found by the Washington State Department of Transportation.

5. The strategies for shock wave reduction, speed harmonization, and bottleneck flow

maximization must be targeted for certain types of road geometry and traffic situations and activated properly. Care needs to be taken not to reduce flow unnecessarily, which could possibly activate traffic congestion earlier or cause congestion or shock waves upstream.

6. Practices in the United States indicated that safety improvement was significant, but impact on traffic flow was somehow controversial. This result was partially due to immaturity of the VSA and VSL algorithms and partially due to institutional issues, such as enforcement.

7. The oblique accumulated flow approach used by Weikl et al. could possibly be used in analyzing aggregated traffic data for performance evaluation [145]. This parameter is complementary to root mean square error or relative root mean square error, popularly used for simulation model calibration.

8. The VSL thresholds related to traffic flow drop observed by Hammond are interesting and could be used as a reference in field testing [148]. It is necessary to find the reasons for traffic changes near those thresholds.

9. In the long run, VSLs need to be combined with coordinated ramp metering (CRM) because the latter controls the demand from the on-ramp and the former controls driver behavior. They are complementary in function. Their combined effect would be more significant than the effect of just one of them.

10. If there are no institutional issues, VSLs should be enforced for effectiveness. However, VSAs may still have positive effects if the posted information can persuade drivers that following the posted VSA will lead to better safety and flow; such persuasion will require adequate outreach to the public. In peak hours, traffic density is rather high in general. If 15% to 20% of drivers follow the posted speed, others have to follow.

11. With gradual market penetration of vehicle-to-vehicle and vehicle-to-infrastructure communication and vehicle automation technologies [157], VSLs and VSAs designed on the roadside could be passed to vehicles for driver speed advisory or used as the set speed for vehicle control if the vehicle has Cooperative Adaptive Cruise Control capability. This direction is the most favorable direction because differences in the driver behavior will be gradually reduced and eventually eliminated.

2.2.3 Route guidance

Freeway, urban, or mixed traffic networks include a large number of origins and destinations with multiple paths connecting each origin-destination pair. Fixed direction signs at bifurcation nodes of the network typically indicate the direction that is time-shortest in absence of congestion. However, during rush hours, the travel time on many routes changes substantially due to traffic congestion and alternative routes may become competitive. Drivers who are familiar with the traffic conditions in a network (e.g., commuters) optimize their individual routes based on their past experience, thus leading to the celebrated user-equilibrium conditions, first formulated by Wardrop [158]. But daily varying demands, changing environmental conditions, exceptional events (sport events, fairs, concerts, etc.) and, most importantly, incidents may change the traffic conditions in a nonpredictable way. This may lead to an underutilization of the overall network's capacity, whereby some links are heavily congested while capacity reserves are available on alternative routes. Route guidance and driver information systems (RGDIS) may be employed to improve the network efficiency via direct or indirect recommendation of alternative routes [1].

Route guidance systems refer to all driver decision aids used before a trip to select a route, a travel starting time, and possibly decide whether or not to undertake the trip, as well as those used during the trip to adjust the route as needed in light of unforeseen events [9]. Route guidance is a sub-component of travel and transportation management, which is in turn a component of ITS as defined by the U.S. Department of Transportation [159]. U.S. Department of Transportation identifies route guidance systems as a major component of ITS [160].

In [161], a review on early versions of route guidance systems / traveler information systems and their technical approaches have been presented. Also, there are two comparison and classification on route guidance systems based on general features of route guidance systems [160, 162]. Both of these reviews proposed some classification for route guidance systems based on some technical aspects without introducing their architectures and communications and also comparing them to find out the future trend. For instance, in [162], route guidance systems have been classified to static vs. dynamic systems, deterministic vs. stochastic systems, reactive vs. predictive systems and centralized vs. decentralized systems.

As explained in [9], Static systems do not affect the proposed optimal route en-route but dynamic systems will affect it according to real-time traffic information and change the proposed route if another better route has been found. Deterministic systems assume deterministic parameters for roadway links regardless of any random nature of the traffic but stochastic systems assume the traffic may be considered either as a stationary or non-stationary stochastic variable. Reactive systems (known also as feedback routing systems), are solely based on current conditions of the traffic network. To find the route, the system reacts to real-time traffic data without insight into future conditions. But Predictive systems (known also as proactive routing systems), are based on anticipated conditions derived from a predictive model for a future time horizon. A predictive system uses an iterative model to predict future conditions on the links of traffic network based on traffic information as well as available historical data. Also, the route planning in a network can be controlled by a centralized system which monitors and optimizes the whole traffic network or by individual users who optimize their own performance by using decentralized systems. Moreover, in [163], a review on in-vehicle systems has been presented.

3 Core Research Topics and Corresponding Research Methods

The important research topics of Traffic Management and Control are listed below. The committee should investigate the models and algorithms that proposed to deal with these topics.

1. TMaC in Urban Traffic Systems
   - Models
     - Macroscopic models
     - Mesoscopic models
     - Microscopic models
     - Vehicular model or Agent-based model
     - Pedestrians models
   - Control Systems
     - Signaling
     - isolated intersection control
     - Coordinated control
     - Perimeter control
     - Route guidance
     - Incident detection
     - Variable message signs
     - Integrated control and advanced system
   - TMaC and the impact of CAV Systems
     - Connected Vehicle system and the interenet of Things
     - Autonomous vehicle
     - Car Following Modeling
     - Lane changing Modeling
     - Traffic Science Basics (New models)
   - TMaC and the impact of Communication Systems and New Technology
     - VANET (v2v, v2i, etc)
     - New communication methods (infrastructure free or based)
     - In-vehicle information and navigation systems
     - advanced driver assistance systems (ACC, CACC, collision warning, Accident Detection etc)
     - Data management and Collection methods
     - Security and cyber

2. TMaC in Freeway Traffic Systems
    - Ramp metering
    - Variable speed limits
    - Route guidance
3. TMaC in Air Traffic Systems
4. TMaC in Maritime Traffic Systems
5. TMaC in Mixed Traffic Systems

Additionally, we identified major conferences and journals concerned with Traffic Management and Control Field or closely related to it. The list of the major journals is described:

J1. Transportation Research Part C: Emerging Technologies

J2. Transportation Research Part B: Methodological

J3. IEEE Transactions on Intelligent Transportation Systems

J4. IFAC Proceedings Volumes (IFAC-PapersOnline)

J5. Transportation Research Record

The list of main conferences:

C1. TRB

C2. IFTTT

C3. hEART

C4. IFAC

C5. ITS

4 Challenges and future perspectives

This manuscript leads to the following future research approaches:

- **Resilient urban traffic control:** Advanced control strategies (traffic signal, routing, pricing, lane allocation) for large-scale urban traffic networks under uncertainties, failures, cyberattacks, based on new methods and approaches, e.g. adaptive control theory, robust optimization, and machine learning techniques.
- **Urban micromobility management:** Managing micromobility control strategies based on traffic flow modeling at a macro level (e.g. a city scale or an urban region), or at a micro level (e.g. an isolated intersection). Micromobility devices includes bicycles, electric bikes, electric scooters, electric skateboards, etc.

- **Urban air mobility:** Real-time operation and control of urban air mobility, including traffic flow management, manned and unmanned aircraft coordination, considering user perception and acceptance, environmental and societal issues, regulations and policy.

- **Parking:** Parking operation, management, and control in the connected and automated era. This includes parking pricing and revenue management, modelling approaches of smart parking control systems with behavioral modeling.

- **Railway traffic management:** Enhanced modelling and control of railway (trains, light urban rails, etc.) operations in stations and networks. This includes routing and scheduling trains in real-time, scheduling methods for automated railway, railway optimizing capacity, passenger-oriented control of trains, energy efficient railway traffic control, advanced transport solutions for container transport.

  Any other new directions in traffic flow control and management.

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