OVERVIEW OF ROAD AND MOTORWAY TRAFFIC CONTROL STRATEGIES

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Abstract. Traffic congestion in urban road and freeway networks leads to a strong degradation of the network infrastructure and accordingly reduced throughput which can be countered via suitable control measures and strategies. A concise overview of proposed and implemented control strategies is provided for three areas: urban road networks, freeway networks and route guidance. The paper concludes with a brief discussion of future needs in this important technical area.

1. Introduction

Transportation has always been a crucial aspect of human civilization, but it is only in the second half of the last century that the phenomenon of traffic congestion has become predominant due to the rapid increase in the number of vehicles and in the transportation demand in virtually all transportation modes. Traffic congestion appears when too many vehicles attempt to use a common transportation infrastructure with limited capacity. In the best case, traffic congestion leads to queueing phenomena (and corresponding delays) while the infrastructure capacity ("the server") is fully utilized. In the worst (and far more typical) case, traffic congestion leads to a degraded use of the available infrastructure (reduced throughput), thus contributing to an accelerated congestion increase, which leads to further infrastructure degradation, and so forth. Traffic congestion results in excess delays, reduced safety, and increased environmental pollution.

The emergence of traffic (i.e. many interacting vehicles using a common infrastructure) and subsequently traffic congestion (whereby demand temporarily exceeds the infrastructure capacity) have opened new innovation needs in the transportation area. A brute-force approach (i.e., the continuous expansion of the available transportation infrastructure) cannot continue to be the only answer to the ever increasing transportation and mobility needs of modern societies. The efficient, safe, and less polluting transportation of persons and goods calls for an optimal utilization of the available infrastructure via suitable application of a variety of traffic control measures. This trend is enabled by the

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rapid developments in the areas of communications and computing (telematics), but it is quite evident that the efficiency of traffic control directly depends on the efficiency and relevance of the employed control methodologies.

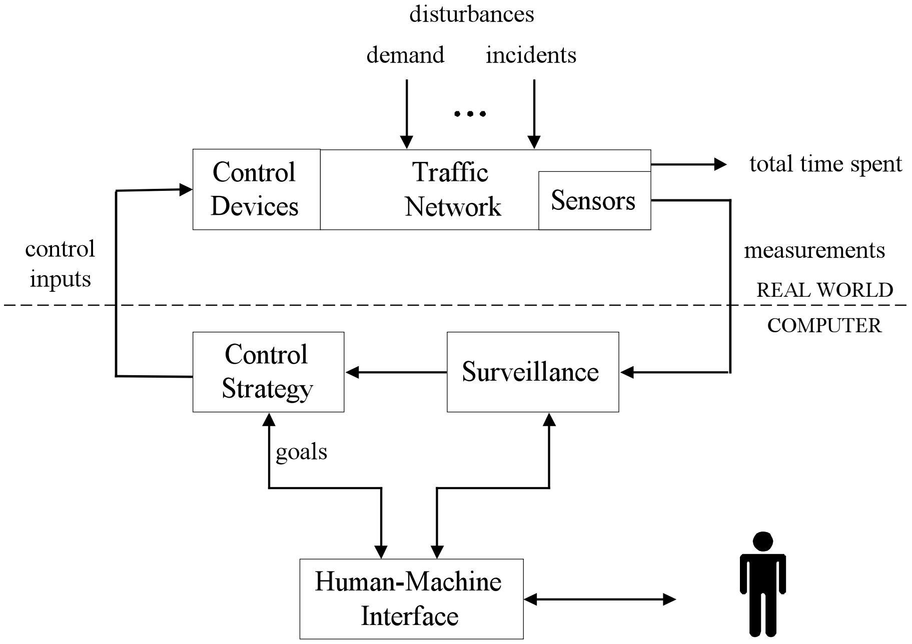


Fig. 1. The control loop.

Figure 1 illustrates the basic elements of a control loop. The traffic flow behaviour in the (road or freeway or mixed) traffic network depends on some external quantities that are classified into two groups: *Control inputs* that are directly related to corresponding control devices (actuators), such as traffic lights, variable message signs, etc.; *Disturbances,* whose values cannot be manipulated, but may possibly be measurable (e.g. demand) or detectable (e.g. incident) or predictable over a future time horizon. The network's output or performance is measured via suitable indices, such as the *total time spent* by all vehicles in the network over a time horizon. The task of the *Surveillance* is to enhance and to extend the information provided by suitable sensors (e.g. inductive loop detectors) as required by the subsequent control strategy and the human operators. The kernel of the control loop is the *Control Strategy*, whose task is to specify in real time the control inputs, based on available measurements/estimations/predictions, so as to achieve the pre-specified *goals* (e.g. minimization of total time spent) despite the influence of various disturbances. The relevance and efficiency of the control strategy largely determines the efficiency of the overall control system. Therefore control strategies should be designed with care, via application of powerful and systematic methods of optimization and automatic control, rather than via questionable heuristics [1].

2. Road Traffic Control

2.1. Basic Notions

Traffic lights at intersections is the major control measure in urban road networks. An *intersection* (or junction) consists of a number of approaches and the crossing area. An *approach* may have one or more lanes but has a unique, independent queue. Approaches are used by corresponding *traffic streams* (veh/h). Two *compatible* streams can safely cross the intersection simultaneously, else they are called *antagonistic*. A *signal cycle* is one repetition of the basic series of signal combinations at an intersection; its duration is called *cycle time*. A *stage* (or *phase*) is a part of the signal cycle, during which one set of streams has r.o.w. (Fig. 2). Constant *lost* (or *intergreen*) *times* of a few seconds are necessary between stages to avoid interference between antagonistic streams of consecutive stages (Fig. 3).

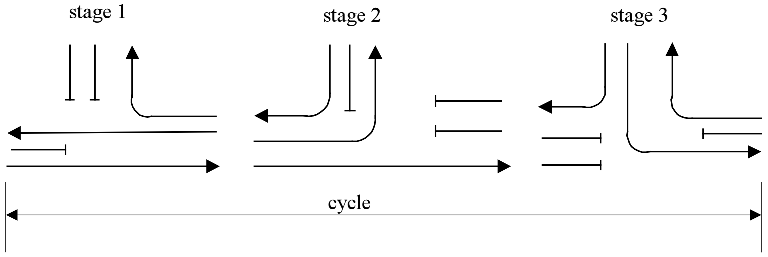


Fig. 2. Example of signal cycle.

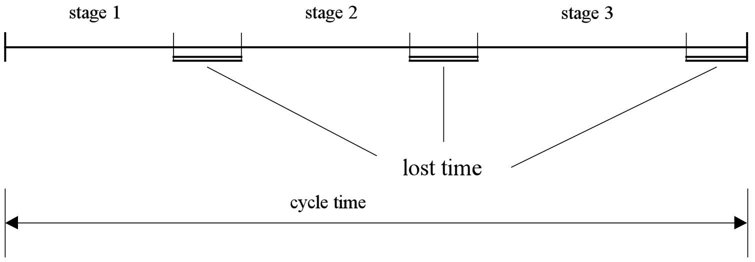


Fig. 3. Cycle time and lost times.

There are four possibilities for influencing traffic conditions via traffic lights operation:

- *Stage specification*: For complex intersections, the specification of the optimal number and constitution of stages is a non-trivial task that can have a major impact on intersection capacity and efficiency.
- *Split*: This is the relative green duration of each stage (as a portion of the cycle time) that should be optimized according to the demand of the involved streams.

- *Cycle time*: Longer cycle times typically increase the intersection capacity because the proportion of the constant lost times becomes accordingly smaller; on the other hand, longer cycle times may increase vehicle delays in undersaturated intersections due to longer waiting times during the red phase.
- *Offset*: This is the time difference between cycles for successive intersections that may give rise to a "green wave" along an arterial; clearly.

Control strategies employed for road traffic control may be classified according to the following characteristics:

- *Fixed-time strategies* for a given time-of-day (e.g. morning peak hour) are derived off-line by use of appropriate optimization codes based on historical constant demands and turning rates for each stream; *traffic-responsive strategies* make use of real-time measurements (typically one or two inductive loops per link) to calculate in real time the suitable signal settings.
- *Isolated strategies* are applicable to single intersections while *coordinated strategies* consider an urban zone or even a whole network comprising many intersections.
- Most available strategies are only applicable to *undersaturated* traffic conditions, whereby vehicle queues are only created during the red phases and are dissolved during the green phases; very few strategies are suitable also for *oversaturated* conditions with partially increasing queues that in many cases reach the upstream intersections.

2.2. Isolated Intersection Control

Fixed-time strategies. Isolated fixed-time strategies are only applicable to undersaturated traffic conditions. *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. Wellknown examples of stage-based strategies are SIGSET [2] and SIGCAP [3] Phase-based approaches [4] solve a similar problem, suitably extended to consider different staging combinations.

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. A more sophisticated version of this kind of strategies was proposed by Miller [5] and is included in the control tool MOVA [6].

2.3. 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.

MAXBAND [7] considers a two-way arterial including several subsequent 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). A number of significant extensions have been introduced in the original method in order to consider a variety of new aspects such as different bandwidths for each link of the arterial (MULTIBAND) [8].

TRANSYT [9] 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. Figure 4 depicts the method's basic structure whereby the procedure is an iterative one: For given values of the decision variables (control inputs), i.e. of splits, offsets, and cycle time, the dynamic network model calculates the corresponding performance index, e.g. the total number of vehicle stops. A heuristic "hill-climb" optimization algorithm introduces small changes to the decision variables and orders a new model run, and so forth, until a (local) minimum is found.

The main drawback of fixed-time strategies is that their settings are based on historical rather than real-time data. This may be a crude simplification because:

- Demands are not constant, even within a time-of-day.
- Demands may vary at different days, e.g. due to special events.
- Demands change in the long term leading to "aging" of the optimized settings.
- Turning movements are also changing in the same ways as demands; in addition, turning movements may change due to the drivers' response to the new optimised signal settings, whereby they try to minimize their individual travel times.
- Incidents and farther disturbances may perturb traffic conditions in a non-predictable way.

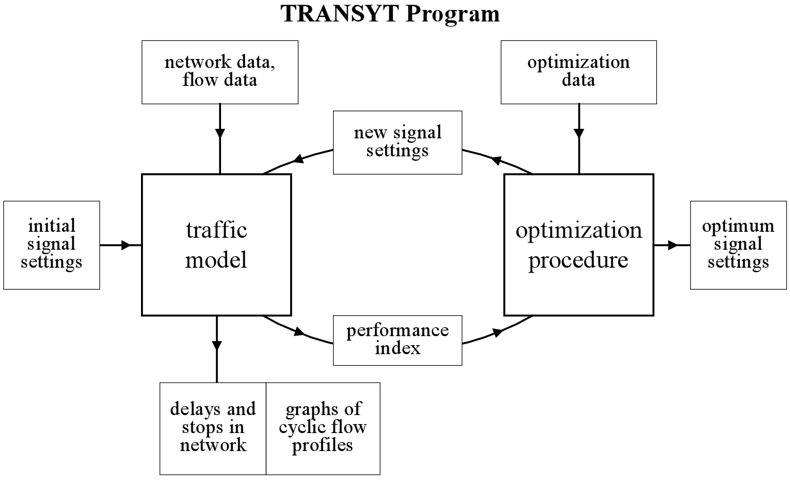


Fig. 4. Structure of TRANSYT (after [9]).

For all these reasons, 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).

2.4. Coordinated Traffic-Responsive Strategies

SCOOT [10] has been applied to over 150 cities in the United Kingdom and elsewhere. SCOOT utilizes traffic volume and occupancy measurements from the upstream end of the network links. It runs in a central control computer and employs a philosophy similar to TRANSYT.

Model-based optimisation methods. More recently, a number of more rigorous model-based traffic-responsive strategies have been developed: *OPAC* [11], *PRODYN* [12], *CRONOS* [13], *RHODES* [14]. These strategies do not consider explicitly splits, offsets, or cycles. Based on pre-specified staging, they calculate in real time the optimal values of the next few switching times τ_i, $i = 1, 2, \ldots$, over a future time horizon H, starting from the current time t and the currently applied stage. The *rolling horizon* procedure is employed for real-time application.

Store-and-forward based modelling has been used in various road traffic control approaches because it opens the way to the application of a number of highly efficient optimization methods (such as linear, quadratic and nonlinear programming). Alternatively a multivariable regulator approach can be employed such as in the signal control strategy TUC [15] to calculate in real time the network splits, while cycle time and offsets are calculated by other parallel algorithms. TUC was recently implemented and compared in Southampton, Munich and Chania with the respective resident strategies SCOOT, BALANCE and TASS [16].

2.5. Integrated Urban-Freeway Traffic Control

Modern metropolitan traffic networks include both urban roads and freeways and employ a variety of control measures such as signal control, ramp metering, variable message signs and route guidance. Traditionally, control strategies for each type of control measure are designed and implemented separately, which may result in antagonistic actions and lack of synergy among different control strategies and actions. However, modern traffic networks that include various infrastructure types, are perceived by the users as an entity, and all included control measures, regardless of their type or location, ultimately serve the same goal of higher network efficiency. Integrated control strategies should consider all control measures simultaneously towards a common control objective. Despite some preliminary works on this subject the problem of control integration is quite difficult due to its high dimensions that reflect the geographical extension of the traffic network.

3. Freeway Traffic Control

3.1. Motivation

Freeways had been originally conceived so as to provide virtually unlimited mobility to road users, without the annoyance of flow interruptions by traffic lights. The rapid increase of traffic demand, however, led soon to increasingly severe congestions, 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. At the present stage, responsible authorities have not fully realized that the expensive freeway-network infrastructure is strongly underutilized on a daily basis due to the lack of efficient and comprehensive traffic control systems. In other words, the expensive infrastructure is intended to deliver a nominal capacity that is not available (due to congestion), ironically, exactly at the time it is most urgently needed (during peak hours). The control measures that are typically employed in freeway networks are:

- *Ramp metering*, activated via installation of traffic lights at on-ramps or freeway interchanges.
- *Link control*, that comprises a number of possibilities including lane control, variable speed limits, congestion warning, tidal (reversable) flow, keep-lane instructions, etc.
- *Driver information and guidance systems*, either by use of roadside variable message signs or via two-way communication with equipped vehicles.

Ramp metering is the most direct 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 arterials.
- Efficient incident response.
- Improved traffic safety due to reduced congestion and safer merging.

Some recent studies have demonstrated that efficient ramp metering strategies may provide spectacular improvements in large-scale freeway networks [17].

3.2. Fixed-Time Ramp Metering Strategies

Fixed-time ramp metering strategies are derived off-line for particular times-of-day, based on constant historical demands and simple static models without use of real-time measurements. This approach was first suggested by Wattleworth [18] and leads to linear programming or quadratic programming problems.

The drawbacks of fixed-time ramp metering strategies are identical to the ones discussed under road traffic control. In addition, fixed-time ramp metering strategies may lead (due to the absence of real-time measurements) either to overload of the mainstream flow (congestion) or to underutilization of the freeway. In fact, ramp metering is an efficient but also delicate control measure. If ramp metering strategies are not accurate enough, then congestion may not be prevented from forming, or the mainstream capacity may be underutilized (e.g. due to groundlessly strong metering).

3.3. Reactive Ramp Metering Strategies

Reactive ramp metering strategies are employed at a tactical level, i.e. in the aim of keeping the freeway traffic conditions close to pre-specified set values, based on real-time measurements.

Local ramp metering. Local ramp metering strategies make use of traffic measurements in the vicinity of a ramp to calculate suitable ramp metering values. The *demand-capacity* and *occupancy strategies* [19] are based on an open-loop disturbance-rejection policy and are quite popular in North America. An alternative, closed-loop ramp metering strategy (*ALINEA*), suggested in [20] is based on classical feedback concepts and is quite popular in Europe. Comparative field trials have been conducted in various countries to assess and compare the efficiency of local ramp metering strategies, see e.g. [21], whereby ALINEA outperformed feedforward-based strategies with respect to all evaluation criteria.

Multivariable regulator strategies. Multivariable regulators for ramp metering pursue the same goals as local ramp metering strategies but they 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 [22]. The multivariable regulator strategy *METALINE* may be viewed as a generalisation and extension of ALINEA. Field trials and simulation results comparing the efficiency of METALINE versus ALINEA lead to the following conclusions:

- While ALINEA requires hardly any design effort, METALINE application calls for a rather sophisticated design procedure that is based on advanced control-theoretic methods (LQR optimal control).
- For urban freeways with a high density of on-ramps, METALINE was found to provide no advantages over ALINEA (the latter implemented independently at each controllable on-ramp) under recurrent congestion.
- In the case of non-recurrent congestion (e.g. due to an incident), METALINE performs better than ALINEA due to more comprehensive measurement information.

Corridor impact. Some system operators hesitate to apply ramp metering because of the concern that congestion may be conveyed from the freeway to the adjacent street network. In fact, a ramp metering application designed to avoid or reduce congestion on freeways may have both positive and negative effects on the adjacent road network traffic. However, if an efficient control strategy is applied for ramp metering, the freeway throughput will be generally increased. More precisely, ramp metering at the beginning of the rush hour may lead to on-ramp queues in order to prevent congestion to form on the freeway, which may temporarily lead to diversion towards the urban network. But due to congestion avoidance or reduction, the freeway will be eventually enabled to accommodate a higher throughput, thus attracting drivers from urban paths and leading to an improved overall network performance. This positive impact of ramp metering on both the freeway and the adjacent road network traffic conditions was confirmed in a specially designed field evaluation in the Corridor Périphérique in Paris [23].

3.4. Nonlinear Optimal Ramp Metering Strategies

Reactive ramp metering strategies are very helpful, but, first they need appropriate set values, and, second, the scope of their actions is more or less local. What is needed for freeway networks or long freeway stretches is a superior coordination level that calculates in real time optimal set values from a proactive, strategic point of view. Such an optimal control strategy should explicitly take into account:

- The current traffic state both on the freeway and on the on-ramps.
- Demand predictions over a sufficiently long time horizon.
- The limited storage capacity of the on-ramps.
- The ramp metering constraints discussed earlier.
- The nonlinear traffic flow dynamics, including the infrastructure's limited capacity.
- Any incidents currently present in the freeway network.

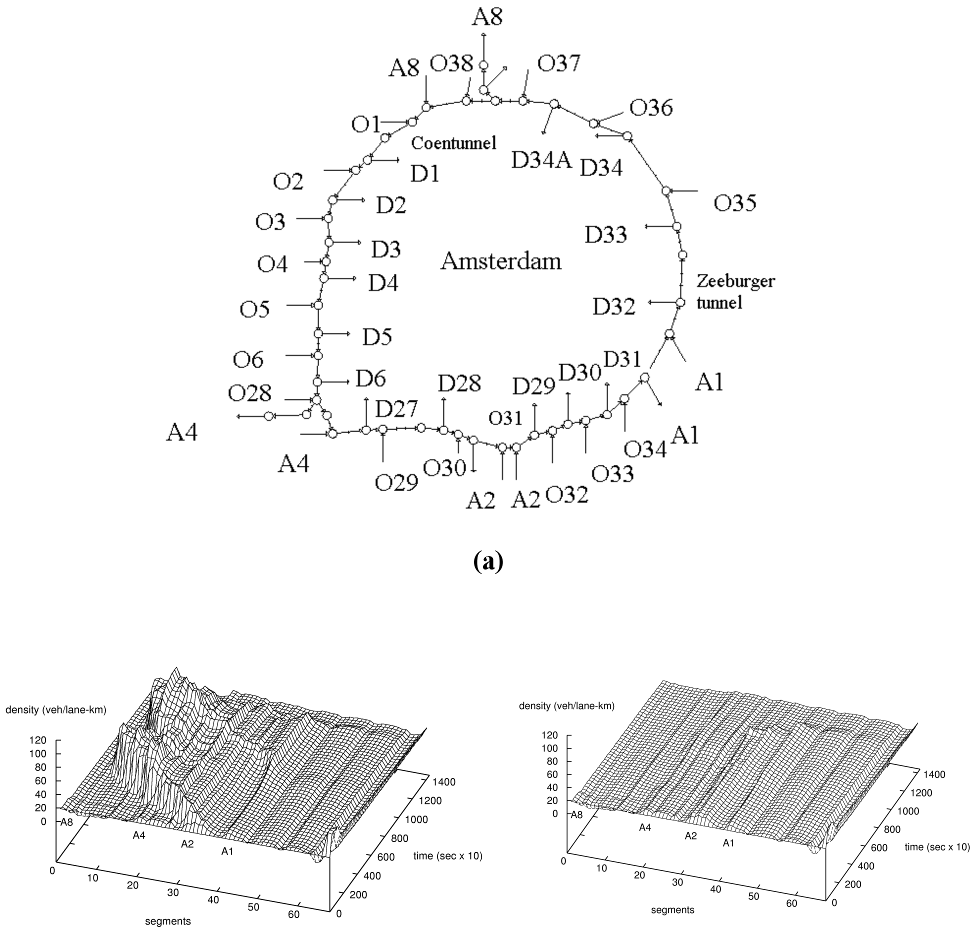
Such a comprehensive dynamic optimal control problem may be formulated and solved with moderate computation time by use of suitable numerical algorithms. This problem or variations thereof was considered and solved in various works, see [24] for an overview Although simulation studies indicate substantial savings of travel time and substantial increase of throughput, advanced control strategies of this kind have not been implemented in the field as of yet.

Figure 5 displays an example of (simulated) optimal control application using the generic software tool AMOC for the Amsterdam ringroad A10 (counter-clockwise direction only) over a typical morning-peak period of 4 hours [17]. When no ramp metering is applied, the excessive demand coupled with the uncontrolled entrance of drivers into the mainstream, causes a time-space extended congestion (Fig. 5b) that blocks almost half of the freeway off-ramps, thus leading to a strongly reduced throughput. With application of optimal ramp metering, congestion is avoided (Fig. 5c), throughput is maximized, and the total time spent by all vehicles (including waiting time at the ramps) is reduced by 43.5% compared to no control.

3.5. Link Control

Link control may include one or a combination of the following actions:

- Variable speed limitation
- Changeable message signs with indications for "keep lane", or congestion warning, or environmental warning (e.g. information about the pavement state)
- Lane control measures (e.g. prohibited lane use upstream of heavily used on-ramps or incident locations)
- Incident or congestion warning
- Reversable flow lanes (tidal flow).



(a)

(b) (c)

Fig. 5. Optimal ramp metering for the Amsterdam ringroad (counter-clockwise direction): (a) Network sketch, (b) Density profile without and (c) with optimal ramp metering control.

There are many freeway stretches, particularly in Germany, in The Netherlands, and, more recently, in the United Kingdom, employing a selection of these measures. It is generally thought that control measures of this kind lead to a homogenization of traffic flow (i.e. more homogeneous speeds of cars within a lane and of average speeds on different lanes) which is believed to reduce the risk of falling into congestion at high traffic densities and to increase the freeway's capacity.

4. Route Guidance and Driver Information

4.1. Introduction

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 [25]. 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 non-predictable 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.

A first classification of RGDIS distinguishes *pre-trip* from *en-route* advice. Pre-trip communication possibilities include the internet, phone services, mobile devices, television and radio. These communication devices may be consulted by a potential road user to make a rational decision regarding:

- The effectuation or postponement of the intended trip
- The choice of transport mode (car, bus, underground, etc.)
- The choice of the departure time
- The (initial) path choice.

If the road user has decided to complete the trip by car, they may continue to receive information or advice via appropriate *en-route* devices such as radio services (RDS-TMC), road-side variable message sings (VMS), or special in-car equipment, in order to make sensible routing decisions at bifurcation nodes of the network. While radio broadcasting services and VMS have been in use for more than 25 years (and their number is steadily increasing) individual route guidance systems employing in-car devices and two-way communication with control centers are in their infancy.

At this point, it is appropriate to distinguish among two alternative policies (which in some cases may be combined) of providing en-route information versus explicit route recommendation. Many operators (particularly of VMS-based systems) prefer the provision of real-time information. Also the majority of drivers (according to some questionnaire results) seem to prefer this option that enables them to make their own decisions, rather than having to follow recommendations by an anonymous system. It should be emphasized, however, that pure information provision has a number of partially significant drawbacks:

- The translation of provided information into routing decisions requires the knowledge of the network which may not be present for all drivers.

- Although the control centre disposes over complete information about the traffic conditions in the whole network, only a tiny part of this information can be conveyed to the users due to space limitations on the VMS and other devices, which may not be sufficient for a rational route decision.
- Even if it would be possible to provide more comprehensive information, the drivers would have to make a route decision within a few seconds, i.e. after looking at the VMS and before reaching the bifurcation.
- There is no possibility for the operator or a control strategy to actively influence traffic conditions, as decisions are left with the drivers.

On the other hand, route guidance systems are constrained by the requirement not to suggest routes that would disbenefit complying drivers, else the credibility and eventually the impact of the whole system may be jeopardized. Moreover, route guidance systems call for a genuine control strategy in the sense of Fig. 1.

4.2. Travel Time Display

A particular type of driver information system that is gaining increasing momentum due to its relative simplicity and its popularity with drivers is the display (on VMS) of travel times for well-defined stretches downstream of the VMS. This information is readily comprehensible by the drivers, and it may either provide a basis for route choice decisions or simply reduce the drivers' stress, particularly in congested traffic conditions. For example, some 350 VMS are installed on the Boulevard Périphérique of Paris (France) and on all approaches that lead to this ringway [26]. A similar system, providing travel times on the two downstream freeway links of each bifurcation node, is operational in the dense freeway network around Paris, see Fig. 6 for an example.

Clearly, any *instantaneous travel* time formula based only on current traffic measurements will induce a systematic estimation error if the traffic conditions in the stretch are rapidly changing, e.g. during congestion growth or dissipation. A scheme that delivers *predicted travel times* that come closer to the travel times that will be experienced by the drivers during their trip may be based on:

- Historical information
- Suitable extrapolation methods (e.g. time series or neural networks)
- Employment of dynamic traffic flow models in real time

or a combination of the above.

4.3. Route Guidance Strategies

Basic Notions. A route guidance system may be viewed as a traffic control system in the sense of Fig. 1. Based on real-time measurements, sufficiently interpreted and extended within the surveillance block, a control strategy decides about the routes to be recommended (or the information to be provided) to the road users. Because of the real-time nature of the operation, requirements of short computation times are relatively strict. Route guidance strategies may be classified according to various aspects:

- *Reactive strategies* are based only on current measurements without the real-time use of mathematical models or other predictive tools; *predictive strategies* attempt to predict traffic conditions sufficiently far in the future in order to improve the quality of the provided recommendations.

Fig. 6. Example of a Variable Message Sign (VMS) display in the Ile-de-France freeway network around Paris (France); this VMS is located just upstream of a freeway bifurcation whose outgoing links A1 and A3 eventually lead to the Boulevard Périphérique (BP). The sign informs (first line) that the current travel time from the VMS on A1 until BP is 12 min with increasing tendency, while (second line) the travel time from the VMS on A3 until BP is 21 min with decreasing tendency.

- *Iterative strategies* run several model simulations in real time, each time with suitably modified route guidance, to ensure (at convergence) that the control goal will be achieved as accurately as possible; iterative strategies are by nature predictive. *One-shot strategies* may either be reactive, in which case they typically perform simple calculations based on real-time data, or they may be predictive, whereby they run one single time a simulation model to increase the relevance of their recommendations.
- Route guidance strategies may aim at either *system optimal* or *user optimal* traffic conditions. In the first case, the control goal is the minimisation of a global objective criterion (e.g. the total time spent) even for the price of recommending routes that are sometimes more costly than the regular routes. In the second case, every recommended route should not be more costly than the regular route, even for the price of sub-optimality with respect to the global objective criterion.

One-shot strategies. Particularly for dense networks, with relatively short links, many bifurcations, and a high number of alternative routes connecting any two nodes, reactive strategies may be highly efficient in establishing user-optimal conditions on the basis of current traffic measurements. Most reactive strategies are decentralized, i.e. they conduct their calculations at each bifurcation node independently of other nodes. Simple feedback regulators of the P (proportional) or PI (proportional-integral) types have been proposed in [27]. An operational system employing decentralized P-regulators in the traffic network of Aalborg, Denmark, was reported in [28].

A different kind of one-shot strategies may employ in real time a mathematical model of the network traffic flow which is run once, in order to provide information about the future traffic conditions under the current route guidance settings. A regulator is then used to control the predicted future, rather than the current, traffic conditions. Such control schemes are preferable to reactive regulators when the traffic network has long links with a limited number of bifurcation nodes. A control scheme of this kind was applied to the Scottish highway network employing P-regulators or a heuristic expert system [29].

Iterative strategies may aim at establishing either system-optimal or user-optimal conditions. For a system optimum the corresponding optimal control problem may be solved by use of the same numerical algorithms as the optimal ramp metering problem. On the other hand, there are also several iterative procedures suggested towards establishing user optimal conditions [30], [31], [32]. The typical core structure of these iterative strategies is as follows:

- Set the initial path assignments or splitting rates (control inputs).
- Run a simulation model over a time horizon H.
- Evaluate the travel times on alternative utilized paths; if all travel time differences are sufficiently small, stop with the final solution.
- Modify the path assignments or splitting rates appropriately to reduce travel time differences; go to (b).

The simulation models employed by different algorithms in step (b) may be microscopic, macroscopic, or mesoscopic. The real-time implementation of iterative algorithms for route guidance purposes employs the rolling horizon procedure in order to reduce the sensitivity with respect to predicted demands and modeling inaccuracies.

5. Future Directions

As in many other engineering disciplines, only a small portion of the significant methodological advancements have really been exploited in the field as of yet. Administrative inertia; little competitive pressure in the public sector; industrial interest in (expensive) hardware rather than in (low-cost) methodologies; the complexity of traffic control systems; limited realization of the improvement potential behind advanced methods by the responsible authorities; and limited understanding of practical problems by some researchers may have a role in this. Whatever the reasons, the major challenge in the coming decade is the deployment of advanced and efficient traffic control strategies in the field, with particular focus on addressing traffic saturation phenomena (congestion).

More precisely, the majority of small and big cities even in industrialized countries are still operating old-fashioned fixed-time signal control strategies, often even poorly optimized or maintained. Even when modern traffic-responsive control systems are installed in terms of hardware devices, the employed control strategies are often naïve, poorly tested and fine-tuned, thus failing to exploit the possibilities provided by the relatively expensive hardware infrastructure.

Regarding freeway networks, the situation is even worse. Operational control systems of any kind are the exception rather than the rule. With regard to ramp metering, the main focus is often not on improving efficiency but on secondary objectives of different kinds. The responsible traffic authorities and the decision makers are far from realizing the fact that advanced real-time ramp metering systems (employing optimal control algorithms) have the potential of changing dramatically the traffic conditions on today’s heavily congested (hence strongly underutilized) freeways with spectacular improvements that may reach 50% reduction of the total time spent.

With regard to driver information and route guidance systems, there is an increasing interest and an increasing number of operational systems employing variable message signs, but once more, the relatively expensive hardware infrastructure is not exploited to the degree possible, as implemented control strategies are typically naïve.

On the side of the research community, any effort should be made to enlighten the road authorities, the political decision makers, and the general public about the substantial improvements achievable via implementation of modern traffic control methods and tools. At the same time, it should be emphasized that many methodological works presented at conferences and technical journals address practical problems and concerns only in a limited way. In some cases, proposed traffic control strategies are not even thoroughly and properly tested via simulation, despite the meanwhile high number of available traffic simulators of various kinds. This poses a burden to real implementation of the methods, and perhaps the best way for researchers to familiarize themselves with the practical requirements and constraints is to get occasionally involved in real implementations.

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