The Future of Road Traffic Management: From Local to Network-wide, from Reactive to Proactive

Jos Vrancken

Delft University of Technology, Delft, The Netherlands

Abstract. This paper describes the current status and future of Road Traffic Management and the key challenges to achieve this future. It proposes a way forward that covers both the traffic management theory development, the development of supporting systems and the necessary standardization effort needed to make large scale deployment of Network Management feasible.

1 Introduction

Road traffic is the most important means of transport, both for people and goods, but also the most problematic one. There are no prospects that this will change fundamentally in the coming decades. On the contrary, with increasing standards of living in many countries in the world, car ownership will continue to grow in an already, at many places, oversaturated network. The heavier the use of a roads network, the more reason there is to manage traffic, even though, in dense conditions, it is also hardest to do this effectively. We can observe each day that just self-organization, although it certainly plays a important and increasing role, is not enough to prevent congestion. Traffic management is necessary for an efficient use of the network near its capacity. The majority of traffic management measures, especially the automated measures such as traffic signals and ramp metering, are stil local measures with a scope of at most several hundred meters. Local measures have obvious limitations: they have a tendency to solve a congestion problem within their own scope by shifting it to a neighbouring area. Moreover, without looking at the network context, it is hard to look into the near future, because the future of one place in a network is, to a large extent, determined by the current status of traffic elsewhere in the network. Proactive traffic management, trying to prevent problems rather than solving them, is hard when looking only locally. So, network management (NM), which is the activity of managing traffic in larger areas, is urgently needed, even more so as networks become more and more overloaded. But denser traffic is also traffic in which events at one point have much wider consequences, which means that a network with denser traffic is a more complex system and harder to manage. The more NM is needed, the harder it is. In order to understand the true nature of the problem of developing NM, one must observe that the problem contains a number of, mutually dependent, components. It's not only about traffic management, but also about system development, both control systems and decision support systems for operators, about the deployment of NM-systems in practice and about measuring

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the effectiveness of NM. In the following section we will describe the current status of NM, other relevant developments in the transport domain, the main reasons why development of NM is inevitably a slow process, and finally we will propose an approach to move forward in this field. The key issues that will be addressed are:

- a framework to describe the problem of control in a network
- the problem of partitioning a network in order to make it manageable
- the problem of assigning priorities to network parts in order to support control strategies
- the necessary standardization of interoperability among traffic control systems, in order to make deployment of NM systems practically feasible

2 Current Status of Network Management

Network management is growing slowly but steadily. The subject is best developed in the area of coordination of traffic lights control systems in urban areas. Research in this area dates back to the seventies and nowadays, many products are available that offer various degrees of coordination over more or less extended, urban areas ([10]). It is well developed, but it is restricted to typical urban traffic and only one kind of control measure. Integrated Corridor Management ([7]) considers virtually all kinds of control measures available but it considers only a linear kind of network, a so-called corridor, the main traffic artery in an area. An example of a system that considers mixed networks and various types of control measures, together with advanced support for managing control scenarios, is the SCM system (Scenario Coordination Module, [14], [15]) in the Amsterdam area. This system was installed in September 2010 and is now in the middle of the process of evaluation and full-scale deployment. In [5], an interesting systems-oriented approach is described that aims at integrating current traffic control systems into a network control system in Sweden. Thus we can conclude that network management does take off, but progress is slow. Mature, full-scale network management systems, covering all networks in an area and coordinating all local measures, are not yet in operation to the best of our knowledge, let apart that it has been proven that these systems have a positive effect on network performance.

3 Other Developments in Road Transport

Several other developments in Road Transport are relevant for traffic management. We mention only a few:

3.1 Cooperative Systems

Cooperative systems are about the increase in data processing and communications on the road, with connections between vehicles and between vehicles and the roadside. This is highly relevant to traffic management in several ways. First of all, this development increases the process of self-organization among vehicles. Especially at the micro level, cars can improve traffic properties by means such as adaptive or connected cruise control. In addition, through the communications facilities, drivers are much better informed about traffic conditions on their intended route. Second, the vehicles become an important source of traffic data. Suppliers of navigation equipment, such as TomTom in The Netherlands, are already using this kind of data from their connected devices, for the purposes of providing their customers with real-time traffic information. To some extent, they are influencing traffic in a way that might be called traffic management (or even network management) but a private party that depends on its customers, will necessarily manage traffic for the user optimum and not the system optimum that governmental traffic management authorities focus on. It is therefore not to be expected that this ”private” traffic management will eventually replace the traffic management authorities. Cooperative systems offer interesting capabilities to supply the necessary sensors and actuators for NM, so instead of making traffic management unnecessary, they greatly extend the facilities for this activity.

3.2 Cross-sectoral Connections

A second important development might be summarized as the increasing level of connection between the road transport system and other systems in society, both within transport and in other sectors. Examples of this are:

Multimodal Traffic. This development is in essence about connecting road transport with the public transport system (both on the road and other forms, such as trains, streetcars, etc.). This is about finding optimal trips, in terms of travel time and cost, by combining different modes of transport (private car, bus, train, shared car, ...);

The Energy Sector. Road transport is highly energy consuming and, by its very nature, strongly dependent on liquid fuels. Much research goes into the introduction of electric vehicles, and the required charging infrastructure, but convincing breakthroughs are still to come. The extra logistics needed for electric driving, the different driving properties, and the stronger emphasis on driving limited distances, multimodal trips and car sharing will certainly have an impact on the characteristics of traffic and will change traffic patterns.

Car Sharing. Car sharing is based on the fact that most cars are idle for 95% of the time, which is of course tremendously inefficient in terms of resources that went into building so many cars, the cost of ownership and the parking place occupied by so many vehicles. Car sharing is an obvious solution to this but it requires extensive information processing in order to discover nearby shared cars that are available for use, and for the administrative handling of trips such that costs are correctly attributed to the users of a shared car. Car sharing will thoroughly change the relationship between a car and a driver, as the car is no longer his or hers. It is no longer considered an extension of private space. It looks more like public transport. This in turn will pave the way towards more outside influence on driving behavior and route choice, which offers interesting leads for traffic management. Spreading traffic over the network, for instance, is a lot easier if one can influence the route choice behavior of a fair percentage of vehicles.

4 What is so Hard about Developing Network Management?

However obvious the need for NM may be, its development is slow. The blanket reason for this is the high complexity of traffic in a network. A single crossing with traffic signals can already be very complex, let apart a large network containing urban, motorway and other types of roads. A number of different factors contribute to NM's complexity, and the list below is in no way exhaustive.

Chicken-egg Dependencies. There are several chicken-egg dependencies in the problem of NM development that greatly hamper quick progress in this area. One of them is the mutual dependency between equipment and network management theory. In order to develop NM theory, we need real-life examples. Such examples require adequate equipment installed in a given area. The roadside equipment that is available was not designed for the purposes of NM. But the investment in adequate equipment is high and should be guided by insight into NM theory. A comparable dependency can be found in the education of operators. NM will strongly depend on human operators in traffic management centers, simply because humans have many capabilities that are very hard or impossible to automate. These operators have to be trained. But as long as we don't know for sure how to do NM, it remains hard to train operators. Without trained operators, we don't get the real-life examples needed for theory development. It can safely be concluded that traffic operators play a crucial role in the development of NM, a role that is still often underestimated.

Measuring Effects of NM is Hard. For those cases in which we do have some degree of NM installed in real life, it turns out that it is hard to measure its effects on network performance. Such effects are inevitably statistical effects, averages over longer periods. They apply to many different traffic states (a specific approach to NM is likely to be more effective in one state than in others), which is a second reason why we need longer periods of measurement, in order to see some differentiation in the data for different traffic states. But networks change during longer periods, for instance due to road works. And also, traffic demand patterns change during longer periods. Both are reasons that make the results of one measurement difficult to compare or to combine with other measurements at different periods in time. More on this problem can be found in [11].

Legacy Systems. Systems for NM will inevitably consist for a large part of existing, legacy control systems. As mentioned before, these systems were not designed to function within an NM system, but in addition to this, it is often hard to connect with these systems. In practice, most of the effort of installing NM systems is spent on connecting to legacy systems, as experience with the SCM system mentioned above has shown. Often these systems are owned by different manufacturers, which may be competitors of the NM system manufacturer. The willingness to cooperate is therefore not always obvious.

Sensors and Actuators. However difficult it may be to connect with roadside equipment, in many cases one will have to cope with the absence of such equipment. The activity of NM is greatly complicated by the fact that it has to be mapped onto the existing equipment. It is always difficult to install extra equipment for purposes that are essentially experimental, not only because of the cost involved, but also because of the necessary permits, the interruption it may cause to traffic, privacy objections, etc. From the point of view of NM, the existing equipment is usually scattered more or less randomly over the area under consideration.

Simulation of networks is Hard. Traffic management research heavily relies on modeling and simulating traffic. The models and simulators currently available are not very scalable. They have difficulty to cope with larger areas, already for performance reasons. Moreover, models and simulators are often purpose specific, or at least have to be configured in a purpose specific way. In order to study effects of network management realistically, calibration data is needed, but the lack of real-life NM systems makes that such data is virtually non-existent. To make things worse, traffic itself has a strongly chaotic nature, due to the fact that it is strongly influenced by its environment, which contains many chaotic, unpredictable effects, so much so that the ”regular” situation is a notion in traffic management which is often used but equally often contested. Predictions based on simulation are most needed in dense traffic, but as mentioned above, dense traffic in a network happens to be the most complex, hardest case to manage or to simulate. Dense traffic in a large area is particularly sensitive to the chaotic influences from the environment. This chaotic behavior of traffic applies not only at very short time scales, but also on larger time scales, in which, for instance, demand patterns change for reasons outside of the transport domain.

5 The Approach to Developing Network Management

Just like the original chicken-egg problem, the problem of NM development will have to be solved in a very gradual, evolutionary fashion. Essential steps and corresponding milestones in the approach are:

Network Partitioning We need a way to partition a network into parts, such that the control problem for the network as a whole, can abstract from the control problem inside the parts. For purposes of scalability, this partitioning will have to be done recursively. In some approaches, a network is split up into a number of main arteries, each artery containing several junctions. Such split-ups are not area-oriented but artery-oriented. In our opinion, this approach is not a good idea. With such a split-up, it is obvious that one can do a further split-up of an artery into pieces, such that each piece contains at most one junction. If two arteries cross each other and share a junction, this would lead to two systems controlling one network element (the junction), which would have to be resolved by giving one of the two arteries priority over the other, which would then effectively be split up. In this way, one obtains an area-oriented split-up in which control is easier.

Control Framework. We need a control framework to organize the many units of control present in an NM system, in order to guarantee that control scopes do not overlap, and that each control unit is governed by only one parent system. A proposal for this has been made in [13]. More research is needed on the control of distributed systems.

Priorities. It is obvious that some parts of a network are more important than others, in the sense that congestion in important road segments has more impact than in less important parts (f.i.: a belt road is more important than a residential area). This plays a crucial role in network management which necessarily must be focused on keeping fluid important parts at the expense of less important parts. Therefore, an effective priority assignment to network parts is needed, which reflects the importance that network parts have and which can be used in control strategies.

System Architecture. NM will have to be supported by automated systems. Although still many details of effective network management are not yet clear, such systems have to be built, lest there will be no progress in NM theory development. Theory, systems, and operator experience will have to evolve together. Systems will have to cooperate, which can be facilitated by a systems architecture which, at the architectural level, explains how the traffic management theory can be expressed in monitoring and control systems and decision support systems for human operators.

Human Operators. Human operators will play a key role. Because of the chaotic nature of traffic, the activity of traffic management is more like stock trading than like controlling an automated production process with few unpredictable disturbances. The capabilities of experienced human operators in assessing traffic patterns and in responding to unpredicted situations with no precedents, are not so easy to automate. In the course of time, some of these capabilities will be automated, but on the other hand, the capabilities of operators will also be strengthened by better visualization of traffic states and better decision support. NM will remain a matter of humans + machines in the foreseeable future, thus operators should have strong involvement in the development process of NM.

Interoperability Standard. In order to make real-life deployment of NM systems feasible from the point of view of cost and effort, and also from the point of view of market reform, an open interoperability standard would be most welcome. Due to the many connections an NM system needs with both the local control systems it coordinates and with the neighboring NM-systems, such a standard should support both horizontal and vertical communication.

6 Key Issues in Network Management

In this section we will go further into a number of the key challenges mentioned in the approach above.

6.1 Abstraction and Network Partitioning

Abstraction and Network Partitioning both aim at reducing the complexity of NM. There is an obvious candidate for abstraction, which is also a basis for network partitioning. This candidate is the property that, when considering a subnetwork S, only the boundary, which consists of a integer number of entries and exits of S, is of relevance to the rest of the network. All internal behavior can be ignored, only what happens on the boundary counts. This abstraction principle is also reflected in the so-called network fundamental diagram ([2], [4], [1]) which relates total flow through the boundary to the number of cars inside the subnetwork. Although mathematically attractive, such a strong reduction to a single number maybe somewhat too strong. It holds only if some degree of homogeneity can be assumed for the network, which in a rectangular streets and avenues network may be a sensible assumption, but for European cities is not very realistic. There are other, more informative quantities, such as OD-matrices for flow and for travel time, that are still pure boundary quantities but contain far more information, and therefore make fewer assumptions about the subnetwork involved. This abstraction principle implies a way of partitioning a network: namely such that boundaries between parts are always cross sections ('points') of carriageways in one driving direction. This partitioning can be applied recursively, resulting in a tree-structure split-up of the network, similar to (and partially coinciding with) the political partitioning of the surface of the earth [8] into countries, provinces, districts, etc. The big challenge however is how exactly to do this for the purpose of effective NM. A number of heuristic rules can be given, such as the high cohesion, low coupling principle and the rule that boundaries should be positioned in quiet areas. In the examples that we know of, the split up has been done by hand, but this is a tedious and error-prone job, and it makes the split up not very flexible. Some people suggest that the partitioning should be traffic state dependent. So for special events or sudden accidents, it should be possible to adapt the partitioning on the spot. For these reasons, it would be most welcome if effective partitioning of networks can be automated. There is some research on this subject [9], [6], [3], [8], which among others points out that many network algorithms tend to be NP-hard, and that the network structure has a big influence on its performance, but a convincing breakthrough in this area is still to be found.

6.2 Priorities

However obvious it may seem that some parts of a network are more important than others, it is still largely unknown how to assign priorities to network parts, and how to use these priorities in control strategies. In addition, priorities are also assigned to kinds of traffic, such as public transport. Both types of priorities will play an indispensable role in future NM, but still a lot of research is needed on the topic of finding effective and implementable algorithms to assign priorities to network parts.

6.3 Interoperability Standardization

An interoperability standard is needed to make deployment of sizeable NM-systems feasible. Here again, there is a chicken-egg dependency. Such a standard should be able to express what one control system would like to request from another one. As long as NM is still not well developed, this remains only very partially known. A recent initiative for an interoperability standard for traffic control systems, focusing on NM systems and connections between NM and local control systems, is described in [12]. This approach harnesses the extensibility of XML to solve the chicken-egg dependency in this challenge.

7 Conclusions

Network Management for road traffic is badly needed in order to cope with our increasingly congested road networks, but its development is slow and its current level of deployment in practice is still limited. The slow development is caused by the inherent high complexity of the problem and the chicken-egg dependencies between the various components of this activity, such as between traffic management theory and the control systems needed for NM. Important components in the approach that we propose in this paper are: real-life pilots, algorithms for network partitioning and priority assignment, architecture and standardization for the systems development needed to support the NM activity, and strong involvement of operators in the development process.

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