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Importance of spillback modeling in assessing ITS

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***Abstract*– This paper discusses the importance of spillback modeling in assessing the impacts of Dynamic Traffic Management. Specifically, the paper compares the influence of route information in a simulation with spillback and without spillback modeling. The considered case entails an evacuation of a city (circa 250.000 cars). The results indicate that in the non-spillback simulation, the network performance is indifferent for route measures, whereas in the more realistic simulation with spillback, there are differences between different types of information provision. It is concluded that a traffic model without simulation of spillback not only gives an underestimation of evacuation times – which is obvious –, but more importantly it completely underestimates the effect that can be obtained by route information. The travel time gain according to the non-spillback model is 1,8%, whereas the spillback model predicts 17% reduction of travel time. It is also shown that for the case at hand, the congestion caused by spillback can be avoided by providing appropriate information.**

I. Introduction

It is known that for a valid representation of a traffic situation and thus for an adequate prediction of the impact of Dynamic Traffic Management (DTM) measures, all relevant processes in traffic operations (route choice, destination choice, flow operations, etc.) need to be represented with sufficient validity. One of the important processes in this context is traffic congestion. Besides a good prediction of the delays caused by a bottleneck, a good description of the congestion dynamics will enable a valid prediction of the time at which spillback occurs and the extent of its impact. Recall that spillback is the phenomenon that a queue on a downstream link affects the possible output volume of the upstream link or links connected to it. Although there are (theoretical) situations conceivable in which spillback is not important, in many cases spillback will be the cause of a large part of the collective delays experienced.

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Still, many modeling approaches describing network flow dynamics do not correctly capture congestion dynamics, especially the spillback and consequent secondary congestion [1]. It is unclear to which extent simulators without representation of spillback can sufficiently estimate delays in oversaturated traffic networks and can assess the effectiveness of measures, such as route information and guidance.

This paper deals with the prediction of the influence of route information and the ability of dynamic network models to assess that correctly. For this purpose a network traffic simulator has been developed in which the spillback can be switched on and off.

Route information is likely to have the most profound effect when the traffic conditions are different from usual, and when the number of possible user choice interventions is the largest. In particular in an evacuation situation, traffic demand is much higher than what the network was designed for. Furthermore, compared to an everyday situation in which the destinations are largely fixed (depending on the demarcation of the network), in an evacuation situation, the destination choice is of less importance as the goal is to get out of a region as quickly as possible. As there are only a few exit points, shelters can be placed after each of them to guarantee a save place for the evacuees at each exit point. Information about the traffic conditions will therefore have a bigger influence on the choice of a destination than in everyday traffic.

This is one of the reasons why in this study, an evacuation situation was considered. Rotterdam, a city in the Netherlands with around 600.000 inhabitants, has been chosen. To assess the possible impact of route information or guidance, two driver assistance devices were considered. The simulated devices either:

1. provided information on the shortest path to a certain destination, taking into account the traffic conditions, or
2. indicated the travel times for the different exit point of the affected area.

The remainder of this paper shows the importance of a correct simulation of congestion dynamics effects in evaluating the effects of these route information provision approaches. Note that although the effects of information provisions have been researched in the past, research on the importance of the way in which congestion is modeled and ITS measures are limited.

In the next section, an overview of the state of the art in traffic flow modeling is given. Then, the scenarios used for simulation are mentioned in "simulation scenarios". In the section "Traffic Operations Modeling Approach" the working of the simulation program is explained in detail, then, in "Travel Choice Modeling and Information" the route choice is explained. In the next chapter, a description of a case study follows; the results thereof are presented in the next section. This is followed by the section "discussion" and the last section in which the conclusions are presented.

II. Congestion Modeling Approaches

In this section, we briefly discuss traffic modeling approaches, in particular focusing on the extent in which they can (principally) capture spillback.

Considering microscopic simulation models, it is easy to understand that the extent in which the congestion dynamics are correctly captured depends on the model specifications (car-following model, lane-changing model). In theory, however, spillback can be correctly represented since cars are represented as elements that occupy a finite space and can only move if the space in front is free.

With respect to the network evacuation studies, simulations are generally performed with macroscopic models due to computational restrictions [2]. In many cases, vertical queuing models are used implying that spillback cannot be captured. Also using horizontal queues will not enable correctly capturing the congestion dynamics, as is illustrated with the following simple example considering a situation in which traffic is temporally stopped (for instance by a traffic light or an incident blocking the road).

In Fig. 1, two space-time diagrams are drawn for this situation; the one (left) describing the (incorrect) predictions made by a horizontal queuing model, and the other (right) by application of shockwave theory. At the upper dashed horizontal line, a traffic light is located. The lower dashed horizontal line indicates a crossing to a next link.

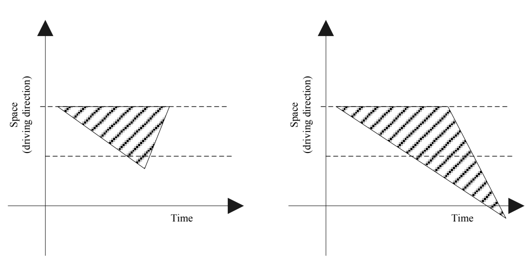

Fig. 1 Traffic state dynamics of a traffic light in a space-time diagram

The left figure shows that when the traffic light turns red, a queue builds up; the tail of the queue moves upstream (shaded triangle under the dotted line). When the traffic light turns green, the queue dissolves at the *head* of the queue, while the queue tail still moves upstream. In comparison, a horizontal queuing model (left figure) would predict that the tail of the queue moves *upstream* when the queue is dissolving, while the head of the queue remains stationary. Note that in the correct model of the right figure, the duration and extent of the spillback are much more than in the incorrect model of the left figure.

As can be seen from the example above, shockwave theory is needed to describe the first-order dynamics of traffic congestion. This in general holds for general continuum flow modeling approaches (LWR model, Payne model, etc.). Second-order phenomena, including spontaneous phase transitions (e.g. from synchronized flow to wide moving jams), are not captured correctly. Although these second-order phenomena will have an impact on the network-wide traffic operations, they are neglected in the remainder of the paper.

III. Simulation scenarios

Our objective is to study the change in the evacuation times in scenarios with different types of information provision. Secondly, we assess the reduction in evacuation speed with two simulations, one without spillback and one with spillback.

Regarding the level of information provided to the users in the simulation, we consider three levels of information provision:

1. The case without information provision.
2. The shortest route to the normal (pre-evacuation, fixed) destination is given by an in-car device, adjusting the route guidance based on the actual traffic situation.
3. The in-car system provides the nearest destination, and the shortest route to it, based on the current traffic conditions.

Table 1 gives an overview of all considered scenarios.

Table I: the six simulations to be compared

No spillback, no information N1	Spillback, no information S1
No spillback, route information N2	Spillback, route information S2
No spillback, route and destination information N3	Spillback, route and destination information S3

IV. Traffic Operations Modeling approach

Spillback implies that the traffic jam may reduce the flow on the upstream link. A queue will grow and its tail may (partially) block upstream intersections, off-ramps or weaving sections. This process often occurs in traffic in saturated and nearly saturated networks, and will be modeled using a first-order macroscopic traffic flow model.

We used a simulator developed by the TU Delft for this study. This is also used for other research [3]. It is a macroscopic simulator. Net network is split into links and the links are split in cells which length can be traversed in 15 seconds if traveled at free flow speed, so a typical cell length is several hundreds of meters. The basic principle of flow modeling is a Godunov scheme [4]. Based on a density of a cell, there is a certain demand to the next cell, according to a triangular (Daganzo) fundamental diagram[5]. The supply of the next cell depends on the density in that cell; that also is based on the fundamental diagram. The effected flow from one cell to the next, is the minimum of supply of the upstream cell and the demand of the downstream cell. The average speed can be calculated by dividing flow by density.

In case of spillback modeling, queues can grow over links. When a queue grows and its tail reaches the end of a link, the supply is less than the demand and the cars on the most downstream cell of the upstream link can not flow to the next link.

In the cases the spillback is switched off, the supply of the most upstream cell of any link equals capacity, independent of the density in the cell. Thus, the traffic jams on a link do not influence the inflow and thus not the flow to other directions, which is the requirement for not modeling spillback.

At the beginning of the simulation, all demand is put onto the virtual origin links. The rate at which the simulation network is loaded with vehicles is determined by the capacity of the links connected to the origin link.

Regarding the route choice and destination choice modeling, we explicitly consider the impact of information provision systems. To this end, we assume that the current state of the network is fed back to the drivers who decide which route and destination is optimal based on this information. This means that road users are modeled as completely free to choose their route and exit point. The wish of the people to leave the dangerous area as quickly as possible leads to the assumption that people take the quickest route that they know to leave the area; their knowledge is assumed to be based on the every situation.

We will investigate whether spillback in simulations is necessary in evaluating the advantages of dynamic route and destination information in an evacuation problem.

V. TRAVEL CHOICE MODELING AND INFORMATION

If no information is provided, the route choice is computed with a probit model based on free flow traffic state. Road users know that congestion is to be expected, but as they do not yet know where, they base their route choice on free flow times. A preference factor is used to indicate driver preference for motorway roads over urban roads. To obtain a reliable result from the stochastic simulator, twenty paths were taken to represent the total drivers population.

The guidance provided to the drivers by the in-car information system is based on the current traffic state. Also these routes were determined by the probit model. In scenarios with route information, every 15 minutes, a new path choice set is generated, based on the actual traffic speeds. To prevent unrealistic swapping of routes every 15 minutes, only half of the travelers get a new route assigned based on the new distribution, the others will stick to the old ones during the next 15 minutes. The group of travelers sticking to the routes of the last period changes every interval, so it should not be interpreted as a penetration rate of a route information device.

The chosen percentage of 50 is an assumption; both smaller and bigger parts can be argued. Commuting people usually have a habit to take a certain route. Even when there are longer queues, they will probably stick to their usual routes. If people are unfamiliar with the routes and the traffic, in a initializing process for a certain daily trip, they will respond more to queue length information [6]. We applied the model for an evacuation case. In an eagerness to leave quickly, it can even be argued that all people will take the shortest route that is announced. It is beyond the scope of this research to find the correct values. We therefore arbitrarily choose to make the trip choices of half of the travelers subject to rerouting.

In the scenarios with rerouting, the number of route choices for the probit model can be reduced compared to the fixed routes because it only applies for half of the population and for a limited time. The number of route computations was reduced from twenty to eight, which also affected the computation time positively.

In an evacuation leaving the dangerous area is more important than leaving it at the preferred side. Therefore, the initial destination choice is based on the travel time to each of the destinations. Thus, in the simulation, the pre-trip distribution of the evacuees over the different destinations is based on the free flow times. For the distribution, a logit model is used. The less time it costs to reach a destination, the bigger the part of the evacuees take that as destination.
In the scenarios with destination information, the interval for a destination update is also 15 minutes. The information is based on travel times derived from the actual speeds. A new distribution of destinations is created with a logit model. As in the route choice, each period half of the people will stick

to their old destination to prevent unrealistic swapping of destinations.

VI. CASE STUDY DESCRIPTION: EVACUATION OF ROTTERDAM

To show the impact of routing measures, we choose a scenario for which the demand is much higher than the demand the road network is designed for. The more queues there are, the more route information can improve the situation. Moreover, an evacuation case lets the possibility to influence the drivers in their destination choice. In an evacuation, the main demand of the travelers is not a trip to a certain destination, but a trip that brings them outside the affected area.

The region around the city of Rotterdam is used as example for the simulation (see Fig. 2a). Both motorways and urban roads are modeled. Only the motorway exits out of the area are considered as exit points as their capacity is much larger than that of urban roads. There are five motorway exit links out of the region, indicated by arrows in Fig. 2b. 44 origins are modeled. The modeled network consists of 468 links (2b). Calibration is done qualitatively on a working day morning peak period.

The sum of the arrivals at each of the 5 exit points is the measure of the performance of a scenario in the simulation of this evacuation.

The network is empty at the start of the simulation. Of course, this is not conform reality. There is, though, a sudden change of the demand at the moment of a call for evacuation. This is the first reason not to include a "warm up period" before starting a measurement or applying statistics.

As the scenarios start to differ in congestion, during first period, there is not much difference in traffic flows between the different scenarios. The main goal is to compare the different scenarios. So, the necessity of setting a warm up period is less than in other simulation studies. That is the second reason why we choose to do this study could do without a warm up period.

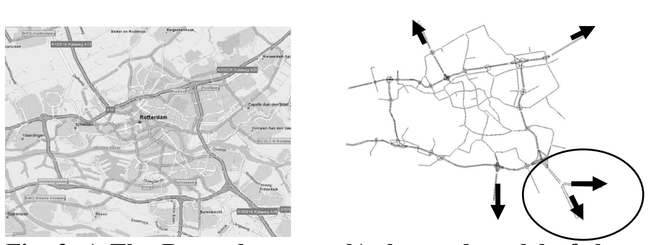

Fig. 2 a) The Rotterdam area b) the used model of the network

For the region with around 600,000 inhabitants, we assume that 239,000 cars are to be evacuated. Cars are proportionally assigned to living and full-time job locations, which in turn are used to determine the closest origin location.

The results of this study are only indicative for a real-life evacuation time of the Rotterdam area due to the coarseness of the input data. Furthermore, a direct start of the evacuation on an empty network is assumed and the exit points are considered to have an unlimited throughput capacity or dispersion capacity. For the objective of this paper, however, the modeling is sufficiently accurate.

VII. RESULTS OF THE CASE STUDY

The arrivals are plotted in Fig. 3 (no spillback) and Fig. 4 (spillback). On the vertical axes, the cumulative number of cars is plotted that has left the network, in an absolute number. On the horizontal axes, time is plotted. Naturally, both in the simulation with spillback as in the situation without spillback, that number increases tot the total number of cars that is evacuating out of the region, 239.000.

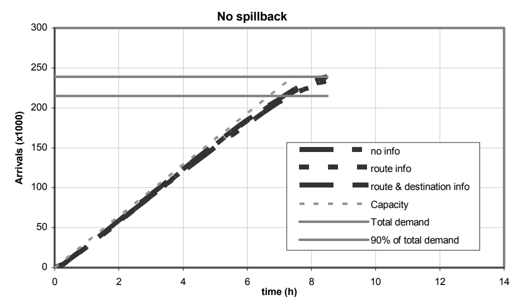

Fig. 3: Arrivals outside evacuation area in time in different information scenarios; results from a simulator without spillback. Also the maximum outflow is indicated

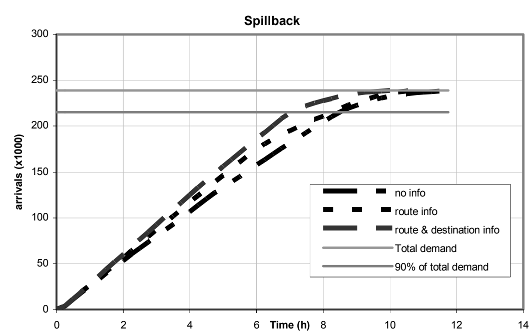

Fig. 4: Arrivals outside evacuation area in time in different information scenarios; results from a simulator with spillback

For each of the three different scenarios, a line indicates the number of cars that has arrived the safe area after some time. The steepness of the line is the arrival rate of the vehicles.

The theoretical maximum outflow rate is the summed capacity of the exit links. But as two of these exit links are connected to the rest of the network by one shared link. This concerns the links in de ellipse in 2 and it enlarged in Fig. 5; also the capacities of the links are indicated.

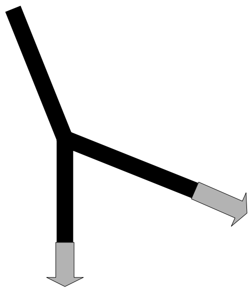

Fig. 5 Enlarged part of two of the exit links; the road capacity of the upper one is 11,200 veh/h; the others have capacities of 6,600 and 8,900 veh/h.

The capacity of the two exit links exceeds the capacity of the one upstream link: 6,600 veh/h + 8,900 veh/h > 11,200 veh/h. Therefore, the maximum outflow capacity is restricted by the one upstream link.
The sum of this capacity and the capacities of the other exit links is 32,200 vehicles per hour. This total capacity is used for the calculation of the shortest possible evacuation time, indicated in Fig. 3. The final split of travelers over these two links is not important for the results as there is no congestion downstream of the junction and so; all travelers will quit the evacuation zone in equal travel times. The split fraction used is determined by the probit model.

VIII. DISCUSSION

For this simulation study, it turns out that the simulation without spillback cannot make a distinction between the different routing strategies (Fig. 3). In the case of a more realistic, spillback simulation model is used, it can be concluded that providing guidance has a positive effect (see Fig. 4).

In line with our expectations, the scenario where both paths as destinations are updated based on the traffic situation is the most efficient, followed by the scenario in which the destinations are fixed and the paths gets updated.

In the case people change their routes and exit points, almost the same outflow rate is obtained as in the non-spillback case. That rate almost equals the outflow capacity. If, however, people do not change their path or their destination, internal congestion yields that not all exits get a demand equal or over their capacity. Simply put, there are too few cars arriving at these exit links.

The scenario in which people change their paths but keep their destination fixed (scenario S2), had a performance in between the performance of S1 and S3. As in this scenario only partially information was given (compared to scenario S3), it was expected that the evacuation result would be in between the scenario without DTM measures and the scenario with full DTM measures.

During the first hours of evacuation, the scenario with only route information (S2) appears to keep up with the scenario with both path update and destination information (S3). After these initial hours, congestion on the main routes and on the alternative routes builds up and people are hindered by others heading to an other direction via a more congested path,. This congestion reduces the demand at the beginning of the upstream links to less then their supply: the arrival rate decreases.

The findings can be illustrated with the time needed for 90 % of the 239.000 cars to flow to a save area. These are listed in Table II.

Table II Evacuation 90% complete: evacuation times and spread for different information levels

	With spillback	Without spillback
No information	8h 14m	7h 06m
Route information	7h 58m	7h 00m
Route & destination info.	6h 50m	6h 57m
Gain due to information	1h 23m	0h 08m

Therefore, models that include modules that update path or destinations should have spillback effects incorporate, for a correct assessment of the route and destination guidance.

In future research, we aim to implement driving behavior as in calamities, which might differ from everyday driving. Secondly, the percentage of vehicles that will change their route is now taken fixed at 50%. Both the research to the actual values of this percentage as the consequences of varying it will give further insight in the subject of this paper. In the further future, both route choice and driving behavior can be modeled on a microscopic scale; in such a way, also individual differences for destination and activity choice can be taken into account.

IX. CONCLUSIONS

The paper considers the impacts of simplified models not including spillback on the assessment of the effects of ATIS. To investigate the effects, a case study was considered in which a regional sized network was heavily loaded and in which the information provision could easily lead to a change in destination. An evacuation scenario was used as case study.

We simulated an evacuation twice: with and without modeling queue spillback to the other side of junctions. In both cases, we evaluated three scenarios of influence of dynamic traffic management (1 no information, 2. information for route choice, 3. information for route choice and destination choice). We analyzed the number of vehicles that have arrived a save exit point as a function of time.

In the case without spillback there are no significant differences between different scenarios for route information provision. Updating a path or updating the destination does not change the performance of the network in the model without spillback. In the more realistic case with spillback, both these measures of dynamic traffic management improve the evacuation speed.

The conclusion is that it is unrealistic to assess the performance of information providing devices based on a non-spillback simulation.

The other conclusion is that the congestion caused by spillback can be avoided by providing route and destination information to the road users.

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