ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Department of Mathematics

Semester Project

Rules and algorithms for an Advanced Traffic Management System

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Part I

Introduction

Chapter 1

Abstract

Heavy congestion on Route 9 in Amherst area in Western Massachusetts is getting a bigger and bigger problem every year. In order to manage traffic during the rehabilitation of Coolidge bridge over the Connecticut river, the IBI Group is developping the design of an Advandced Traffic Management System. Our task is to develop a set of rules permitting the traffic operator to react on the following traffic situations (and combinations):

- An emergency vehicle coming from the UMASS-Amherst region is trying to reach Cooley-Dickinsson Hospital situated east of the bridge in Northampton;
- An accident occured on the bridge;
- Congestion during peak hour.

To inform the traffic operator on the current situation, there are two cameras installed on the bridge; one for each traffic direction. The traffic operator has the possibility to react on the traffic using variable message signs and traffic control signals.

Our simulation will be based on the Free Quad Map issued on Dec. 07, 1998 by the Executive Office of Transportation and Construction, Mass Highway and traffic counts conducted by the Pioneer Valley Planning Commission in 1997 [7] as well as information on signal timing on three intersections provided by Ammar Kanaan (IBI Group).

Chapter 2

Methodology

2.1 Hypotheses

To simulate the traffic system, we will use EMME/2, a static simulator based on user equilibrium. Such a simulation is based on the following hypotheses:

- Each network user is perfectly informed of the current traffic situation;
- Each user will take the fastest path from his origin to his destination (time used for one arc in the network may depend on the traffic-flow (vehicles per hour) on that arc and user characteristics, but *not* on other arcs);
- Each user will start from his origin and arrive at his destination within the time of simulation (one hour);
- The network characteristics will not change within the time of simulation (physical dimensions stay fixed);
- The Origin-Destination matrix is known (number of users for every O-D pair);
- The Volume-Delay function on each arc of the network is known (travel time on arc for a given flow).

In reality O-D matrices are rarely known but they can be estimated using traffic counts by several methods. We will use a gradient based method developped by Spiess [3]. This approach is formulated as a convex minimization problem where, by following the direction of steepest descent, it is ensured that the original O-D matrix is not changed more than necessary (as we didn't have any other information than traffic counts, we filled the original matrix with ones). The objective function to be minimized is a measure of distance between observed and assigned volumes. At each step of the algorithm the current O-D matrix is assigned to the network, the objective function as well as its gradient is calculated and the new O-D matrix is obtained by translation along the direction of maximal gradient.

2.2 Volume-Delay Functions

The Volume-Delay functions we will use in the simulation are the ones used by the Bureau of Public Roads (BPR):

$$t_a(\omega) = t_a^0 \left(1 + \alpha \left(\frac{\omega}{c_a^p} \right)^{\beta} \right)$$

where a is an arc in the network,

ω is the flow on a,

$t_a(\omega)$ is the travel time on a for a given flow,

t_a^0 is the zero-flow travel time on a (distance/design speed),

c_a^p is the "practical capacity " of a (3/4 of the actual capacity).

We will use the parameters $\alpha = .15$ and $\beta = 4$ as proposed by C.J. Khisty [1]. On links we will generaly set the capacity to 2000 cars/h per lane [1, 6] (exceptions see chapter 5). On signaled intersections capacities will be calculated according to the procedure in the Highway Capacity Manual [6], on unsignaled intersections according to Blunden's Method [1] (conflicting traffic being estimated from a first assignment without delay).

2.3 User Equilibrium

For the assignment of the traffic demand (O-D matrix) to the network, the simulator EMME/2 uses an iterative algorithm converging to the user equilibrium. This equilibrium is reached when no traveller can improve his travel time (being a function of flow on the arcs of the network) by changing routes. Every user will therefore travel along the shortest paths.

The algorithm used in EMME/2 is the Linear Approximation Method by Frank and Wolfe [2]:

0 Initialization:

Initial solution v^0 is obtained by an all-or-nothing assignment of demand on shortest paths computed with arc costs (times) at zero flow $s^0 = s(0)$;

$k = 0$ (iteration count).

1 Update Link Costs:

Link costs are computed according to current flow $s^k = s(v^{k-1})$;

$k = k + 1$.

2 Descent Direction:

y^k (virtual flow) is obtained by an all-or-nothing assignment of the demand on shortest paths computed with arc costs s^k.

3 Compute Optimal Step Size:

Find λ^k that solves

$$\min_{0 \leq \lambda \leq 1} \sum_a \int_0^{v_a^{k-1} + \lambda(y_a^k - v_a^{k-1})} t_a(\omega) d\omega$$

where a represents the arcs and $t_a(\omega)$ is the Volume-Delay function on arc a.

4 Update Link Flows:

$v^k = v^{k-1} + \lambda^k (y^k - v^{k-1})$.

5 Stopping Criterion:

If $\mid s^k v^{k-1} - s^k y^k \mid < \epsilon$ then $v^* = v^k, s^* = s(v^k)$ and **stop** (total travel time not significantly (ϵ) different from total travel time on shortest paths),

if $k \geq N$ then $v^* = v^k, s^* = s(v^k)$ and **stop** (maximum number of iterations is reached),

otherwise return to **1**.

Part II

Modelling

Chapter 3

Network

The region we considered for our model is situated in the triangle of Sunderland, Northampton and Amherst/UMASS (University of Massachusetts). As this region is quite large and detailed information on the traffic situation were only partially available (traffic counts on a few arterials only), we considered almost only major arterials, which we modelled at a quite low level of detail. We concentrated our attention on the three intersections that can be controlled by the traffic operator. In EMME/2 an intersection is a set of links (arcs) connecting the arcs of the network starting or ending at the node of the intersection.

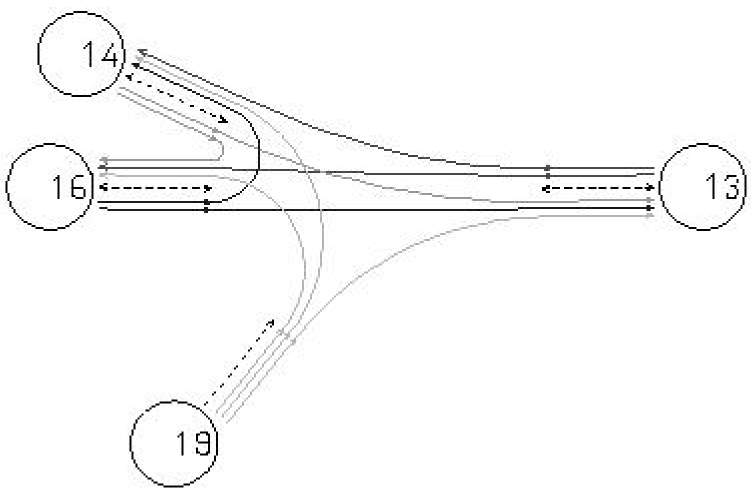
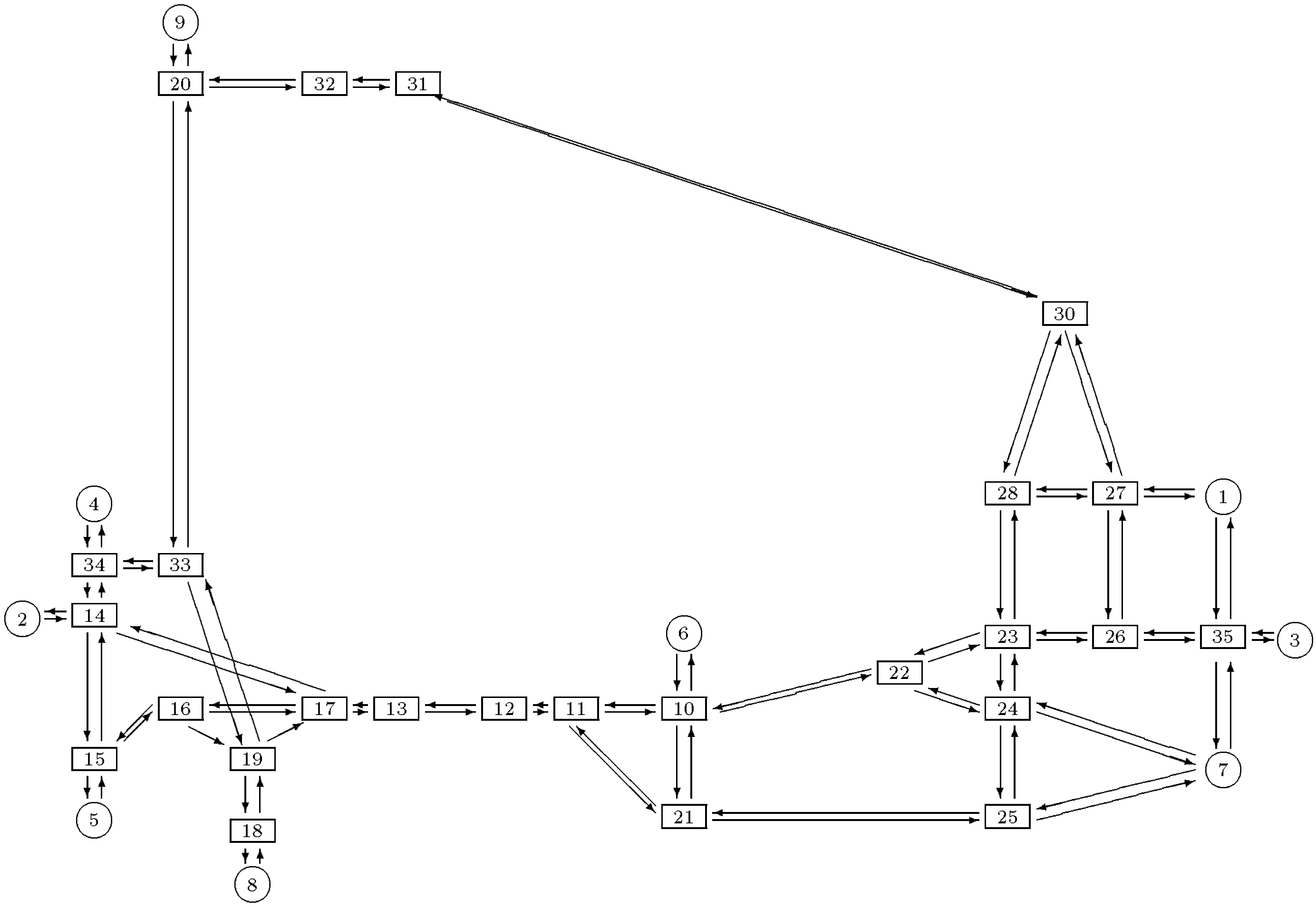


Figure 3.1: Example: Intersection Node 17

The following figure shows the bare network (intersections aren't detailed):



Centroids (points of departure and arrival):

1	UMASS
2	Cooley-Dickinsson Hospital
3	Route 9 east of Amherst
4	Route 10 north of Northampton
5	Route 10 south of Northampton
6	Hadley
7	Amherst
8	Interstate 91 south of Northampton
9	Interstate 91 north of Sunderland

Roads and bridges:

Route 9:	15 - 16 - 17 -. . . - 10 - 22 -. . . - 35
Route 116:	20 - 32 - 31 - 30 - 27 - 26
Interstate 91:	20 - 33 - 19 - 18
Bay Road:	11 - 21 - 25
Damon Road:	14 - 17
Mill Valley Road:	22 - 24
Maple Street:	28 - 23 - 24 - 25
Coolidge Bridge:	13 - 12
Sunderland Bridge:	32 - 31

Figure 3.2: The Network

Chapter 4

Scenarios

As traffic varies during the day, we considered two main scenarios corresponding to am and pm peak-hours. Based on those two scenarios we estimated the two corresponding O-D matrices (Spiess method, see 2.1) which we then used in the following sub-scenarios:

4.1 Intersection Signals

To model an emergency vehicle coming from the UMASS-Amherst region we changed the signalization phase-plan for 3, 6, 9, 12, 15, 18, 21 and 24 minutes (as average travel time between intersection 11 and the end of the bridge is less than 7 minutes, the four last scenarios aren't usefull in this context but we only noticed this fact after having already done the simulation; see chapter 6).

In the new phase-plan[1], westbound traffic on Route 9 would get a red light at the Bay Road intersection (node 11) as well as traffic from Bay Road while traffic eastbound would get green.

At the Damon Road - Route 9 intersection (node 17) traffic on the I-91 off ramp crossing Route 9, on Damon Road turning left and on Route 9 eastbound turning left into Damon Road would get a red light; all other movements would get green.

At Damon Road - Route 10 intersection (node 14) all traffic on Route 10 (north- and southbound) would get red (except for right turns); all other traffic would get green (except for left turns).

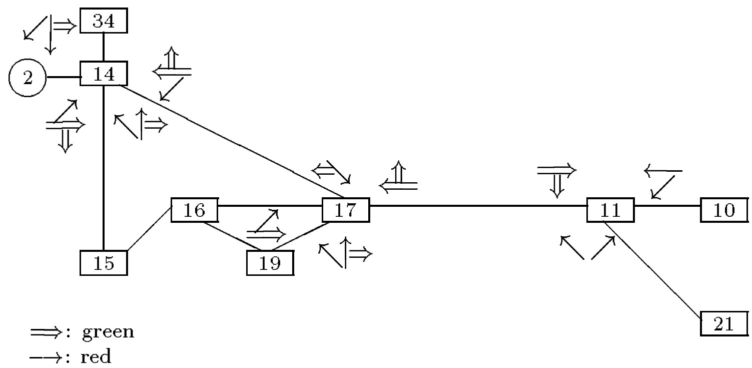


Figure 4.1: New Phase-Plan

[1]proposed by the IBI Group

To model this situation we changed the V-D functions on the links (turns) of the intersections 11, 14, 17 as follows:

- on green turns:

$$t_a(\omega) = t_a^0 \left(1 + (1-g)\left(\alpha\left(\frac{\omega}{c_a^p}\right)^\beta\right) + g\left(\alpha\left(\frac{\omega}{\tilde{c}_a^p}\right)^\beta\right)\right)$$

- on red turns:

$$t_a(\omega) = t_a^0 \left(1 + \alpha\left(\frac{\omega}{c_a^p}\right)^\beta\right) + T\frac{g^2}{2}$$

where a is an arc on the intersection,

ω is the flow on a,

$t_a(\omega)$ is the travel time on a for a given flow,

t_a^0 is the zero-flow travel time on a (distance/design speed),

c_a^p is the "practical capacity " of a for the "normal" phase-plan,

$\tilde{c}_a^p$ is the "practical capacity" of a for the changed phase-plan,

g is the ratio of the time we changed the phase-plan versus T,

T is the time of simulation.

The green turns formula is based on the change of capacity during gT. We derived the second formula by assuming that the average travel time would increase by $Tg^2/2$; g being the probability for a user to arrive at the intersection during the changed phase-plan (red!), $Tg/2$ being the average waiting time for a user arriving uniformly during the changed phase-plan.

4.2 Information

As the traffic operator will have some freedom with the positions of the PVMS (Variable Message Signs that can be moved) and with the message he will write on it (and on the VMS: Variable Message Signs that can't be moved) we have tested three different rates of information: 0% if no user is informed on the current traffic situation, 50% and 100% if every user is informed (this last case is the "normal" case). We modelled this by first assigning 100%, 50% and 0% of the traffic as "background traffic" (this traffic would follow the "normal" paths); then do a new assignment for the rest (the informed users).

Obviously, this scenario only makes sense in combination with one of the others.

4.3 Incident on the Bridge

This case is the most simple to simulate (using EMME/2): If the incident blocks one lane of the bridge (no matter which it is) there would be two remaining lanes for the vehicles to cross and the only change we had to make was to remove one lane westbound on the bridge. We also considered the case of 2 blocked lanes; we modelled this by putting 0.5 lanes in each direction on the bridge (the one remaining lane would be used alternatively in each direction).

4.4 Combinations

As several of the situations above might happen at the same time, we considered the following combinations:

- the three levels of information in combination with four cases of signalization;
- the three levels of information in combination with four cases of signalization and the two incident situations.

Chapter 5

Problems and Limitations of the Model

As in every simulation, a few simplifying hypotheses had to be made (see chapter 2). The first one (each user is perfectly informed) isn't as far from reality as one might think (in the "normal" scenario; in the other scenarios we tried to model lack of information by combining them with two information-scenarios). After several weeks without major changes to the actual traffic situation (fluctuations being more or less the same every week-day), local users will know which are the best paths. Nevertheless, in an area with lots of tourists (users that won't stay for several weeks) this might be a major problem. In our case though the only roads tourists are bound to use (reasonable alternatives) are Interstate 91 (north - south direction) and Route 9 (east - west); roads that are used by local users as well.

As there are no scenic drives in the region, the hypothesis that people use the shortest paths is reasonable (second hypothesis).

Considered the size of our network, the third hypothesis is justified without problem (travel times actually are below 30 minutes).

For the signalization scenario, the fourth hypothesis causes a serious problem: Our simulation consists in a mean of two signalization situations, thus creating an average flow. In reality, the traffic operator can't inform all users; this would create queues in front of traffic signals, a fact that can't be simulated in EMME/2 at all. Moreover the average flow calculated by EMME/2 doesn't correspond to the real average flow as the queues discharging create a flow at capacity just after the phase plan returns to "normal" (as a vehicle can discharge from the queue at any moment if there is available space on the street ahead, vehicles will travel at capacity-flow on that street).

With the Spiess-method, we calculated an O-D matrix which we believe to be quite accurate for the O-D pairs that create traffic on arcs on which we have traffic counts[1]. For the other O-D pairs (like 9 - 8 or, at first 9 - 1) the O-D matrix obtained is clearly wrong (demand = 1). This clearly is a serious limitation of our model (though not having any counts on Interstate 91 only decreases demand between centroids 8 and 9 and has little impact on the rest of the network as we have counts on off- and on-ramps in Northampton), especially for Route 116: As we didn't have any traffic counts there was only a flow of three vehicles per hour in each direction. Route 116 is an important alternative to Route 9 (the focus of our simulation) and should be modelled as close as possible to reality. We asked therefore Ammar Kanaan for any traffic counts on Route 116. He furnished us

[1] Only drawback: Demand on 1 - 2 equals demand on 3 - 2, something we think is wrong but is a consequence of not having any traffic counts on either 3 - 35 or 1 - 35.

with a rough estimation of 13000 vehicles per day (total in both directions). We compared this with similar data [7] and derived a flow of approximately 520 veh/h in each direction at peakhour. As these counts were derived in other conditions as the ones conducted by the Pioneer Valley Planning Commission [7], results concerning traffic changes on Route 116 should be used carefully.

The two further serious problems we encountered are the following::

Travel times between UMASS and Northampton (1 - 2) are supposed to be around 20 minutes in the current situation. When we first conducted the simulation with EMME/2, we got travel times of about 10 minutes. What went wrong? The most probable explanation is that we didn't model intersections and (most important) traffic lights that do exist but on which we have no information. To get a more accurate model, we decreased capacity on the links we assumed[2] to contain signaled intersections (16 - 15 - 14 - 17, 11 - 10 - 22 and 11 - 21 - 10) to the same value per lane as on the Bay Road - Route 9 intersection (node 11). This increased the travel times by two to three minutes. The fact we hadn't yet considered was congestion due to queues before traffic lights. These would decrease capacity on arcs just before lights. We know that traffic westbound on Route 9 at the Bay Road - Route 9 intersection (node 11) has a capacity of approximately 1150 veh/h whereas traffic counts on Route 9 near the Mill Valley Road intersection are about 1550 veh/h. This gives us a surplus of 400 veh/h. Therefore we further decreased the capacity of arcs before (assumed) signaled intersections by 400 veh/h, getting travel times of about 20 minutes.

The simulation results (based on **average** V-D functions) we obtained, indcate that the **average** flow on the bridge doesn't change for reasonable phase-plan modifications (see chapter 6). We therefore couldn't derive any conclusion on optimal phase-plans by this method. The final conclusions are based on the following (rough) reasoning:

- We konw the capacity of intersection 11:

$$c_{int}(r) = c_{int}^0(1 - r)$$

  where r is the ratio of the time we changed phase-plan versus the time of simulation and c_{int}^0 is the capacity of the intersection without changing phase-plan.

- The flow after (eastbound) the intersection is lower or equal to this capacity. As explained before this flow will probably reach capacity.

- We can therefore calculate the time the ambulance uses on the bridge in function of the ratio of changed phase-plan time r:

$$t_{br}(r) = t_{br}^0 \left(1 + \alpha \left(\frac{c_{int}(r)}{c_{br}^p}\right)^\beta\right)$$

- This function can be inverted, thus giving the ratio r in function of the time one wishes the ambulance to use on the bridge:

$$r(t_{br}) = 1 - \frac{c_{br}^p}{c_{int}^0} \left(\frac{1}{\alpha}\left(\frac{t_{br}}{t_{br}^o} - 1\right)\right)^{\frac{1}{\beta}}$$

[2]Using MapQuest [8] we got more detailed maps.

Part III

Results

Chapter 6

Simulation Results

For each combination of scenarios as described in chapter 4, we calculated congestion (total travel time of every user) and stored the travel time used on the bridge. In Appendix A, this results are reported in tabulated form.

As we can see in the following figure travel time on the bridge doesn't change for modification of the phase-plan up to 12 minutes, which means that flow on the bridge doesn't decrease in the simulat for those changes. For modifications of 15 minutes and more, the am-simulation might imply a linear dependence between travel time and congestion, though this conjecture must be rejected once the pm-simulation is considered.

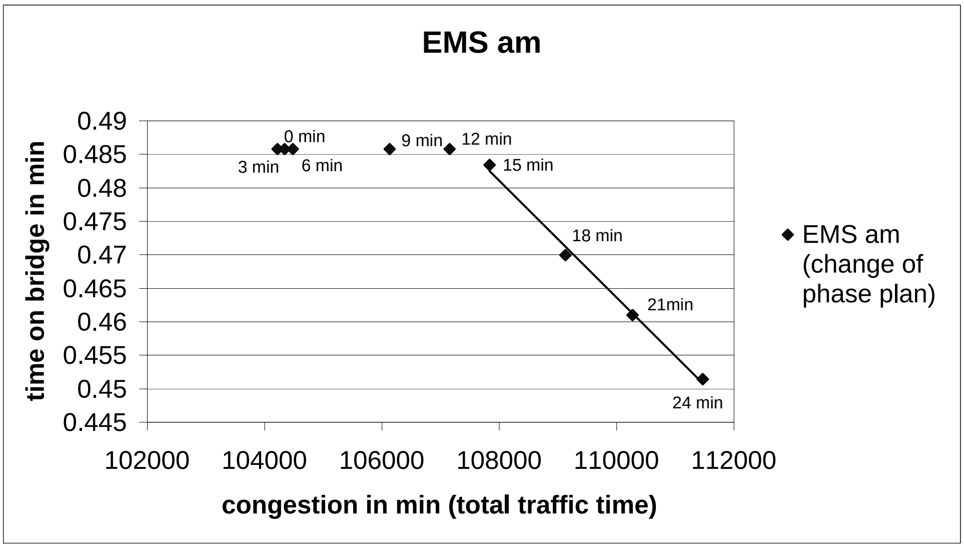


Figure 6.1: "Normal" Case am

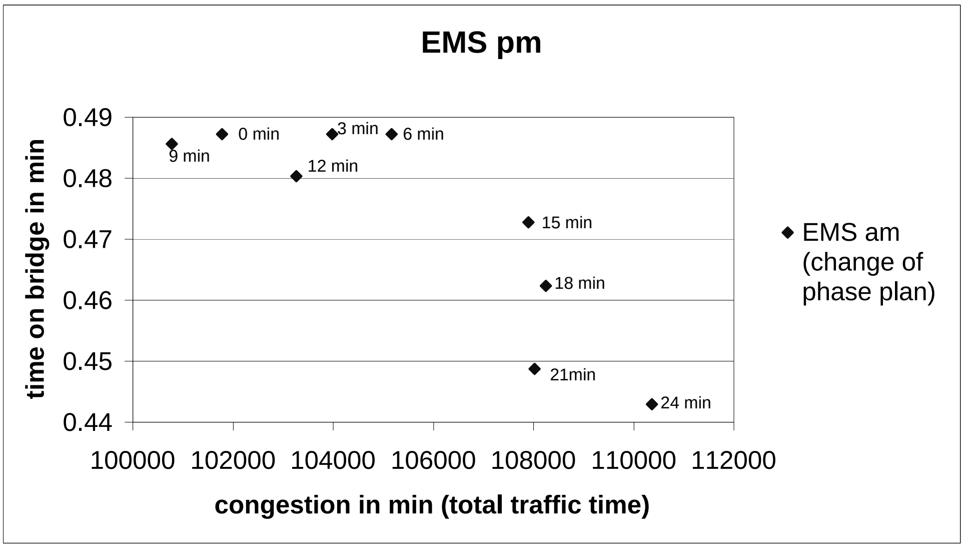
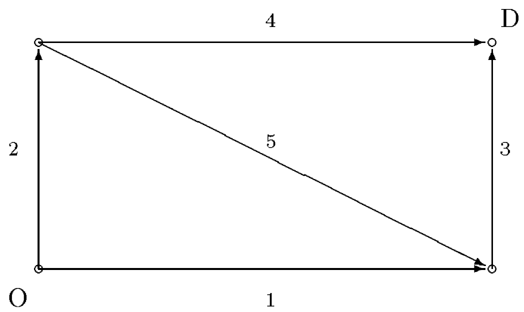


Figure 6.2: "Normal" Case pm

At first it might sound strange that an increase of the time the phase-plan is changed can result in a decrease of congestion. On second thought tough this fact is linked to definition of user equilibrium: time of each user is minimized **not** the total travel time. This is illustrated in the following example:

In a network with the V-D functions as in figure 6.3 and a demand of six users from O to D, the user-equilibrium is reached when 2 users follow the path allong arcs 1 and 3, two users the path allong arcs 2 and 4 and two users the path allong arcs 2, 5 and 3. In this situation congestion is 552.

If there were three users on the path allong arcs 2 and 4 and three users on the path allong arcs 1 and 3, congestion would be only 498 but there would be a path (allong arcs 2, 5 and 3) that would take less time (70) than the ones used (83).



$$t_1(\omega) = 50 + \omega$$
$$t_2(\omega) = 50 + \omega$$
$$t_3(\omega) = 10\omega$$
$$t_4(\omega) = 10\omega$$
$$t_5(\omega) = 10 + \omega$$

Figure 6.3: Paradox

A similar paradox arrives with a decrease of information (congestion sometimes decreases too) as can be seen in the following figure. For a change of phase-plan of 12 minutes, congestion at a level of information of 100% is higher than at a level of information of 50%.

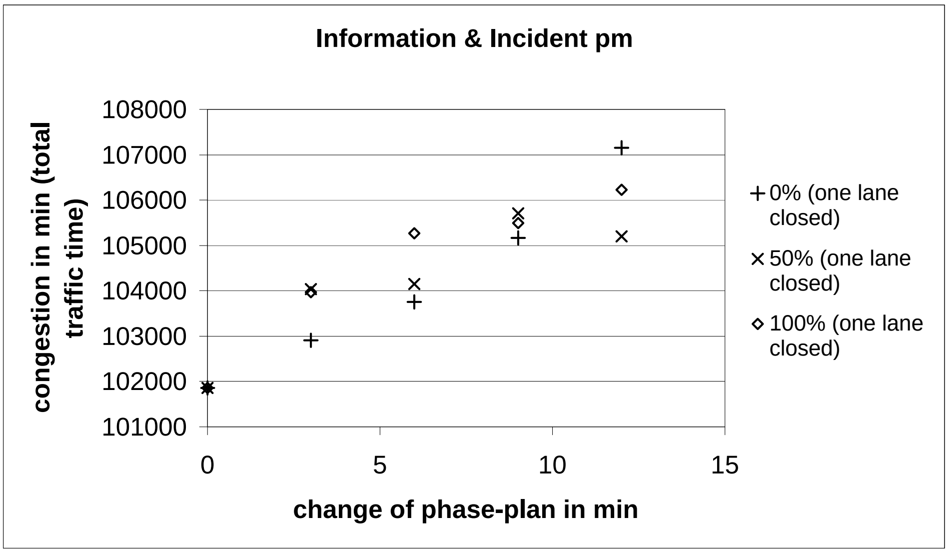


Figure 6.4: Paradox 2

Chapter 7

Discussion and Conclusion (Rules and Algorithmes)

As mentioned in chapter 5 the simulation results coulnd't be used to obtain conclusions because changes of phase-plan up to 12 minutes didn't change traffic flow on the bridge, whereas travel time between the beginning of the intersection and the end of the bridge are about 6 minutes in the "normal" case. We therefore derived a formula of maximum change of phase-plan for a given maximal time one wishes the ambulance to use on the bridge by the method described in chapter 5:

$$r(t_{br}) = 1 - \frac{c_{br}^{p}}{c_{int}^{0}} \left(\frac{1}{\alpha} \left(\frac{t_{br}}{t_{br}^{o}} - 1 \right) \right)^{\frac{1}{\beta}}$$

where c_{int}^{0} =1664 [veh/hour]

c_{br}^{p} =1500 [veh/hour]

α =0.15

β =4

t_{br}^{0} = distance/speedlimit = 0.3 m/45 mph = 0.00667 h = 24 sec

r is the ratio between the times the new phase-plan and the "normal" phase-plan is used (in reality one complete cycle of the old phase-plan would be followed by $r/(1-r)$ times the duration of that cycle of the new phase-plan)

t_{br} should have the same dimension as t_{br}^{0} (seconds)

This gives us the explicit formula for r:

$$r(t_{br}) = 1 - 1.448 \left(\frac{t_{br}}{24\text{sec}} - 1 \right)^{0.25}$$

Therefore if the system operator gets a call informing him that the ambulance arrives at the intersection in about 10 minutes, and the wished travel time for the ambulance on the bridge is 25 seconds (this value should be discussed with the ambulance staff; see below), he should start in three minutes (seven minutes before the ambulance passes the intersection; six minutes being the time used in "normal" conditions to cover the distance between the intersection and the end of the bridge[1]) to alternate one cycle of the old phase-plan with 32 seconds ($= r/(1-r)\cdot$ 60 sec)

[1] This time should be checked in reality, we derived it from the simulation which shouldn't be that far from reality in the "normal" case.

respectively 55 seconds ($= r/(1-r)\cdot$ 105 sec) and 50 seconds ($= r/(1-r)\cdot$ 95 sec) on intersections 11 respectively 17 and 14.

The fact that we can't have a negative value to the power of 0.25 (i.e. a travel time under 24 seconds) expresses that users on the bridge will not travel faster than the speed limit. Nevertheless it is clear that on a very low-congested bridge, the ambulance will be able to travel faster than the users and probably cross the river under 24 seconds.

Notice also that for values of t_{br} higher than 29 seconds r becomes negative. This is a consequence of the V-D function used on the bridge which produces a travel time of precisely 29 seconds, when congestion is at the intersection's practical capacity level.

Thus for travel times on the bridge between 24 and 29 seconds our formula is applicable. For higher and lower values boundary values for r can be used as follows:

Speed of EMS vehicle	t_{br}	r	$\frac{r}{1-r}$
≤ 37	≥ 29	0	0
40	27	0.14	0.16
≥ 45	≤ 24	1	∞

Table 7.1: Plan of Operation

In case of "∞" the new phase-plan should be used during the six minutes before the ambulance passes the intersection (without interuption).

In case of an incident on the bridge at the same time this formula might still be used as long as there is one lane remaining which should be uniquely used for eastbound traffic.

As can be seen from these results it's not appropriate to use a static simulator based on user equilibrium for a traffic simulation where queues play an important role.

Part IV

Appendix

Chapter 8

Tabulated Simulation Results

peak	scenario	change of phase-plan (min)	congestion (min)	time on bridge (min)
am	"normal"	0	104343	0.485761
		3	104214	0.485761
		6	104482	0.485761
		9	106127	0.485761
		12	107156	0.485761
		15	107836	0.483439
		18	109122	0.469926
		21	110268	0.461012
		24	111466	0.451445
	information 50% users informed	3	104517	0.485761
		6	105313	0.485761
		9	105604	0.485761
		12	107518	0.485761
	information 0% users informed	3	104617	0.485761
		6	105447	0.485761
		9	106835	0.485761
		12	108781	0.485761
	incident (one lane closed)	3	104274	0.485761
		6	104999	0.485761
		9	106232	0.485761
		12	106638	0.485761
		15	108083	0.483712
		18	109141	0.469968
		21	110268	0.460849
		24	111573	0.451502
	(two lanes closed)	3	107249	1.772177
		6	107603	1.772177
		9	106880	1.749634
		12	107704	1.678955
to be continued...				

continued:				
peak	scenario	change of phase-plan (min)	congestion (min)	time on bridge (min)
		15	108085	1.574986
		18	110204	1.384502
		21	111602	1.267239
		24	112241	1.184187
	incident (one) + information 50%	3	104860	0.485761
		6	104751	0.485761
		9	105831	0.485761
		12	107860	0.485761
	incident (one) + information 0%	3	104846	0.485761
		6	105676	0.485761
		9	107064	0.485761
		12	109010	0.485761
	incident (two) + information 50%	3	107073	1.772177
		6	107567	1.772177
		9	108868	1.772177
		12	109349	1.703985
	incident (two) + information 0%	3	110614	1.7721771
		6	111444	1.772177
		9	112832	1.772177
		12	114778	1.772177
pm	"normal"	0	101775	0.487192
		3	103982	0.487192
		6	105166	0.487192
		9	100782	0.485601
		12	103265	0.480308
		15	107898	0.472779
		18	108244	0.462363
		21	108017	0.448774
		24	110366	0.442903
	information 50% users informed	3	104099	0.487192
		6	104586	0.487192
		9	105554	0.487192
		12	105027	0.481475
	information 0% users informed	3	102694	0.487192
		6	103539	0.487192
		9	104954	0.487192
		12	106937	0.487192
	incident (one lane closed)	3	103966	0.487192
		6	105269	0.487192
		9	105491	0.485913
to be continued...				

continued:				
peak	scenario	change of phase-plan (min)	congestion (min)	time on bridge (min)
		12	106228	0.482199
		15	106242	0.467981
		18	107607	0.461807
		21	108198	0.44873
		24	110472	0.4429
	(two lanes closed)	3	105616	1.687856
		6	104230	1.654319
		9	103596	1.67651
		12	106019	1.5219
		15	108625	1.443988
		18	108000	1.243107
		21	109110	1.137767
		24	111425	1.086295
	incident (one) + information 50%	3	104041	0.487192
		6	104149	0.487192
		9	105713	0.487192
		12	105196	0.481794
	incident (one) + information 0%	3	102910	0.487192
		6	103755	0.487192
		9	105170	0.487192
		12	107154	0.487192
	incident (two) + information 50%	3	105586	1.719215
		6	105733	1.795075
		9	104577	1.595603
		12	107258	1.579547
	incident (two) + information 0%	3	108523	1.795075
		6	109368	1.795075
		9	110783	1.795075
		12	112767	1.795075

Table 8.1: Simulation Results

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