The development of area wide traffic management scenarios

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ABSTRACT

Traffic management in cities with congestion is a big challenge with still unused opportunities. Intersection control is a corner stone but this should be done in an area-wide context. The dominant traffic process on urban roads is the traffic flow on the intersections. Spill back is a most important cause of malfunctioning networks. The methodology described in this paper gives a structured approach to develop scenarios for dynamic traffic management. The detection of spillback can be done by the analysis of probe vehicle data. Using the conflicts at the intersections as the basic elements of the network capacity analysis and the basis of traffic control, this paper develops a method to define control scenarios by evaluation and adaptation of local traffic control, buffering and metering strategies and rerouting. To support the task of traffic managers, the monitoring, traffic management scenarios and evaluation by simulation are integrated in a decision support system, iTides. This methodology is applied in a network in the CBD of Changsha, the capital of Hunan Province in P.R. China.

Keywords: spill back, probe vehicles, buffers, rerouting, conflict group, decision support system.

INTRODUCTION

Traffic management scenarios are the combination of traffic states and appropriate traffic management strategies. The traffic states are characterized by the flows, queues and traffic control. The traffic management strategies consist of suitable traffic control measures on intersection level, ramp metering control, and information provision to drivers on Variable Message Signs (VMS), radio and onboard devices like smart phones and navigation systems.

For the development of traffic management scenarios three issues are important:

1. How to identify the traffic state in the road network,
2. How to choose and optimize traffic management measures,
3. How to decide what the most applicable scenario is.

In this paper a methodology is described for these three issues for urban road networks. The methodology is applicable in any urban road network where suitable monitoring, control and information equipment is available. The implementation details are specific for the particular network where it is applied and the technical and organizational possibilities.

Queues are normal phenomena at signalized intersections: they build up during the red phase and should disappear during green. Also queues that do not completely disappear in the green phase are unavoidable in time periods of large traffic demand. The problem becomes serious when queues spill back to upstream intersections and block there the movement of vehicles that will not pass the bottleneck or when the queue spills back to the beginning of a turning lane and prevents turning traffic to enter these lanes. If this happens the network performance is reduced, which can be observed as a reduction of traffic flows.

The traffic management options can be distinguished in three categories (*1*)

- Local measures on single intersections
- Coordination measures for adjacent intersections
- Rerouting measures on a network wide scale.

The local measures are especially the adaptation of the traffic control, for instance to restore the balance between traffic demand and green phases and adapt the signal cycle to the actual traffic flows. The traffic controllers often work on a fixed cycle when there is congestion since vehicle actuated signals will have green phases that extend to the maximum green length. A balance between demand and flows can lead to a different cycle time and green splits, different from the predetermined maximum cycle and green times. Especially if spill back occurs, the traffic control on the downstream can be modified to increase the outflow of the link with spill back. Since the 60s of the last century several studies have been made on the optimal setting of signals in oversaturated network. Gazis (*2*) analyzed a store and forward network and developed a method to minimize delays assuming fixed routing, predictable flow, simple two phase signal control and a linear queuing model. Gazis and Potts (*3*) found the well-known bang-bang control strategy where one direction of the oversaturated intersection gets the maximum green time and the other the minimum, until a moment that this green allocated is reversed. As far as the authors know, this control strategy is not widely used in practice.

Coordination measures are taken to reduce the inflow to a link with spill back. We call this ‘metering’. The consequence might be that the queue on that link disappears, but the queue on this metering intersections increase and may cause new spill back and grid lock. The constraints on queue length are an important issue in urban networks. Michaelopoulos and Stephanopoulos (*4*) took this into account in their analytical method to get an optimal control for simple two phase control and predictable traffic flows. Lieberman et al. (*5*) developed a method to control congested road networks by managing the queue lengths by coordinated intersection control.

Rerouting is the measure to stimulate or force drivers to take a route that reduces the congestion in some area. The simplest way to induce rerouting is to forbid left turning on congested intersections (*6*). It is obvious that such measures may just shift queues, unless the alternative route has sufficient capacity (*7*). Therefore, such rerouting measures should be well analyzed before they are implemented.

The third issue is the decision making to choose the scenario that is most suited in the actual situation. In practice such a decision making should be based on insight in the situation and knowledge of the control possibilities. Traffic management officers should have these qualities, but often the situation in the network is complex and not every officer has the same experience. A decision support system is suitable to help the traffic managers to choose the best management measures.

The challenges of the area-wide traffic management are discussed in the following sections and suitable methodology is explained. The focus is the development of a decision support system for area wide traffic management. Section 2 deals with the monitoring and the application for network diagnosis. Section 3 explains how an intersection based analysis can be used to optimize network rerouting. Section 4 brings these concepts together in an evaluation and decision support system.

The methodology described in this paper has originally been developed for the city of Beijing (*8*). Now it is being adapted and generalized for Changsha, the capital of Hunan province in China. In Changsha the intersections are controlled by a SCATS system (*9*). This system monitors the traffic streams by loop detectors on nearly all lanes of the signalized intersections. Furthermore, all taxis in the city have a GPS on board that gives the position, driving direction and speed every 30 seconds. Both data sets have been used in this study.

TRAFFIC MONITORING ON LINKS AND SUB NETWORKS

Congestion during peak hours is normal in many bigger cities. In most cases the capacity bottlenecks are the intersections. Queues are normal even in time periods without oversaturation. Due to the periodic access to the intersections by traffic control, queues build up and resolve during a control cycle. In the case of oversaturation, the queue cannot fully resolve during a green phase. The resulting overflow queue is also a normal phenomenon in peak hours. As Viti and van Zuylen (*10*) show, this overflow queue even exists in conditions that are on under-saturated on average, due to the fact that arrivals of vehicles on the intersection have a random character. The overflow queue becomes structural when the average inflow is larger than the saturation flow of the lanes available for the inflow, multiplied with the fraction of the cycle that these lanes have the green signal.

Queues have a periodic character based on the cycle of the signals. The overflow queues have a steady character growing or reducing from cycle to cycle, depending on the degree of saturation, the present overflow queue and the equilibrium value of the overflow queue (*10*). As long as the periodic queue plus the overflow queue can be stored on a link without spilling back to an upstream link, the traffic conditions can be considered as acceptable. If spill back occurs, the back of the queue reaches the upstream intersection and reduces its performance. This can even result in complete blocking of all flows in that intersection.

Therefore, the criterion for additional control action is the position of the back of the queue with respect to the length of the link. In Changsha the queues are estimated from the behavior of taxis as probe vehicles. There is some doubt about the question whether taxis are representative samples of the road traffic. Taxi drivers have to pick up and deliver passengers and stop for that purpose. Incidental stops of less than 2 minutes at locations where other taxis pass without stopping can be considered as such events. A second issue is that taxi drivers are experienced with the traffic conditions. Routes with a lot of congestion are avoided by taxi drivers, which makes the percentage probe vehicles low at roads for that are most important for monitoring. A third aspect of taxi drivers is that they may drive more aggressive as other drivers. In the observations in Changsha we found indeed some taxi drivers who used parallel roads for bicycles to pass the queue, but their trajectories can easily be identified and eliminated.

The criterion for the back of the queue needs some further analysis. The definition of a queue as stopped vehicles is too narrow. Drivers often drive with lower speed when they approach a standing queue. This anticipation effect reduced the driving speed and is not necessarily related to traffic density or traffic volume on the road.

FIGURE 1 and FIGURE 2 show the analysis of taxi GPS data on Laodong Road, a busy road with frequently occurring spill back in Changsha. The data refer to the road section between two intersections: the Furong Road in the West and the Shaoshan Road in the East.

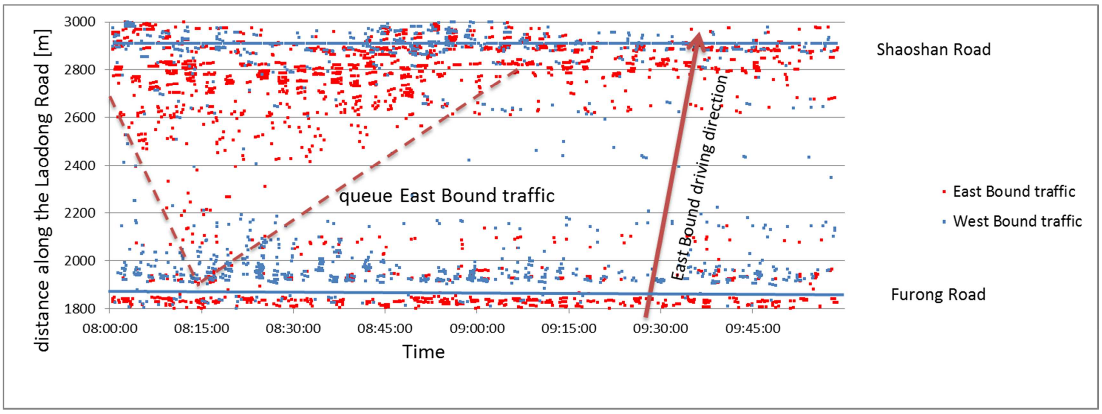


FIGURE 1 Positions of taxis at low or zero speed along a road (Laodong Road in Changsha) and emerging queue spillback of the East bound traffic.

In Figure 1 the GPS position of stopped and slowly driving taxis are visualize between 8:00 and 10:00 (time is on the horizontal axis). Their position in meters along the road is along the vertical axis. The intersections are 1870 m and 2910 m resp.

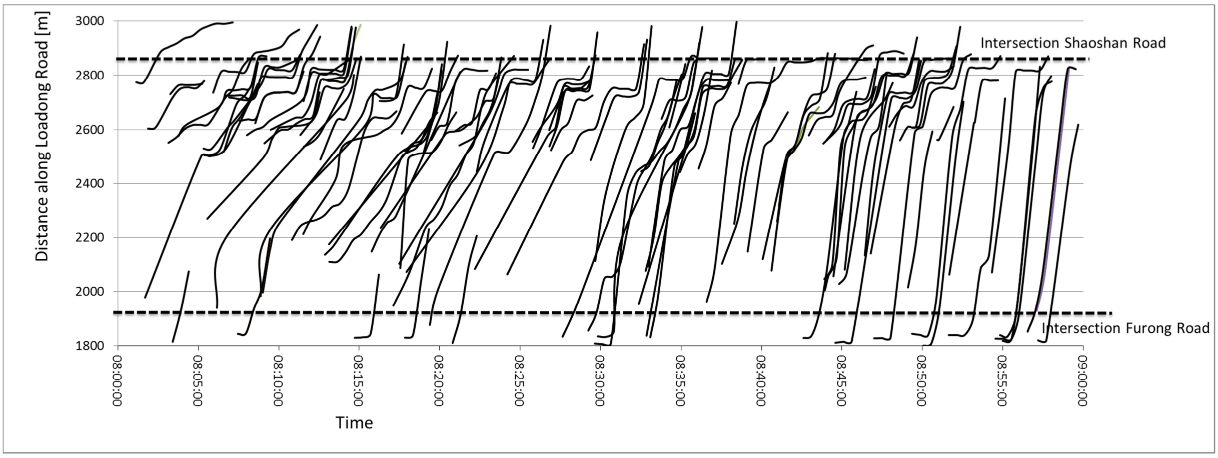


FIGURE 2 Trajectories of taxis along the Laodong Road. The speed of the taxis until 8:20 is considerable lower than in the time afterwards

FIGURE 2 shows the trajectories of taxis. The slope of the trajectories represents the speed. This is significantly lower in the time until 8:20, which shows the existence of a slowly moving queue. One can observe in FIGURE 1 that in East-bound direction a queue builds up between 8:00 and 8:15 and that this queue spills back to the Furong Road intersection. In observing the threatening spill back is not too complicated using the GPS data, the flow data and the traffic control. This is a mesoscopic monitoring approach based on average microscopic traffic data. Therefore, the trigger for taking measures to avoid spill back is the observation of low speeds at the upstream road segment (or the downstream road segment of the upstream intersection).

Recently, the Macroscopic Fundamental Diagram (MFD) is proposed for the assessment of the traffic state in urban road networks (*11*). The MFD is an empirical macroscopic diagram showing the relation between the generalized vehicle density (GVD) on one axis and the generalized traffic flow (GTF) on the other axis. If the GVD becomes higher than a certain level, the network becomes less effective because of spill back of queues. This results in a lower GTF. The MFD is a typical macroscopic monitoring method with the disadvantage that several completely different traffic states can give the same GVD. For instance, in the example of Figure 1 only the East bound direction had the spill back, the West bound flow (the blue dots in Figure 1) was much smaller and gave no problems. If we would have the total flow on the link balanced over both the East bound and West bound directions, there would no spill back on neither of the directions. That balanced situation has the same GVD as the situation shown in Figure 1. This means that a macroscopic measure as the GVD is not the best criterion to monitor the traffic state of a link in a network unless the whole network has a homogeneous loading (*12*). As Knoop et al. (*13*) show the MFD should have at least a third axis which gives a measure of the spatial inhomogeneity of the density. Gridlock is direction-dependent and is, at least in the case studied in this paper, not uniform over an area and the queues appear to have a stochastic character.

Therefore, we used the estimated queue length from the 6000 taxis with GPS, the traffic flows as measured with loop detectors on the lanes at the stop lines and the link saturation flows as measured on the spot (*15*).

CONFLICT GROUPS AS CONTROL UNITS

Most methods for the optimization of congested networks assume simple two phase control. Often the traffic control is more complex and an analysis of the capacity of an intersection and the appropriate traffic control should be done. In the method described in this paper the concept of *conflict groups* is used, sets of directions on an intersection that all have pairwise a conflict. For instance, on the intersection of FIGURE 3 some conflict groups G are G_1 = {02, 31}, i.e. the conflict between the crossing pedestrians 31 and the motorized traffic 2, G_2 = {03, 06, 08}, G_3 = {03, 07, 34}, G_4= {04, 08, 32} etc.

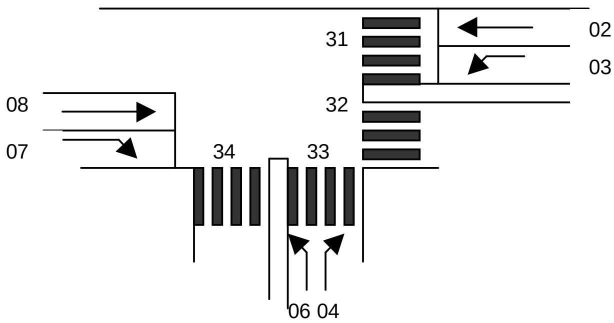


FIGURE 3 Example of an intersection with conflicting flows.

Of course, some conflicts might be permitted, such as 03/08 and some might be completely ignored, such as when right-turn-on-red is permitted. Such permitted and ignored conflicts are only safe and acceptable if there is not too much traffic for such conflicts or if special measures are taken to control the conflict (e.g. control signs showing that right turning traffic has to give priority to other traffic). For the remainder the directions of the conflict group have to be given consecutive green. The whole signal plan can be considered as the integration of the control of the different conflict groups.

A direction i with a flow rate q_i and a saturation flow s_i needs at least a fraction $q_i/s_i = y_i$ green time, thus per cycle with duration C the different directions of a conflict group G, the time to be given to all direction should be at least $\sum_{i \in G} y_i C$. If the remainder of the cycle time is necessary for the transitions (L_G is the sum of unused yellow time, clearance time, and startup delay) C_{min}, the minimum value of the cycle time for a conflict group G is

$$C_{\min} \geq \frac{L_G}{1 - \sum_{i \in G} y_i} \quad (1)$$

Due to the fact that the arrival process of traffic is stochastic, the cycle time should be considerably larger than C_{min}. Webster found many years ago a formula for the cycle time that minimizes the delay for simple two phase intersections. Recalculation shows that Webster's formula (*16*) gives too long cycle times for multi-phase controlled intersections and that a suitable cycle time is given by

$$C_{opt} \geq \frac{1.4L_G + 4}{1 - \sum_{i \in G} y_i} \quad \forall G \tag{2}$$

.

It is obvious that the denominator in equation (2) should be larger than zero and that the cycle time becomes larger when $Y_G = \sum_{i \in G} y_i$ becomes larger. A good traffic control strategy is to try to reduce the maximum value of this sum for all conflict groups. This methods is similar to the approach followed Xu et al. (*17*) who determined the capacity of an urban network by analyzing the capacity of conflict groups on the intersections..

Another rule for signal control is to balance the green times by allocating the available green time $C – L$ to direction i proportional to y_i.

The strategy for network wide traffic control can be explained now within this framework. There are three levels to control traffic when queue spillback is threatening:

- Local tuning of the traffic control
- Controlling in- and outflow of critical links
- Rerouting traffic through the network in order to reduce the load on a critical intersection.

For the first kind of control we have to check the present structure of the traffic control and the timing. In the example of the case study, the intersection had the geometry as given in FIGURE 4. The intersection was at the off- and onramps of an elevated road, making it possible for traffic from the elevated road to turn right or left and for traffic from the sides roads to pass under the elevated road or to enter an onramp.

The control structure was a three phase control plan where the East and West approach had consecutive phases and the South and North approach had simultaneous green. For traffic conditions outside the peak hours this three phase control worked rather well, but in heavy traffic conditions the conflict between 11 and 6 causes problems.

Therefore the first recommendation to solve the spill back on the East approach is to modify the structure of the control scheme by making all phases conflict free. The next step is to verify the length of the cycle and the green phases. This is simply done by verifying the degree of saturation of each direction in the present traffic control. Volumes are measured by the loop detectors, the saturation flow has been measured for the signalized intersections in Changsha (*15*), so the degree of saturation x_i defined as $x_i = (y_i/s_i \cdot C/g_i)$ where g_i is the green time given to direction i. (In fact x_i is the ratio between the minimum green time needed by flow I and the actual green time). By redistributing the green times - if necessary and possible – and changing the cycle time, oversaturated directions can be relieved unless the intersection is really over saturated and $\sum_{i \in G} y_i > 1$ or one or more conflict groups.

FIGURE 4 The critical intersection with the numbered directions (intersection Laodong Road with Shaoshan North Road in Changsha). The background is from Google Earth.

If for one of the conflict groups at an intersection Y_G is too large (a value $Y_G > 0.85$ is already large, because in that situation the intersection does not have sufficient reserve capacity to handle the fluctuations in the arrival rates). In the case that the queue problem cannot be solved by adapting the signal timing, a decision has to be made:

- allocate the queues on links that can act as buffer space with sufficient room to avoid spill back to critical intersections, or
- reroute traffic over intersections that have still sufficient capacity.

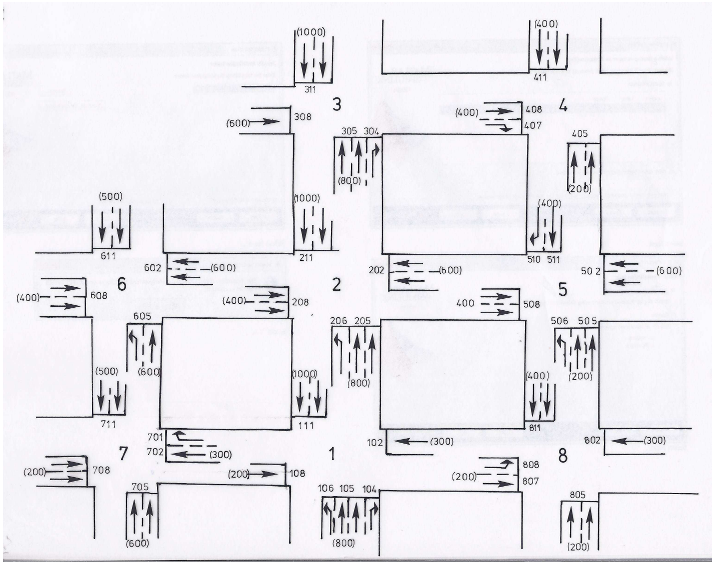
Buffer space has a limited storage capacity and will have a temporal character. If we assume that traffic will continue to follow the same routes, buffering is simply done by metering the inflow of the critical link or by giving the flow on the critical link more green time at the cost of other direction on the critical intersection (*5*). The consequence of both solutions is that queues develop at other links than the critical on. This reallocates the queue and is, of course, a temporal solution.

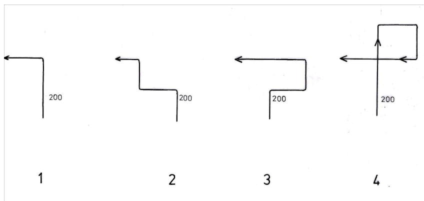
The other approach is to reroute traffic such that the critical conflict group is relieved. The next section gives a possible methodology.

A METHODOLOGY FOR OPTIMUM REROUTING IN A SIGNALIZED NETWORK

The basic principle to choose optimum rerouting is that traffic streams are reallocated to the network such that the maximum value of the load ratio for all conflict groups in the controlled area is minimized. This approach is basically applicable if there are rerouting alternatives with spare capacity. If it is not possible to find sufficient spare capacity, the methodology still gives the possibility to distribute the oversaturation in a balanced way.

As an example we use the network of **FIGURE 5** where intersection 2 is oversaturated. The critical conflict group is {202,206, 211}. In order to reduce the intersection loading, we can consider the possibility to reroute (a part of) flow 206. Some options are to reroute over one or more of 4 alternatives **FIGURE 5** b explains this.





a **b**

FIGURE 5.a Example network to explain the rerouting methodology. FIGURE 5.b Alternative routes for 206: 1 is the original one, 2 goes via 106, 701 and 606, route 3 takes the path via 104, 808, 506 and 202 etc.

The result of rerouting is that traffic that originally passed intersection on direction 206 is now using other directions. The consequence is that 206 gets less traffic and the critical conflict group gets a lower value of *Y*, while other conflict groups have more traffic and get a higher value of *Y*.

A suitable assignment of the rerouted flow can be determined by minimizing the *Y* value of all conflict groups that are influenced by the rerouting.

If we assume that fraction α_1 of the flow still uses route 1 and passes intersection 2 via direction 206, α_2 travels via route 2 etc. and that the volume of the traffic that has to be rerouted is *V*, while the volumes of the other flows is given by q_i, the *Y* value of the conflict groups that are influenced by the rerouting are:

$G_{2,1}$ = {206, 202, 211}
$Y_{2,1} = \alpha_1 V/s_{206} + (q_{202}+\alpha_3 V)/s_{202} + q_{211}/s_{211}$

$G_{2,2}$ = {2,5}
$Y_{2,2} = (q_{202}+\alpha_3 V)/s_{202} + q_{205}/s_{205}$

$G_{2,3}$ = {5,8}
$Y_{2,3} = (q_{205}+\alpha_4 V)/s_{205} + q_{208}/s_{208}$

$G_{2,4}$ = {6,8,11}
$Y_{2,4} = \alpha_1 V + q_{208}/s_{208} + q_{211}/s_{211}$.

In the same way the relevant conflict groups on the intersections 1, 3, 4, 5, 6, 7 and 8 can be analyzed and the *Y* values can be expressed as linear functions of α_1 .. α_4.

The best rerouting strategy can be solved by a simple optimization procedure:

$$\{\alpha\} = \arg \underset{\{\alpha\}}{Min} \underset{\forall G}{Max} Y_G(\alpha_1, \alpha_2, \alpha_3, \alpha_4) \qquad (3)$$

Under the condition that $\sum_i \alpha_i = 1$.

If an all-or-nothing rerouting is applied, the values of α_i should be 0 or 1, for a soft rerouting also non-integer values can be allowed.

It is obvious that there is not a general best solution. Depending on the structure of the network, the flows and saturation flows of the other directions involved, different optimal solutions will be found. Furthermore, the solution depends on the selection of feasible routes. We selected 4 possible routes, in reality the choice of possible routes depends on the geometry of the network and the range within which feasible routes are chosen. The wider the range, the more routes might be identified. Since the optimization (3) is simple and fast, the number of alternatives is not critical.

The difference of this simple rerouting method and other methods in the literature is that the other methods try to minimize delays, while this method tries to optimize the utilization of the network, especially the intersections. This might be more interesting for the traffic management that the optimization of delays. The solution gives also input for the calculation of signal settings.

APPLICATION OF THE REROUTING TO THE NETWORK OF CBD CHANGSHA

The network for which we applied the queue management methods is a part of the CBD of Changsha, the capital of Hunan, P.R. China. The city center experiences frequent congestion. Notwithstanding investments in traffic control, installation of Variable Message Signs (VMS) and adaptation in the road geometry, congestion occurs daily during the peak hours. In several cases congestion spills back to upstream intersections causing a reduction of their performance.

FIGURE 6 Map of the application area with the queue spillback (red line) on the Laodong road. The critical intersection is shown with a blue circle. The best rerouting is to turn left already to the Huangtuling Road

The map of the area is given in FIGURE 6. As shown in Figure 1, spillback (marked in red line in FIGURE 6) occurs on the Laodong Road between the intersection (marked in blue circle) with the Shaoshan North Road and the Furong Middle Road. The critical intersection is the one between Laodong Road and Shaoshan North Road. According to Figure 1, the critical time is between 8:00 and 8:30, while the queue spillback occurs around 8:15.

A check on the available queuing space in that time period showed that some buffer space was still available on the Laodong Road West of the intersection with the Furong Middle Road. The intersection between Shaoshan Middle Road and Chengnan East Road had a rather high traffic load. On the South side of the critical area, the Huangtuling Road still had space and intersection capacity.

The metering and rerouting strategy became, therefore, to restrict the inflow to the Laodong Road from the intersection with the Furong Middle Road during the period 8:00 to 8:15, and to give traffic coming over the Shaoshan Road from the South the advice to use the Huangtuling Road to turn Westwards instead of turning left on the critical intersection, as depicted in black lines. This advice can be given by a VMS on the Shaoshan Road before the intersection with the Huangtuling Road.

The different traffic management measures were evaluated with a simulation program Dynasmart (*18*). The program was used initially for off-line simulation. In the future it will be used for real-time simulation as well. The simulation results are given in FIGURE 7. They show that this rerouting plus the traffic control optimization at the critical junction reduces largely the spillback, reduces travel times and delay. The average number of vehicles travelling in the study network is reduced, which means that the average travel time has become less. Since some traffic had to take a longer route, the total trip distance increased. This example shows that an effective scenario could be found for a given bottleneck.

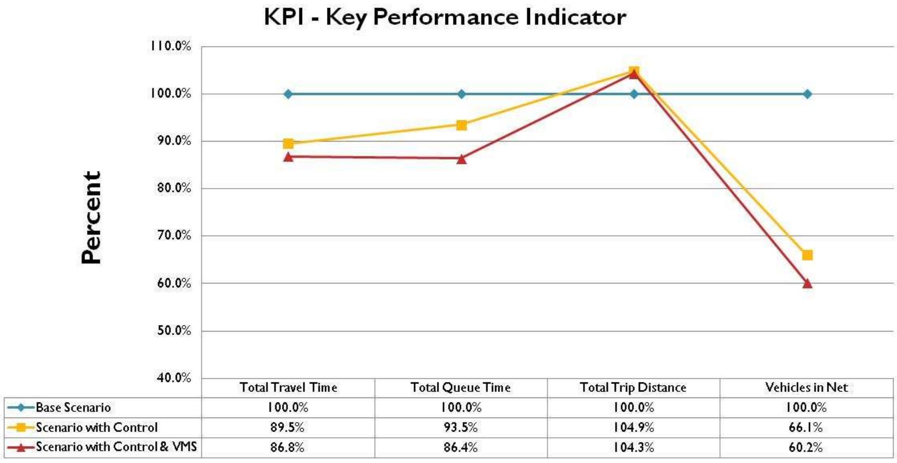


FIGURE 7 Simulation results for three scenarios with evaluation of different performance indicators

A SCENARIO BASED DECISION SUPPORT SYSTEM FOR THE TRAFFIC MANAGERS

As mentioned before, the combination of a traffic state and suitable traffic measures is called a *scenario*. Several of such scenarios can be prepared in advance. If the traffic conditions of some scenario occur, the traffic measures that can deal with this situation can be recommended to the traffic managers.

The structure of such a decision support system is that traffic data is collected in real time and stored in a database after initial processing. The historical stored data are used to develop scenarios. The scenarios are also stored in the database. If some specific situation occurs, a scenario can be presented to the traffic managers who can chose to implement the measures. That can be done using the traffic signals, by giving information on VMS, by manual control by police men on the spot and by giving information to road users by Internet, mobile phone, or navigation system.

The total decision support system with the name iTides (*19*) is being developed now for the city of Changsha and will be implemented this year. It will contain a database for the historical and real-time traffic data, a set of traffic management scenarios and a simulation program that can be used on-line with the input of measured traffic volumes. FIGURE 8 shows the structure of the iTides decision support system.

CONCLUSION

Traffic conditions during peak hours or special events like incidents often require measures to avoid situations that reduce the capacity of the network. Queues are often unavoidable, but it should be avoided that queues block the access of parts of the infrastructure and reduces their performance. This can be a full intersection or just special lanes. The criterion for applying queue management is the threatening or occurrence of spillback. Since this is a phenomenon on a link more than on a whole network, the use of queue length detection is an appropriate mesoscopic method to trigger queue management measures. Probe vehicles give a suitable monitoring instrument when the percentage probes is sufficiently high. Queue lengths can be estimated from stopped vehicles, but an analysis of trajectories gives more detailed information about queues.

In case of threatening spill back traffic management scenarios can be chosen. The measures should work as well on local as on area scale. The methodological approach to develop control and rerouting scenarios that we follow is that the measures are chosen based on a conflict group analysis of intersections involved. First of all the loading factors of the conflict groups is checked, then the cycle time and green split. If the adaptation of these control parameters is sufficient to avoid queue spill back the scenario measures are sufficient, otherwise metering of the inflow can be a solution, when the queues that will be caused by the metering can be stored on links with sufficient storage space. Finally rerouting can be considered, where one has to take care that rerouting will not cause problems on other intersections in the network. This is achieved by minimizing the maximum load factor of all conflict groups that are influenced by the rerouting.

Since the diagnosis and selection of suited traffic management measures is rather complex, a decision support system is developed which gives advice to the traffic managers and informs them about the impact of the measures.

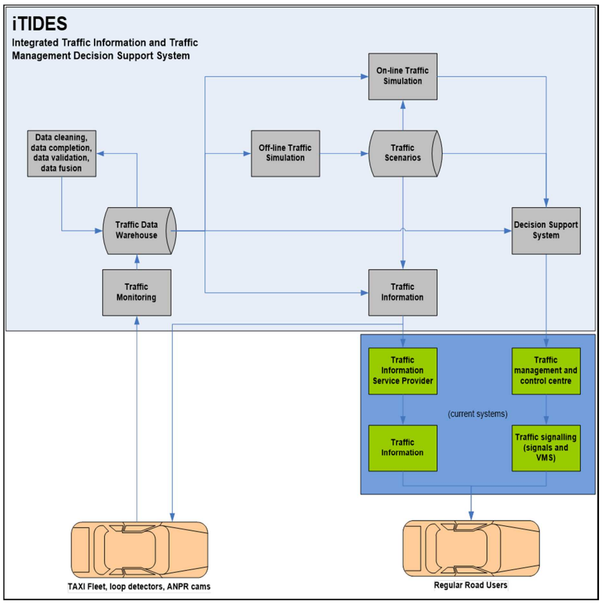


FIGURE 8 iTides Framework

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