Managing Infrastructures of Limited Resources

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Abstract: It is hardly impossible to limit traffic by administrative measures. There are, however, chances of using innovative procedures of traffic telematics in order to manage traffic demands and, above all, traffic flows in an optimal way on the basis of available resources. A conclusion concerning the expected resources capacities can be made by predicting the presence of a mobile object at a certain location at a certain time. On the basis of the comparison of available and finally required resources it is possible to give effective anticipatory routing recommendations within a large area.

Keywords: Traffic telematics, LBS, GIS, large-area traffic management, reliability

1. Introduction

The basis for the scenario described below and its possible technical implementation is general knowledge in the field of transport engineering:

- It is not possible to limit traffic by administrative measures.
- Mobility is a fundamental requirement of all actors in the modern economic life and
- The private environment as well.
- It is necessary to develop and use innovative procedures of telematics with the purpose
- of an optimal management of traffic requirements and traffic flows.

The target has to be to improve the use of the available resources in the infrastructure (improvement of infrastructure), to implement an intelligent routing with individual route planning and digital traffic control [1]. The subject of consideration is a large-area traffic network, such as the motorway system. For a regional or urban network there are different effective approaches which are available.

While approaching to the solution of the problem, a considerable quantity of object-related and possibly even personal data are captured and processed. Handling these data safely is therefore particularly important. For this paper the questions of data security have not been considered. They will be subject of different considerations.

2. Approach

On the basis of anticipatory actions it is possible to provide a location-based content, before the relevant location is reached in a traffic activity. If the traffic activities are controlled within a large-area infrastructure such as the German motorways, a lot of information for an optimal traffic management can be gained from the inflowing traffic, the traffic flows in the individual directions and the road users' behavior.

There are potentials of avoiding an overload situation to be expected at a future location by taking anticipatory actions. For this purpose it is necessary to provide a location-based content, before the relevant location will be reached [2]. It is typical that a backed prediction is not possible about which information will be required for a decision in the current case [4]. Hence, the following items have to be considered:

- Predicting the presence of a vehicle at a certain location at a certain time,
- Concentrating individual movements into a traffic flow,
- Predicting an expected traffic density on a certain route at a certain time,
- Comparing available and required resources,
- Identifying the overload situations to be expected and
- Object-related, individual traffic management or measures for controlling the inflow on the basis of a resource-relevant routing.

3. Application to a large-area traffic management

3.1. Scenario

Basis of the approach is the analogy between telecommunications and logistics networks. The basic principles of a traffic control in telecommunications networks can be summarized as follows:

- Recording or measuring the traffic density in the case of usual capacities,
- Determination of destination factors from the inflowing traffic,
- Comparison of the destination factors in the case of usual capacities with the current traffic density,
- Comparison of expected traffic density of individual network elements,
- Routing decision.

For an effective large-area traffic management it is useful to know the source and destination areas of a movement so that effective paths between these areas can be determined before the mobility activity starts. For the solution of the problem it is necessary to segment the total area of the traffic movements. These segments could be structured e.g. on the basis of post code areas. For long-distance mobility activities the accuracy reached in that way should be sufficient. The movement can be shown as a model, as to be seen in Fig. 1.

Start area Transit area Target area

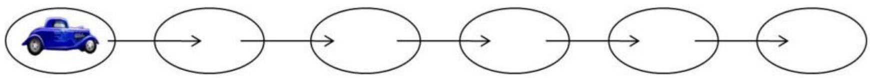


Figure 1. Movement ranges of a vehicle [4]

There are two questions which can be derived from Fig. 1. concerning routine decisions [3]:

- What do I have to expect where?
- How do I have to react when and why?

The movement at a certain speed is integrated in a model. The prognosis of when a certain point of the traffic infrastructure will be reached, is the essential criterion for the routing using an integrated strategy of avoiding overloads in the infrastructure elements, in which the required and the available resources do not match. Marginal requirements for a decision are the movement at a certain speed and the time prognosis of reaching a certain point of the traffic infrastructure. In logistics networks solving the path-time problem is critical, whereas it does not play any role in telecommunications networks.

3.2. Modeling

The requirement for the feasibility has been met, it is connected, however, with the following conditions [4]:

- Movement profile of (all?) vehicles can be shown,
- Movement at predictable average speed,
- Car – to – infrastructure communication,
- Real – time information transmission,
- Reliable routing in good time,
- Background model.

This background model in its essential components is shown in Fig. 2.

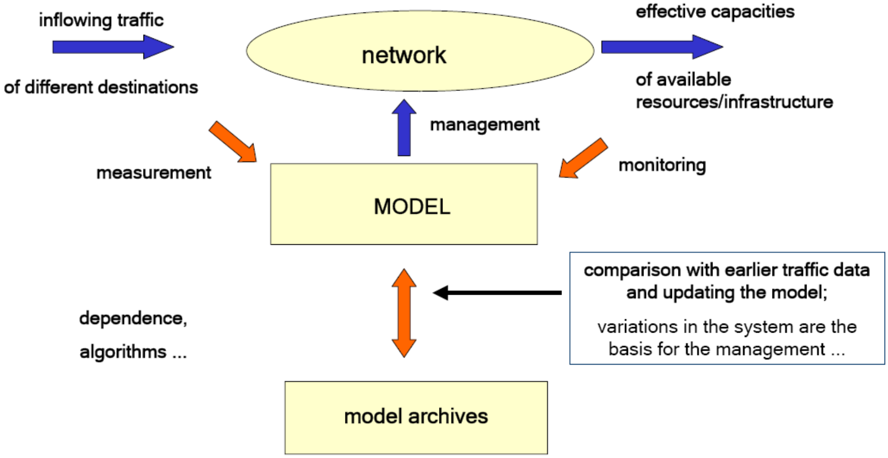


Figure 2. Background model [4]

For a reliable decision there are not only the currently captured data which have to be processed. Essential findings concerning the development of traffic capacities under certain circumstances can also be drawn from historic data. It is, therefore, reasonable to extend the model and consider relevant time series as it can be seen in Fig. 3.

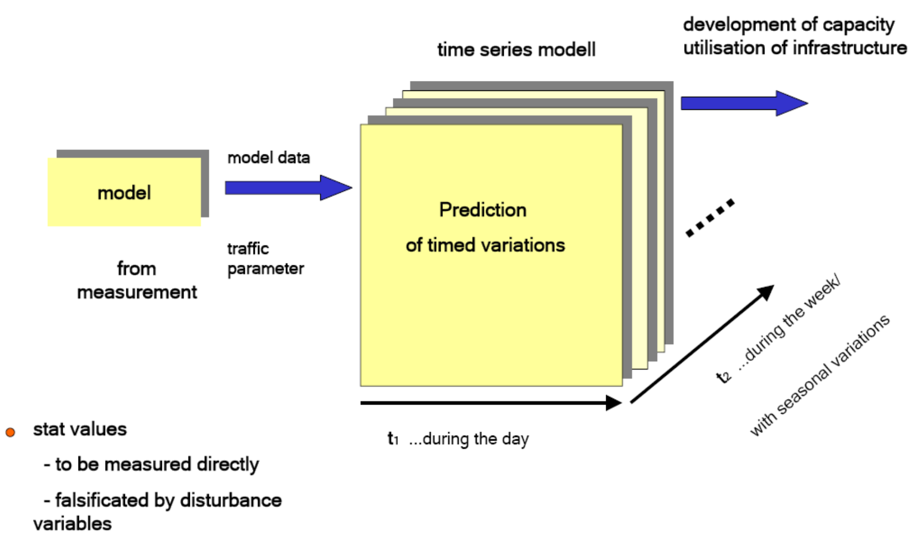


Figure 3. Extended model with time series [4]

3.3. Algorithm

The basic principles of the prognosis procedure for avoiding overload situations in resource-limited traffic infrastructures can be summarized in an algorithm. The algorithm of an application example could be designed as follows:

1. When starting a journey the post code of the destination area is entered via an onboard unit (OBU). This OBU is technically integrated in the mobility process. By this entry the source-destination relation is fixed.
2. Integration of this temporary source-destination relation in the model according to Fig. 2. Measurement or prediction of the source-destination traffic density x_{ij} in a traffic network $G = (W, E)$ which consists of a quantity W of nodes and a quantity E of edges. The individual elements of the graph are continuously indicated with the nodes being referred to as $w_i, i \in [1, \hat{w}]$ and the edges as $e_j, j \in [1, \hat{e}]$. Hence the symbols $\hat{w}$ and $\hat{e}$ also stand for the number of elements in the quantities of nodes or edges. The individual edges are assigned to the weighting of the edge between w_i und w_j by one or several rational, predominantly positive integers g_{ij}. They indicate characteristics of the edge and represent the quantity of parameters which are required for assessing the traffic load-dependent transport period $T_{Tr_{ij}}$ of motor vehicles on an edge between w_i and w_j.

   These weightings comprise a static and a dynamic part. The static part describes the load on the edge due to the free traffic. In our case it is described by the expectance variable of the transport period $E(T_f)$. The dynamic part considers the real influences of the current traffic situation, such as congestion, accident, high traffic density. In accordance with [5] the process reliability $Z_{\Pi}(t)$ is defined.

$$Z_{\Pi}(t) = Z_{Tr}(t) \cdot Z_{Sy_\eta}(t) \cdot Z_{Sy_\nu}(t) \cdot Z_{Sy_\iota}(t) \tag{1}$$

with:

Z_{Tr} Transport reliability,

Z_{Sy_η} Operator reliability,

Z_{Sy_ν} - System reliability of the means of transport and

Z_{Sy_ι} System reliability of the itinerary (Infrastructure reliability)

The transport reliability $Z_{Tr}(t)$ which is defined as the probability that a vehicle goes from i to j within the period t can be characterized by the transport process, whereas the other components of the process reliability are accessible via the failure and recovery processes.

3. Calculation of the destination factors f_{ij} (from destination post code and others) as the quotient of the number of vehicles X_{ij} to the total quantity X. The destination factors can be represented as the following matrix

$$\vec{F} = [f_{ij}] \tag{2}$$

with the condition of standardization

$$\sum_{i=1}^{\hat{e}} \sum_{j=1}^{\hat{e}} f_{ij} = 1 \tag{3}$$

4. The vehicle volumes are subject to temporal and stochastic fluctuations. The temporal variations can be illustrated by day and week curves (model of time series acc. to Fig. 3.). These curves show considerable differences on the individual relations. It is, therefore, difficult to develop an analytic model of the temporal dependences of the individual relations.

   These dependences also have an effect on the destination factors. It is sufficient that the temporal dependences of the destination factors are indicated within the time intervals τ to be fixed

$$\vec{F}(\tau) = [f_{ij}(\tau)] \tag{4}$$

5. Determination of the static weighting factors $g_{stat_{ij}} = E(T_{f_{ij}})$ as the expected value of the transport period of the free traffic under consideration of the following influencing variables:

   – legally fixed maximum speeds,
   – road conditions,
   – traffic conditions,
   – utilization of the payload,
   – specific drive power and
   – drivers' behavior.

   There is

$$g_{stat_{ij}} = E(T_{ij}) = \frac{s_{ij}}{\bar{v}_{f_{ij}}} \tag{5}$$

6. Determination of the shortest paths on all source-destination relations on the basis of an algorithm for calculating minimum paths, e.g. a matrix algorithm following Floyd [6]. Initially these paths are determined without considering the traffic capacity.

7. Determination of the dynamic parts of the weighting factors termed as the process reliability $Z_{\Pi}(t)$. For the individual parts acc. to formula (1) the following items have to be considered:

7.1 Concerning the transport reliability constraints are considered which are caused by excessive traffic volumes. It can be determined in a simplified way by the quotient of the speed dependent on traffic density to the speed of the free traffic. An analytic approach concerning the mean speed $v_m(\rho)$ depending on the traffic density ρ is the approach following Kühne [7]

$$v_m(\rho) = v_f \left[1 - \left(\frac{\rho}{\hat{\rho}} \right)^a \right]^b \tag{6}$$

The mean transport speed is a function of

- the empiric road specific parameters a and b,
- the capacity of the road (traffic density) ρ
- the maximum utilization of the road $\hat{\rho}$ and
- the average speed of the free traffic $\bar{v}_f$.

In Fig. 4. there is a model calculation with a = 2.05 , b = 21.11, $\bar{v}_f$ = 100 km/h and $\hat{\rho}$ = 168 cars/km.

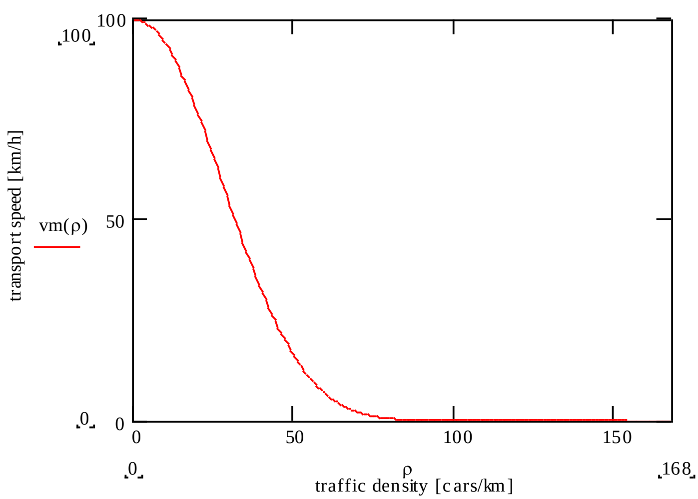


Figure 4. Diagram of speed and traffic density

For the transport reliability the following is applied:

$$Z_{Tr}(t) = \frac{v_m(\rho(x,t))}{v_m(0)} = \frac{v_m(\rho(x,t))}{v_f} = \left[1 - \left(\frac{\rho(x,t)}{\hat{\rho}}\right)^a\right]^b \tag{7}$$

For the purpose of determining the transport reliability the quality of the available data has to be considered. For the transport process on the currently used edge or the edge onto which the vehicle wants to enter immediately (near-future transport process) it is possible and reasonable to consider the current state data of the traffic process (mean density ρ_m, mean speed $v_m(\rho_m)$, maximum possible speed of free traffic v_f,). The farther the vehicle is away from the present location, the more inaccurate the calculations become, since the above parameters can only be estimated or have to be determined by prognosis models. For this far-future transport process a different algorithm for determining the transport reliability will be required.

The (discrete) Hilliges-Weidlich model acc. to [8] is used for modeling the near-future transport process. The continuity equation for this model is

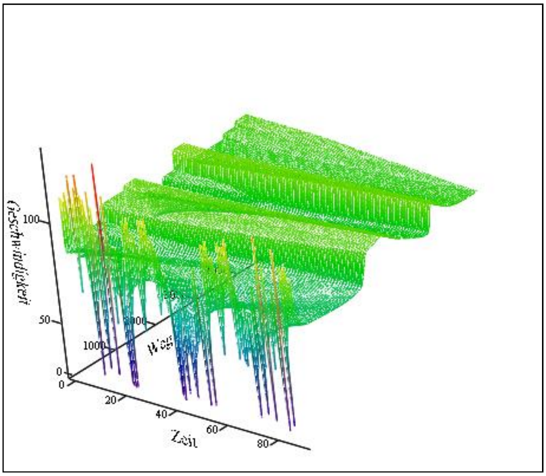
$$\frac{\partial \tilde{\rho}(j,t)}{\partial t} = \frac{\tilde{\rho}(j,t)\tilde{v}(j+1,t) - \tilde{\rho}(j-1,t)}{\Delta t} = 0 \tag{8}$$

and the dynamic velocity equation is

$$\frac{\partial \tilde{v}(j,t)}{\partial t} + \tilde{v}(j,t)\frac{\tilde{v}(j+1,t) - \tilde{v}(j-1,t)}{2\Delta x} = \frac{1}{\tau}\left[v_m(\tilde{\rho}(j,t)) - \tilde{v}(j,t)\right] \tag{9}$$

with the traffic density $\tilde{\rho}(j,t) = \rho(j\ \Delta x, t)$, the length of a road cluster $\Delta x = 100m$, the relaxation time $\tau = 5s$ and the relation of velocity and traffic density acc. to formula [6]. Fig. 5. shows the qualitative simulation of the density-dependent velocity $v(\rho)$ for this model on the basis of fictitious data.

Concerning the far-future transport process the traffic density $\tilde{\rho}_{prog}(x,t)$ has to be determined on the basis of the available prognosis data of the destination factors $\vec{F}(t)$ and the actual traffic data ρ_{akt}. Intensive research work will be required for this purpose.



V
Geschwindigkeit nach der Bewegungsgleichung

Figure 5. Traffic flow diagram (qualitative) acc. to the Hilliges-Weidlich model

7.2 The system reliability $Z_{Sy}(t)$ falls into the categories of facilities reliability $Z_{Sy_\nu}(t)$ - for the transport process also referred to as reliability of transport means-, the operator reliability $Z_{Sy_\eta}(t)$ and the infrastructure reliability $Z_{Sy_{\tau(t)}}$.

The operator reliability describes the driver's work capability, which shall not be detailed here. There is $Z_{Sy\eta}(t) = 1$.

The infrastructure reliability describes the traffic breakdowns or restrictions on an edge caused e.g. by accidents, broken vehicles, unplanned construction sites. The following operational areas are distinguished:

- Nominal operation mode: All traffic lanes are available at a fixed maximum speed.
- Malfunction mode: There are either fewer lanes available and/or the maximum speed is restricted.
- Collapse: There is no lane available.

By using non-stationary reliability models the infrastructure reliability can be determined analytically by approximation. The following simplified example shows the approach. There is a single lane with the following speed ranges:

- Free traffic (in the case of long-term restrictions this can also be the relevant reduced speed) = state Z_0 = nominal operation mode

– Restricted traffic = state Z_1 = malfunction mode

– Stationary traffic ($v = 0$), i.e. congested lane = state Z_2 = collapse.

There is the equivalent diagram of reliability acc. to Fig. 6.:

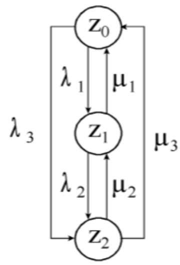


Figure 6. Equivalent diagram of system reliability of a single-lane road

For the purpose of simplification the transition rates λ and μ are assumed to be equal, i.e. there is: $\lambda_1 = \lambda_2 = \lambda_3 = \lambda$ and $\mu_1 = \mu_2 = \mu_3 = \mu$. Concerning the start vector $\vec{P}(t) = \begin{pmatrix} 0 & 1 & 0 \end{pmatrix}^T$, i.e. the state Z_1 is active, the non-stationary state probabilities are determined using the abbreviation $\rho = \dfrac{\lambda}{\mu}$ as follows

$$\begin{pmatrix} Z_0(t) \\ Z_1(t) \\ Z_2(t) \end{pmatrix} = \begin{pmatrix} \dfrac{1}{2\rho+1}\left(1-\exp\left[-(2\lambda+\mu\right]t\right) \\ \dfrac{3\rho}{2+5\rho+2\rho^2} + \dfrac{1}{2\rho+1}\exp\left[-(2\lambda+\mu)t\right] + \dfrac{\rho}{2+\rho}\exp\left[-(2\mu+\lambda)t\right] \\ \dfrac{\rho}{2+\rho}\left(1-\exp\left[-(2\mu+\lambda)t\right]\right) \end{pmatrix} \tag{11}$$

For the stationary case there is

$$\lim_{t\to\infty} Z_0(t) = \frac{1}{2\rho+1}$$
$$\lim_{t\to\infty} Z_1(t) = \frac{3}{2+5\rho+2\rho^2}$$
$$\lim_{t\to\infty} Z_2(t) = \frac{\rho}{2+\rho}$$

The result is the qualitative correlation acc. to Fig. 7.

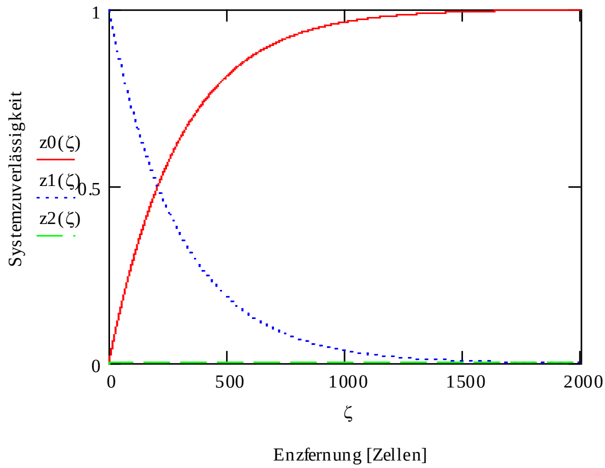


Figure 7. State diagram of a single-lane road

For calculating the dynamic weighting factors the nominal operation mode $Z_{Sy_t(t)} = Z_1(t)$ is used.

Using the facilities reliability $Z_{Sy_v}(t)$, in this case the reliability of the transport means, the availability of the vehicle can be determined. As an analytic model the maintenance theory offers the model of scheduled preventive maintenance (PVI) following a life-related cycle with total maintenance being done in the case of breakdowns, see e.g. [9]. For calculating the dynamic weighting factors we use the availability of the system $Z_{Sy_V}(t) = V_{Sy_v}(t)$.

8. Determination of the weighting factors from the individual relations of the static and dynamic parts as follows

$$g_{ij} = g_{stat_{ij}} \cdot g_{dyn_{ij}} = \frac{\frac{s_{ij}}{v_{f_{ij}}}}{Z_T(t) \cdot Z_{Sy_t}(t) \cdot Z_{Sy_v}(t)} \tag{12}$$

9. On the basis of route determinations for the free traffic and using the matrix of weighting factors $\vec{G} = [g_{ij}]$ alternative routes can be calculated in accordance with the same routing algorithm.

4. Results

If an edge or a node of a network has been identified as an essential location for the trouble-free traffic management within the total network, this location can be integrated in a management model. For this purpose the inflow is measured, the traffic directions are selected, the capacities at a location are predicted and on the basis of the available capacities the inflows to that location are limited or modified by an alternative traffic guidance. Identifying an overload situation at an integrated location of the infrastructure at a future time means that avoiding strategies can be activated by

- reducing the inflow,
- alternative routing with time restrictions,
- time impacts such as speed regulations in terms of maximum or minimum speeds etc.

5. References

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