Traffic Network Guidance using Area Accumulation and Spatial Variation in Density

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1 Routing with the Macroscopic Fundamental Diagram

Network management has become more relevant in recent years. Urban areas have become larger, and the road traffic more intense, such that local disruptions can have effects which stretch to different locations. Road authorities have to manage the traffic accordingly, meaning it is required that they take network effects into account in their management actions. Large traffic models can be built, allowing to study the effects of all combinations of measurements. However, running these models in real time is not feasible. This paper investigates whether it is possible to have control based on a more aggregate level, requiring less calculations.

1.1 Background

Geroliminis and Daganzo [3] re-introduced the Macroscopic Fundamental Diagram, or Network Fundamental Diagram (NFD) for modern traffic control. This NFD describes the traffic flow phenomena as function of one parameter, being the accumulation A, i.e. the number of vehicles in an area. For a fixed area, the amount of available roadway length is fixed, and hence the accumulation can be translated into the average density. The NFD relates this accumulation to the network production, P, i.e. the average flow in the area.

It has been shown that network variability also affects the production [6]. Last year, we therefore proposed a generalized macroscopic fundamental diagram [4] which gives the production in an area as function of the variation of the density in the area (expressed by the standard deviation of the density of the cells in the area, γ) and the accumulation

$$P = P\left(A, \gamma\right) \tag{1}$$

1.2 General idea

The idea described in this paper exploits the fact that not many data are needed to get this average flow. It would be time consuming, costly and computationally hard to collect traffic data at all locations, to transmit these, and to process these in a traffic state estimation procedure which gives the detailed state at each location in the network. Instead, we will split the network into different parts, *areas*, for which we only use the accumulation and the inhomogeneity in the area to estimate the traffic state. The accumulation and production together give the average speed in the area, v:

$$v = \frac{P}{A} \tag{2}$$

This speed, different for all areas in the network, can be used to guide traffic through the network. This way, we separate the routing strategies on the network level, the *high level* routing strategies, from the detailed routing within an area, which can be optimized separately.

1.3 Goal

The aim of this paper is to study the effectiveness of high-level routing algorithms, using only these aggregate data, production, spatial spread of density and accumulation. These routing algorithms can be used in large networks, in which it is difficult to collect all detailed data, and even more difficult to get a state estimation (let alone prediction) of the network on link level. The advantage of the high-level routing strategies we propose in this paper is that the inputs can be estimated on an aggregate level, and the state estimate can be relatively coarse. Data-wise, accumulation can be estimated directly and the variation of density can be estimated by the spread in density over some detection points. In particular, we are interested in the added value of the variation of densities on the performance. In this study, the total delay is chosen as measure of performance.

2 Experimental Setup

To test the effectiveness of the routing strategies, we implement several routing strategies in a simulation model. This section describes the experimental setup, in terms of the traffic flow model (section 2.1), the network and origin-destination matrix (section 2.2), and the considered routing strategies (section 2.3).

2.1 Traffic flow model

For this study we use a cell transmission model [1] to generate the ground truth data. In this simulation we guide the traffic according to different routing schemes (see section 2.3). The nodes are modeled according to the model of [7]. This means that in congestion, the supply will be divided over the inlinks proportionally to the capacity. It is important to note we use a macroscopic traffic simulation program, in which the traffic lights are not modelled as such.

2.2 Network and OD

For the network we use a regular grid network of size 20 x 20 nodes with periodic boundary conditions, similar to the setup in [5]. We have 19 randomly chosen nodes in the network which act as origin and destination.

A base, fixed, OD matrix is multiplied by a time varying factor to better resemble traffic dynamics. For the first three hours, the demand level are based on a morning peak (i.e., the average flows from 7-10 am, see figure 1). After 3 hours, we choose to reduce the demand to zero to study how congestion solves in the network.

2.3 Routing strategies

We consider five main routing strategies, summarized in table 1. In the first one, routes are fixed to the (stochastically determined) shortest path in distance. This will lead to congestion. In all other routing strategies, drivers will adapt their routes en-route based on congestion. In the second routing alternative, traffic will use speed information on all links to find the fastest route.

For the other routing strategies, information per area is calculated. We define an area as all links in a block of 4x4 nodes. For the third routing strategy the average speed in an

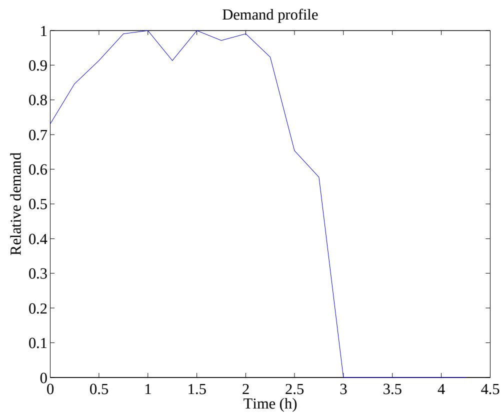


Figure 1: The dynamic demand profile

Table 1: The compared routing strategies

Type	Dynamic	Shortest...	Aggregation	type of info
Fixed	No	...distance	None	Distances
Speed	Yes	...time	None	Distances and speeds at all locations
Average speed	Yes	...time	area	Average speed in an area
Accumulation (NFD)	Yes	...time	area	Accumulation in an area
Area state	Yes	...time	area	Accumulation and variation in density in an area

area is measured perfectly and drivers react to that. This leads to fastest routes (speed is directly related to the travel time) if routing is only possible on an aggregate level (i.e., no route control down to the individual links is possible). It is unrealistic to assume the average speeds are known perfectly, but this routing strategy is introduced as benchmark as best possible routing if only aggregated routing measures can be taken. The fourth routing strategy, the same strategy as described in [5], uses the accumulation in an areas and from this accumulation, using the NFD, speed is calculated. This is assumed to be the average speed for all links in the area. Earlier, we investigated the effect of several accumulation-production relationships (i.e., shapes for the NFD). The relation proposed by Drake [2] was found to give the best routing. Therefore, we use the same relationship here as benchmark for the routing strategies:

$$P = Av_{\text{free}} \exp\left(-\frac{1}{2}\left(\frac{A}{A_{\text{crit}}}\right)^2\right) \tag{3}$$

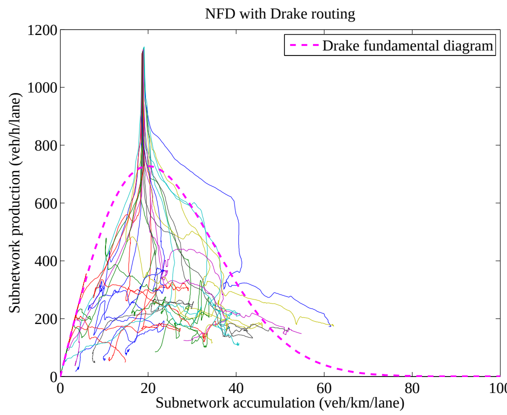
In this equation, we follow our earlier paper and take v_{free}=60 km/h and A_{crit}=20 veh/km. Drivers are routed over the fastest route in time.

Finally, the fifth routing strategy estimates the speed in an area based on the accumulation and the spatial variation in density. We will refer to the comination of accumulation and spatial spread of density as *area state*. This is of particular interest since it will show the added value of estimating the inhomogeneity in the area. Also in this routing strategy, the same speed is assumed for all links in the area.

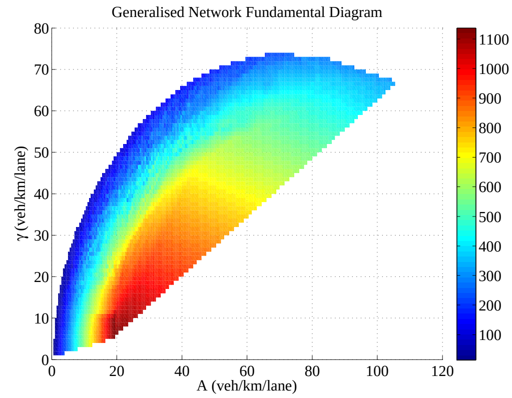
3 Estimating the production from accumulation and variation in density

This section describes how the production can be estimated from the accumulation and spatial spread of density. First, the traffic simulations are run for the scenarios in which the spatial variation of density does not yet play a role. An example of the traffic operations in an area predicted by a simulation with accumulation traffic routing is given in figure 2(a). This shows that the actual traffic operations clearly do not follow the NFD. The underlying reason for it not to have the crisp relationship shown by [3] is outside the scope of this paper.

What is important for this paper, is that we can – empirically – create the function



(a) The NFD and the estimated form



(b) The production as function of accumulation and spatial spread of density

Figure 2: The influence of the variation of density

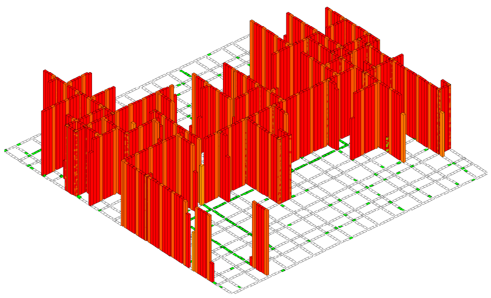
$P = P(A, \gamma)$ (equation 1) out of these simulation runs. Of course, the measurements will not form a grid in (A, γ); for each point on the grid (A, γ) we determine the production by interpolating the surrounding points. The resulting function is visualized in figure 2(b).

Now we use this relationship to predict the production (and hence the speed, equation 2) for areas, and thus use it as the base for routing. Every 15 minutes a new routing needs to be calculated. The accumulation and spatial spread of density at that moment is taken as input for determining the production. Generally, these will not lie at the grid (A, γ), so now an interpolation of the function values is made to find the correct production. For traffic states with area state outside the area found in the earlier simulations, the production according to Drake (equation 3) is used instead.

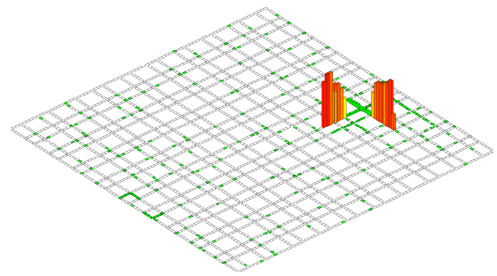
4 Results

Figure 3 shows the traffic situation after 3.75 hours simulation time. Without traffic control, a gridlock has occurred and the network is blocked (figure 3(a)). With control based on speed on all links, almost all traffic has reached the destination in 3.75 hours and the network is almost empty (figure 3(b)).

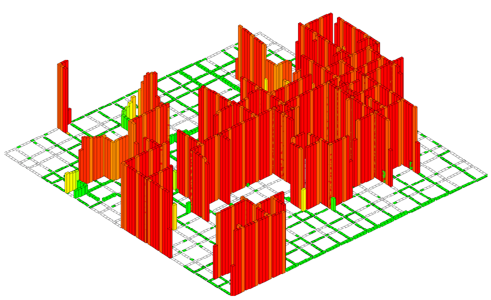
With traffic control based on the average speed in an area, the situation is better than without control, but not as good as with detailed control. This is shown in figure 3(c). The same can be said for the scenarios with traffic control based on the accumulation



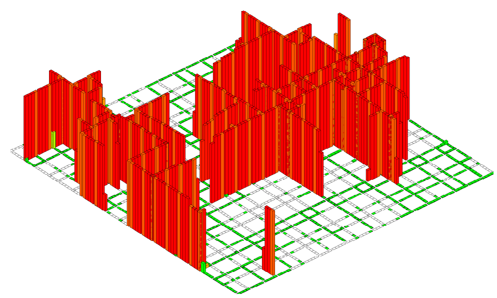
(a) No routing



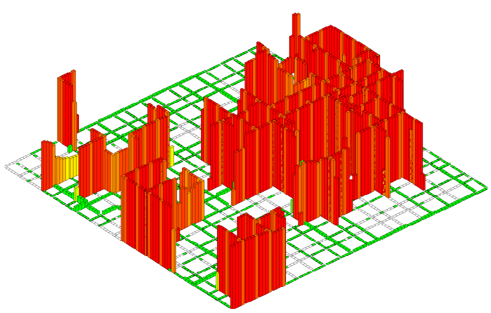
(b) Routing based on speed



(c) Average speed routing



(d) Accumulation routing



(e) Area state routing

Figure 3: Traffic states after 3.5 hours of simulation. The height of the bars indicate the density and the color the speed.

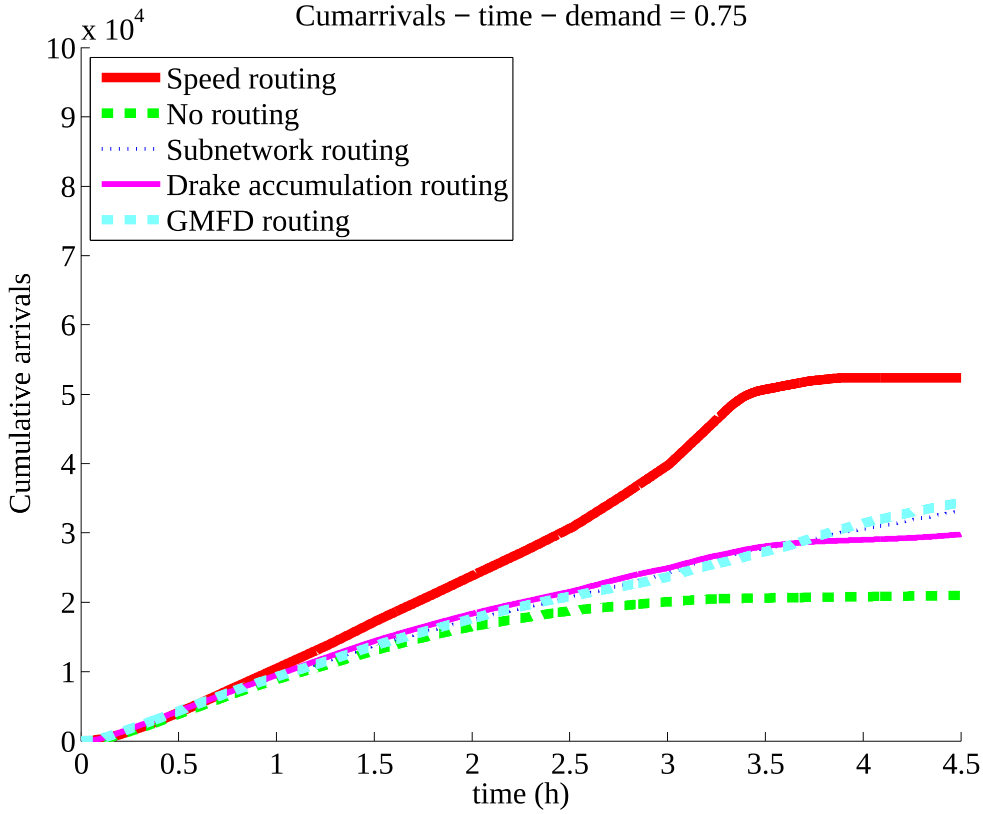


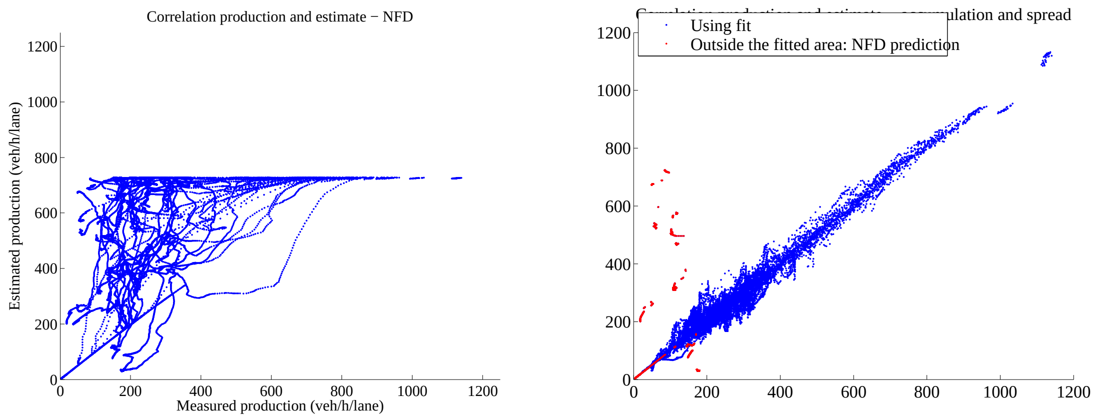
Figure 4: Cumulative arrivals as function of time

(figure 3(d)), and the control based on the area state (figure 3(e)).

These figures do not show quantitatively the differences between these last three scenarios. This is shown in figure 4, showing the cumulative arrivals over time. Clearly, the scenario with speed routing is the best (the steepest) and is the only scenario in which all travellers arrive. The scenarios with fixed routing is the worst, leading to a gridlock (no arrivals from 2.75h).

While building up congestion, both scenarios with aggregated routing perform similar, in between the scenario with fixed routing and that with speed routing. From the moment the demand drops, at t=3h, the scenario with accumulation and variation of density to predict the production outperforms the scenario with accumulation routing. In fact, the scenario with the speed prediction based on area state performs as good as the scenario with the routing based on the average speed, the benchmark for routing by aggregated area.

Both the method with the accumulation and the method using the area state predict



(a) Drake NFD

(b) accumulation and variation of density

Figure 5: Correlations of the measured production and the predicted production

the speed in an area. Figure 5 shows the quality of these predictions: both figures show the actual production and the predicted production. Figure 5(a) shows that the production is often underestimated using the NFD (equation 3). In the previous paper [5] we argued that an underestimation is not a problem for routing purposes, as long as the underestimation is consistent. The figure shows that this is not the case since the points are quite scattered in the plane. The correlation coefficient R^2 is 0.42 for this prediction, indicating the correlation is not very high.

The estimation based on area state does much better. Figure 5(b) shows the correlation and this is very good indeed. The red dots indicate the production predictions made by the NFD in case the area state is out of the area for which the fit of the production as function of the area state is made. For these points, the correlation between the predicted production and the actual production is much worse. The other predicted productions actually based on the area state are almost perfectly correlated with the measured production, judged by a correlation coefficient R^2=0.98.

The total performance is slightly better than the performance with accumulation routing and almost equal to the routing based on the average speed. There is some room for improvement, since the routing using individual link speeds performs much better.

5 Conclusions and outlook

This paper investigated the possibilities to use aggregated information for routing in an urban grid network. The routing was one the best based on: (1) distance (fixed), (2) speed per link, (3) average speed in an area, (4) average speed derived from the accumulation in an area, (5) average speed derived from the accumulation and the spatial spread of density in an area. This was tested using a dynamic demand: first traffic jams built up and then demand reduced allowing the network to solve the traffic jams.

As expected, the fixed routes gave the worst performance, leading to gridlocks, and the speed-based routes gave the best performance. Both routing strategies using area-wide accumulation performed almost equally well during the build-up of congestion. During the final phase, in which traffic jams dissolved, the scenario also using the spread of density performed slightly better. In fact, the performance of this routing strategy was almost the same as the routing based on the average speed in the area. What the paper shows, is that the accumulation and spatial spread of density give a good enough representation of the traffic state for the purpose of high-level traffic control. Hence, to answer the research question, area-level control using aggregated information is possible.

The prediction of the traffic production only using the accumulation is much worse than the prediction also incorporating spread of density. The bad performance of the accumulation routing might be related to the small size of the area or the inhomogeneity. The performance of aggregated control, whatever way the average speed is computed, is worse than unaggregated control, i.e. if the speeds at all links are known and routes can be controlled down to link-level. This is something that can be considered in a lower-level control scheme, which is computationally less demanding, since it can operate at a smaller spatial scale.

In all the considered scenarios, the routing for the following time period is based on current traffic speeds. A possible way to further improve the routing based on aggregated information is to incorporate the future traffic states. What hence seems a promising control strategy is model predictive control using aggregated information: accumulation and spatial spread of density.

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