

The Effect of Traffic Signals on the Macroscopic Fundamental Diagram



Boudewijn Zwaal, Victor L. Knoop, and Hans van Lint

Abstract Since the recent empirical evidence of the existence of the macroscopic fundamental diagram (MFD), there are already numerous applications for it, ranging from traffic management to traffic flow modelling. However, little is known what effect internal network control has on the shape of the MFD. This research will investigate the shape of an MFD on a regular network with and without traffic lights. To this end, we consider a regular grid network of infinite length. This is represented in a microscopic traffic simulation model as a two-ring network. We compare the situation without traffic lights to the situation with traffic lights with fixed timing. The uncontrolled case shows a higher flow for lower densities, while the controlled case shows a higher flow for higher densities. Analysis of the underlying process shows that this is due to the fact that traffic lights keep the vehicles spread more homogeneously over a network. In contrast, uncontrolled intersections result in an unstable situation where one part of the network becomes fully congested and the other part almost empty. This shows that traffic lights are reducing the performance for the low-density situations, but improving the traffic performance in high-density situation. In particular, the stability of a homogeneous spatial traffic distribution can be improved, even with fixed traffic light settings.

1 Introduction

The idea of describing traffic dynamics within a neighbourhood, or zone, by means of a single function is very recent. This macroscopic fundamental diagram (MFD) relates traffic production (i.e., the average flow) to traffic density within an urban network and can therefore be used in traffic flow models for large urban areas. Introduced by Godfrey [11], the MFD has been shown to exist empirically [9], where they averaged loop-detector data from the city of Yokohama in Japan. This

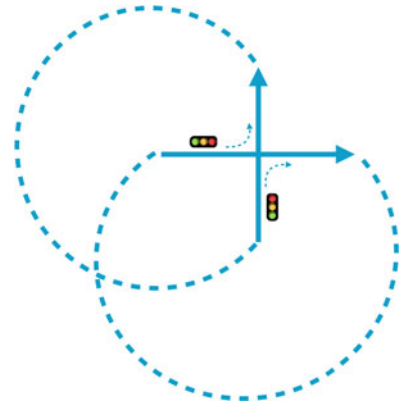
B. Zwaal · V. L. Knoop (✉) · H. van Lint
Delft University of Technology, Delft, The Netherlands
e-mail: v.l.knoop@tudelft.nl

concave relationship appears to have one value for the density at which the flow in the network is maximal, which is called the critical density. Increasing the density beyond this value decreases the flow and this is where we speak of congestion. Daganzo [1] proposed that a necessary condition for the existence of an MFD is that the spatial distribution of traffic (and therefore of congestion) is homogeneous over the network. While Geroliminis et al. [10] indeed showed that the spatial distribution has an important impact on the shape and the amount of scatter in the MFD, Knoop et al. [12] showed that the MFD is actually a cross-section of a generalized MFD. This GMFD is a continuous three-dimensional function relating density and inhomogeneity to average flow, therefore suggesting that there is no single MFD for every traffic state. Another condition often considered as necessary to have an MFD is that the demand changes slowly over time. Daganzo [2] states that in rapidly changing demand situations, the MFD may exhibit too much scatter. Next to these conditions, little is known about network-specific properties that influence the MFD.

The most common urban-network elements are intersections, with or without traffic lights. A first step to find the influence of specific urban elements on the MFD would therefore be to investigate the effect of traffic lights at intersections on the MFD. Gayah et al. [6] propose a simple network of two one-way roads with periodic boundary conditions, which intersect each other at one location. At this location it is possible to change from one road to the other road, see Fig. 1. While the authors study the flow using different densities and turn fractions, therefore creating an MFD, they do this using kinematic wave theory. This means that they assume a fundamental diagram (FD) for each road.

The shape of an MFD considering (adaptive) traffic lights has already been researched with microscopic simulations [4, 8]. Both papers conclude that the network outflow is higher when the traffic signals are adapted such that they prevent gridlock from happening, especially in the uncontrolled parts of the network. Both studies test this however on a relatively large network with multiple intersections,

Fig. 1 The network



where we will try to bring the shape of the MFD back to the very basics by means of one single intersection.

The research as presented in this paper is therefore to investigate the impact of traffic lights on the shape of the macroscopic fundamental diagram, using a microscopic traffic simulation on the simple double ring road as presented in Fig. 1. The results show a more stable traffic state for the controlled intersection, which can be used in determining the layout of an aggregated network for which we assume an MFD, which in turn can be used in large-scale traffic models that utilize the MFD.

The outline of this paper is as follows. We first present the methodology in Sect. 2, stating the simulation set-up, the calculation of the MFD, the model parameters, traffic light and turn fraction settings in respectively Sects. 2.1–2.3. We then present the analyses that we have performed in Sect. 2.4. The results of these analyses are shown in Sect. 3, and we discuss and conclude these results in, respectively, Sects. 4 and 5.

2 Methodology

2.1 Simulation Set-Up

To study the effect of traffic lights on the MFD, we use a simple intersection where two one-way roads cross, see Fig. 1. Here, the vehicles that exit the intersection on road 1 return to the intersection on road 1, so there are periodic boundary conditions. We assume that both roads have the same length (1 km in our simulations) and that all vehicles have the same probability to turn according to predetermined turning probabilities. The model includes the intelligent driver model for the car-following behaviour of the vehicles.¹ At the start of the simulation, a predetermined number of vehicles are evenly spread along the two roads, and all start with a speed of zero. The simulation is run for 10,000 s, or 2.8 h, with a time step of 0.1 s, after which it terminates. To compute the average flow we use Edie's generalized definitions [5] for $t = 5000$ – $10,000$ s, yielding one observation.

2.2 Car-Following Parameters

For the intelligent driver model, we aimed to choose the most appropriate and realistic parameters. A list is given in Table 1. For an explanation of these parameters, see [13].

¹See, for example, [13, chapter 2].

Table 1 Parameters used in the intelligent driver model

Free-flow speed	15 m/s
Safe time headway	1.6 s
Maximum acceleration	0.73 m/s ²
Comfortable deceleration	1.67 m/s ²
Acceleration exponent	4
Length of car	4 m
Linear jam distance	2 m
Non-linear jam distance	3 m

2.3 Traffic Lights and Turn Fractions

The intersection consists of a simple traffic management system which allows vehicles on one road to pass through (where vehicles either continue on the same road or change roads) while the vehicles on the other road have to wait for red. During all simulations we use a cycle time of 60 s with a green time of 30 s. Every vehicle in the simulation chooses to either stay on their road or turn to the other road at the intersection. The four probabilities are thus: p_{11} to stay on road 1, $p_{12} = 1 - p_{11}$ to change from road 1 to road 2, and in a same manner p_{22} to stay on road 2 and p_{21} to change from road 2 to road 1. During all simulations we set $p_{11} = p_{22} = 0.5$ since this is required for a stable situation, at least stable as a result of the turning fractions. We should remark here that in the uncontrolled situation, the priority rules are such that the vehicles cross the intersection alternately, which is equivalent to an all-stop intersection as is often used in the USA and Canada.

2.4 Analyses

The analyses we will perform with this model consist of the comparison between the uncontrolled intersection and the controlled intersection. We will compute the average flow as described above for all total number of vehicles between 0 vehicles and 160 vehicles (jam accumulation) per road, using an interval of 10 vehicles, for both scenarios. Notice that this results in 256 simulations per scenario. These 256 number of average flows will be visualized in an MFD and a contour plot, where the latter helps to visualize the impact of the initial distribution among the two roads. As described above, we will use the same cycle time and turning fractions for all simulations.

3 Results

In this section we will present the results of the analyses. Both MFDs from the uncontrolled and controlled simulation are shown in Fig. 2. Here all data points are shown, where one point is based on one simulation. The white line represents the median, the dark blue filling represents the first and third quartiles, and the light blue filling represents the outliers. Both the uncontrolled and the controlled MFD show a linear increase of flow for densities lower than 50 vehicles, which is the case where all or nearly all vehicles can drive at free-flow speed. Then we see in both figures a line representing the capacity, which in the case of the uncontrolled simulation is higher (380 veh/h) than the controlled case (260 veh/h). The uncontrolled MFD starts to decrease when exceeding an accumulation of 100 vehicles, where the controlled declines after 140 vehicles, allowing some simulations up to an accumulation of 200 vehicles to keep their flow at the high value of 260 veh/h. The fact that there are different outcomes of different initial accumulation distributions that have the same total number of vehicles can be seen in Fig. 3. When the initial spatial distribution is more balanced in the controlled situation, i.e., a total number of 200 vehicles consisting of 100 on the first road and 100 on the second road in contrary to, for example, 140 and 60, the flow will remain higher. This is not seen in the uncontrolled case, visible through the straight diagonals in Fig. 3a. This ‘plateau extension’ of high flows in initially unbalanced high-accumulation situations on the controlled intersection, visible between a total accumulation of 150–200 vehicles and a total accumulation of 240–300 vehicles, is the biggest difference between the controlled and uncontrolled designs.

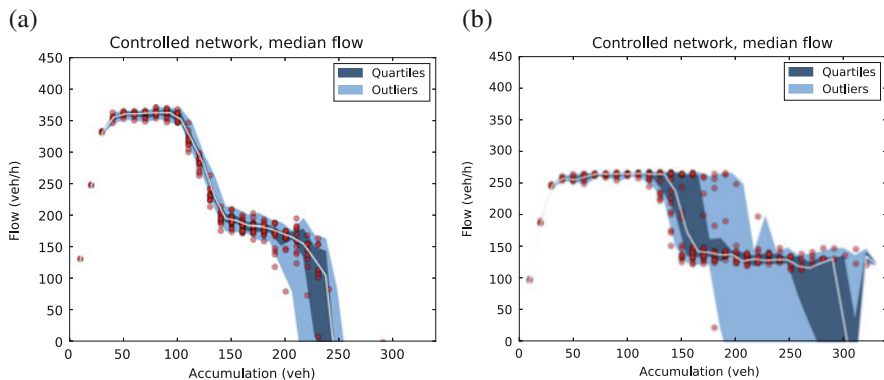


Fig. 2 Macroscopic fundamental diagrams. (a) Without traffic lights. (b) With traffic lights

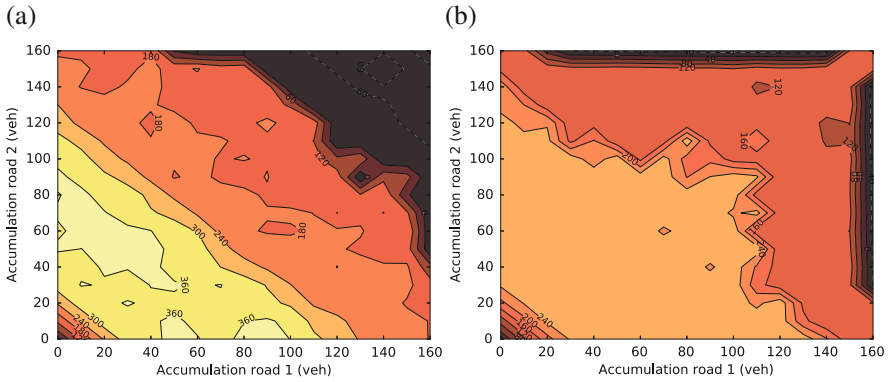


Fig. 3 Average flow (in colours). **(a)** Without traffic lights. **(b)** With traffic lights

4 Discussion

In this research we studied the effect of a simple intersection with and without traffic lights on the shape of the corresponding macroscopic fundamental diagram. We used a microscopic simulation on a double ring road with an increasing number of vehicles on both roads. For each case we computed the average flow which we plotted against the accumulation in an MFD graph. We showed that both situations lead to a concave MFD. The uncontrolled case had a higher peak at lower densities but a steeper and sharper decline after the peak, while the controlled case had a lower flow at lower densities but was able to maintain this flow also for higher densities. In the controlled scenario, it is interesting to see that there are two ‘plateaus’ in the MFD. The first plateau is the one which has a flow of 260 veh/h, which corresponds to the situation where most of the cars are driving at free-flow speed, while a part of them is standing in a queue to wait for green. The second plateau in the controlled MFD has a flow of 130 veh/h, and is especially interesting because it extends up until a total accumulation of 300 vehicles. These are situations where there are almost no vehicles driving at free-flow, and most vehicles are driving in a stop-and-go manner with the same frequency as the traffic light cycle. As long as there is space for such a stop-and-go wave to exist, the flow remains at a relatively high value of 130 veh/h. This shows that for higher densities, a traffic management system increases the throughput at a basic intersection such as the one used in this simulation, and thus that it would be interesting to turn the traffic lights off at lower densities, and on at higher densities.

When we investigate the different simulations from the uncontrolled case, we notice that after the critical accumulation of 100 vehicles in total, the system became unstable. Here we mean that there always will be one road filling up almost completely while the other roads empty itself. The system is unable to recover from this, and the flow therefore becomes remarkably low from an accumulation of 130 and onwards. It causes the flow to rapidly decline after an accumulation

of 200 vehicles, and this is an important difference between the uncontrolled and the controlled case. The controlled intersection is much better at abiding a stable configuration where the flow remains at a higher level. This also has the consequence that the vehicles are more homogeneously spread along the network, which is what we generally accept as a necessary condition for a low-scatter MFD.

Drawbacks of our approach are obviously that both the network and the intersection itself are very simplistic. While this does give us interesting insights in very basic situations, the applicability of this research to real urban networks is limited and therefore extending this research to larger networks is vital for our understanding of the macroscopic fundamental diagram. Another drawback is that the car-following model, the intelligent driver model (IDM), is very sensitive to its parameters and although we attempted to choose the parameters as realistic as possible, further research using different car-following models might give us more feedback on the effect of the model on the MFD.

Another interesting application of the double ring road is the two-bin model presented firstly by Daganzo et al. [3] and extended by Gayah et al. [7]. Here they start with a square-grid network, which they divide into two halves, each represented by a bin, i.e., the aggregated accumulation of that half of the network. They assume a homogeneous spread in accumulation and model each bin with an MFD, investigating the dynamics and more specifically the instability of the dynamics considering different densities. They conclude that the recovery of congested areas is relatively slow causing an unstable situation in which this hardly recovers at all. In Gayah et al. [8] the authors extend upon this research by comparing it with a network that uses adaptive traffic lights, giving green time according to the upstream demand. This showed to improve the stability. They did not, however, use static traffic lights as well in their comparison, which could be interesting as our study shows that they already improve the stability by quite a margin. Their network size is also relatively large, which makes the comparison with our results difficult.

5 Conclusions

Our study shows that the spatial distribution of traffic on a small network with at least one intersection using (static) traffic lights is much more homogeneous and stable than without any form of traffic control. This shows that when partitioning a network into reservoirs for which an MFD is assumed, this assumption might be invalid if the reservoir contains mostly un-signalized intersection, since this may lead to a more unstable and heterogeneous distribution of vehicles.

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