Network Fundamental Diagrams and their Dependence on Network Topology

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Abstract Recent studies have shown that aggregated over a whole network a rather crisp relation between average density (accumulation) and average flow (production) exists. This relationship is called the Network Fundamental Diagram (NFD). We developed a tool to automatically design networks. Using this tool, different networks are created for which the following general properties are the same: (1) the number of intersections, (2) length of signalised multi-lane arterial roads, (3) length of single-lane urban roads. The main contribution of this paper is that it shows that NFDs are not only dependent on these properties, but also on the exact network layout (e.g., which link connects to which link) and/or origin-destination pattern. As a consequence, the NFD needs to be determined for each network separately and cannot be derived from these general properties.

1 Introduction

The Network Fundamental Diagram (NFD) is the relationship between the number of vehicles and the average flow in an area. After [2] it gained attention. Recently developed control concepts as for instance perimeter control [6] or routing [8] require the shape of the NFD to be known. This shape can of course be measured in real life. For networks which are not yet implemented in real life, determining this curve empirically is impossible. Therefore it is useful to have techniques to determine this curve based on other principles.

An analytical method has been proposed [4], but this holds only for arterial roads with traffic lights. The network specific effects or influence of road types cannot be captured by this methodology. The question addressed in this paper is there: is the NFD dependent on road types and the specific network layout?

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In this paper we will show that the the network design can change the shape of NFD, even though the main statistics as roadway length and road types are the same. Mixing road types also has an effect. Methodologically the approach taken in this study is that random networks are being designed with similar properties. This could be networks with and without hierarchical structure (e.g., a ring road and minor roads inside).

The methodology to test different networks with all the same properties raised an issue, namely to create networks with all the same properties. This paper develops a method and a tool to do so, which is described in section 4. This tool is used in the study to create similar networks. The goal of this paper is to test the influence of the road layout. All active traffic management measures are hence not incorporated in this paper and for the traffic lights, a fixed timing is adopted.

The remainder of the paper is set-up as follows. The next section gives an overview of the ways to estimate the NFD. Then, section 3 gives the research set-up and methodology. Section 4 describes the tool which has been developed to create networks. Section 5 presents the resulting NFDs and finally, section 6 presents the conclusions.

2 Network Fundamental Diagrams

The field of research into the NFD is rapidly developing. The number of papers on the NFD which appeared recently is too large to discuss all, so we restrict ourselves to the shape of the NFD. For estimating the NFD, an analytical method has been developed [4]. The authors apply variational theory to traffic operations. Integrating the effect of traffic lights into the variational formulation, they are able to present an analytical approximation of the NFD. This is extended by [9] where the effect of route choice is included. Both papers use routes in one dimension, so effects of crossing flows cannot be studied with either of these methods. Effects of signal timing in a regular lattice network are shown by [11].

The dynamics of traffic play an important role in the shape of the NFD. This has been studied for instance for simple insightful networks [3] or grid networks [7]. They show that traffic networks tend to get more congested once traffic congestion sets in and that production decreases with decreasing traffic homogeneity. This feature is explained and seems to be independent of the network layout.

The design of a network itself is also of importance. With design we mean what the exact connections of the links are. The link length and the number of connections can be similar, but how these links are connected by intersections or T-junctions. The influence of these effects is – as far as the authors are aware – not been studied in depth yet, and this will be studied further in this paper.

3 Methodology

The goal of this paper is to study the effect of specific network design on the NFD. We do so by creating different networks which share the same basic properties. This means that the main road (arterials) are the same, as well as the locations of the connections between the main roads and the underlying road network. For the underlying road network, the roadway length is similar. However, the exact layout of this underlying road network is different. For instance, the underlying network may consist of several housing blocks, and a block of sport facilities. These can be arranged in a different order, changing the network connections. We say that the basic properties of these networks are the same, but the exact network is different.

The NFD represents traffic operations at the network level. It can therefore be conceived that the exact layout is an issue. On these changing underlying road networks, there are no traffic signals, so they cannot play a role. The main question addressed in this paper is: "Can the NFD been constructed from the roadway length, speed limit and capacity?"

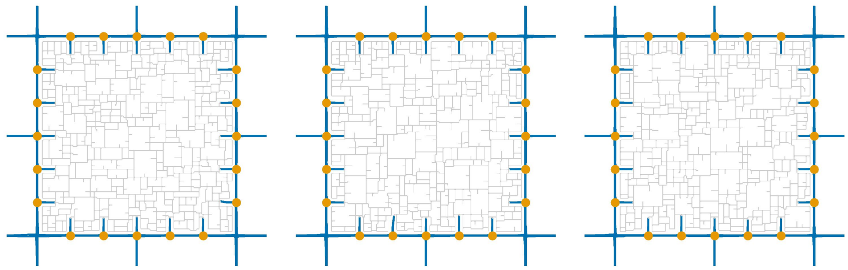
Creating similar networks is challenge on its own, which will be tackled by a tool which will be described in section 4. The tool will be used to create three different networks, all 3x3 km with an arterial ring road. However, they differ in the unsignalised roads.

The networks are in the end compared on the relationship between production and accumulation. These are calculated as follows. The production is the average flow, here calculated by the distance that all vehicles cover in a aggregation time divided by the aggregation time and the road length in the network (units: veh/h/lane). The accumulation is the average density, calculated here as the total number of vehicles divided by the road length in the network (units: veh/km/lane). The capacity of the network is the highest production.

4 Designing random networks

The networks are created using a tool which takes an input. For a microscopic network simulation program – in this paper, we use *Vissim* – an exact intersection design and signal timing are required as well. The steps to come to a detailed network design are described here. Due to limitation of space, the paper does not describe all steps of the algorithm in detail – for this, we refer to [5] – but describes the main principles.

We want to have three different networks of 3x3 km with an arterial at the outer edge and local roads within. Every 500 m there is an entry point to the local road network, which also acts as OD-zone. Following the Dutch guidelines [1] the intersections are created. A demand of 100 veh/h is set to each directions of the intersections and than the signal scheme for each intersections is determined [10]. The length of auxiliary lanes is set to the minimum for which there is no blocking of the main traffic.



(a) Network 1 (b) Network 2 (c) Network 3

Fig. 1 The networks

For each OD pair a uniform number between 0 and 1 is drawn, and there are no trips within the same zone. The demand is then scaled to a predefined total number of trips. To compare the shape of the NFD there need to be congested and uncongested conditions. Therefore, simulations are repeated with different demands, proportionlly scaled for all OD pairs.

With the obtained flows, first the number of lanes for each link is determined and the layout of each intersection is updated. Within this update, the flow of each link is assigned to the corresponding turn and a new intersection layout with corresponding signal scheme is calculated. If the cycle time is too long (> 120 s), an additional lane is added to the turn with the highest flow per lane after which the layout and signal scheme are recalculated. This process is repeated until the cycle time is within the limits.

After the general network layout is created, the areas between the major roads are converted to subnetworks. Along the border of each subnetwork a safety zone is added, in order to accommodate the roads of the main network. Also inserts are made, which are used to accommodate the connection to the main network, using the temporary subnetwork nodes created earlier.

For each of these areas a street pattern, consisting of local, bi-directional, single lane roads is created. This is based on the size of the blocks. Using Google maps, the typical sizes of blocks with different land use houses are determined; we differentiate between high rise buildings, parks and sport facilities. Also, it is determined which fraction of the blocks is used for what purpose. Using these values, a block type and its dimensions are drawn at random, after which the block is inserted at the first possible bottomleft position. Then a local road is added around that block. This process is repeated until the block is filled for a certain percentage, or no more blocks can be added. The remaining areas which are too small to fit any other purpose are filled with parks.

Next the subnetwork is divided in smaller sections. The demand is assigned to the original temporary subnetwork nodes, are now originating at different locations within the subnetwork, inversely proportional to the relative distance to each of the intersections. This avoids demands originating from the eastern intersection to be

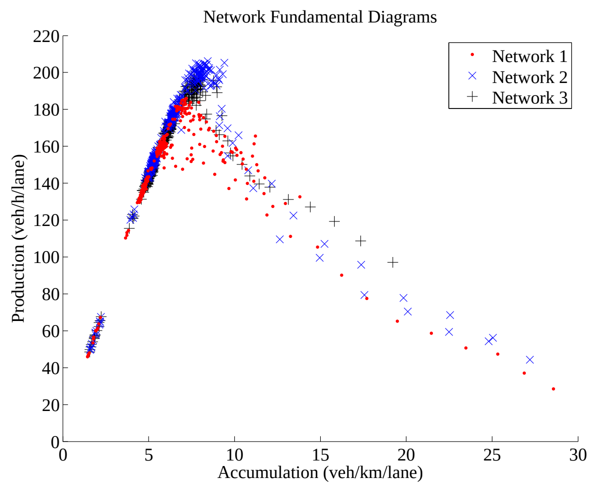


Fig. 2 The fundamental diagrams for all networks

assigned to a feeder at the west of the subnetwork, resulting in a mismatch of the demand at each intersection. The three resulting networks are shown in figure 1.

5 Traffic operations

Figure 2 shows the NFDs for the different networks. It shows that although the general pattern is the same (going up and down, quite sharp peak), the differences in the fundamental diagram are – measured by traditional traffic management standards – considerable. The capacity of network 1 is lower by approximately 15% compared to network 2. There is also quite some spread in the first part of the congested branch of network 1. The free speeds are similar, as well as the expected accumulation for which the speed approaches zero.

After the top, all NFDs decrease to the congested branch. This transition is much sharper than the analytical method with cuts for a ring road with traffic lights [4] suggests. Moreover, the congested branch shows a convex part, which cannot be found using the above mentioned method. Possibly network effects with spillbacks to other links cause this shape. The NFDs, created by averaging all traffic operations on the arterial and the inner network, are quite crisp.

It is remarkable that network 3 the increased demand has a lower effect on the speeds, i.e., the speeds do not decrease as much as for the other two networks (i.e., the congested branch does not reach gridlock accumulation), although the demands are the same. That means that not only the shape of the NFD is different, but also the position of the traffic state on the NFD given a specific demand.

6 Conclusions

This paper studied NFDs of various road networks. It presented a tool to create random networks based on required properties of the network. This tool has been used to analyse the effect of the network layout on the NFD.

It has been known that signal timing plays an important role in the NFD. However, also Changes in the underlying road network in which no traffic signals are present, result in differently shaped NFDs. That implies that the network structure also has an important role. Traffic control schemes based on the NFD are currently being developed. The findings in this paper show that it is required to determine the NFD for each network layout specifically, and it cannot be based on the general characteristics as network length or road type.

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