20th EURO Working Group on Transportation Meeting, EWGT 2017, 4-6 September 2017, Budapest, Hungary

Network Fundamental Diagram (NFD) and traffic signal control: first empirical evidences from the city of Santander

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Abstract

According to recent literature, the aggregate traffic conditions of an urban road network may be measured by an asymmetric inverse-U shaped diagram, called Network or Macroscopic Fundamental Diagram (NFD or MFD). The research on NFD was finalizes for applications connected to congestion control by means of gating, pricing schemes, multi-modal network analysis, freight vehicle routing. The control of urban road networks by means of NFD is a promising research area, where new methods and models are proposed to reduce traffic congestion and delay. The general objective of the research is to investigate if and in which measure the NFD profile (estimated by means of observed traffic data) changes according to the control strategy adopted for junction signals in an urban area. The first empirical evidences presented in this paper are related to a portion of Santander urban area, where a specific zone has been identified according to traffic characteristics and land uses. Data from traffic loops are collected and correlated with the signal control plans during a working day at link (flow-density diagrams) and network levels (NFD). Some preliminary considerations are derived from the empirical results. The cycle length with a fixed regulation plan does not influence the main traffic variables (flow, density) at link and network level, but these results cannot be generalized.

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1. Introduction

Current management and control methods of road urban networks (e.g. traffic signals, gating, pricing) generally operate with traffic data disaggregated at link and junction level (e.g. vehicular flows, speeds and densities, turning percentages, …). The necessity to collect and elaborate huge amount of disaggregated data imposes the deployment of sophisticated Intelligent Transportation Systems (ITS) (see Chilà *et al.*, 2016), in order to perform monitoring, management and control of large scale urban road networks, especially in a within-day dynamic environment.

Aggregate traffic conditions on an urban road network (or on a portion of it) may be synthetically represented by Network Fundamental Diagram (NFD), or Macroscopic Fundamental Diagram (MFD), indicator. This allows shifting the emphasis from microscopic level to macroscopic monitoring and control.

In the last decade, some works are proposed in order to finalize the NFD concept for applications connected to congestion control by means of gating, pricing schemes, multi-modal network analysis, freight vehicle routing. The control of urban road networks by means of NFD is a promising research area, where new methods and models are recently proposed in order to reduce traffic congestion and delay of road users (Marcianò *et al.*, 2015, Vitetta, 2016).

The general objective of the research is to investigate the influence of the cycle length on the NFD profile with a fixed signal setting plane strategy in term of green sequence and green and cycle length ratio. The specific objectives are: to analyze observed traffic data in order to verify the influence of junctions regulation to the main traffic variables (flow, density); to calibrate link flow-density diagrams for different regulation conditions.

The paper presents the first empirical evidences from the Santander urban area, where a specific zone has been identified according to traffic characteristics and land uses. Traffic data (flow, density) from traffic loops have been collected and correlated with the signal control plans in different periods of a working day. It emerges from the preliminary analysis on the available data that the cycle length with a fixed regulation plan does not influence the main traffic variables (flow, density) at link and network level. However, the above consideration must be further investigated with a broader set of data that include new cycle lengths and traffic data related to the unstable region of the flow-density diagram.

The paper is articulated as follows. Section 2 briefly reports the state-of-the-art concerning the recent application of NFD concept. Section 3 reports the steps of a proposed methodology to investigate the influence of the cycle length on the NFD profile with a fixed signal setting plan strategy. Section 4 presents a pilot application of the above methodology to an urban zone of the city of Santander (Spain). Finally, some preliminary conclusions and research perspectives are presented in section 5.

2. State-of-the-art

Network Fundamental Diagram (NFD), puts in relation two aggregate variables: the product of average link flow and link length, called production, and the product of link density and link length, called accumulation (see Daganzo, 2007). Most common methodologies for deriving NFD are (Leclerq *et al.*, 2014): (i) the analytical method proposed by Daganzo and Gerolimins (2008), (ii) trajectory-based and (iii) the loop detector method. The loop detector method has been used in this work. This method depends on the detector location (specially, the distance from the signalized intersections) and their distribution on the network.

The network partitioning and the definition of more homogeneous zonal NFDs opened a wide range of applications of NFD concept. Many authors used it for different purposes such as congestion control by means of gating (Keyvan-Ekbatani *et al.*, 2013, Yildirimoglu *et al.*, 2015), pricing schemes (Zheng *et al.*, 2016), multi-modal network analysis (Chiabaut, 2015), freight vehicle routing (Musolino *et al.,* 2016) finalized to reaching green goals (Russo and Comi, 2016).

According to the authors, the NFD concept to support the strategy design of the signal plans in urban road networks is not investigated in the scientific literature. The aggregate traffic information obtained with NFD could contribute to find optimal solutions of signal control strategies in order to reaching green goals.

3. Methodology proposed

The objective of the research is to investigate the influence of the cycle length on the NFD profile with a fixed signal setting plane strategy in term of green sequence and green and cycle length ratio. The NFD is built with observed traffic data of a (portion of) an urban area.
The proposed methodology is articulated into three steps, reported in the next subsections.

3.1 Single variable analysis at link level

In the first step, the pattern between the cycle length and each single traffic variable (flow, density) is evaluated. For each cycle length, the frequency distribution of each traffic variable is estimated. Some statistical tests could allow comparing similar frequency distributions in the case of different cycle length. The non-parametric test of Kolmogorov-Smirnov could support this comparison, as it gives information about similar distributions of two observed samples. However it is not necessary if the two distributions have a quite different shape, in this case a qualitative test could be accepted.

One relevant element concerns the correlation between cycle length and level of congestion. An adaptive signal control strategy generally assigns a cycle length for each level of congestion. The frequency distribution of each single variable depends on the cycle length, but this does not imply that the resulting NFD is different, because it depends on a couple of variables (flow and density).

A focus on road link capacity (f_C), as maximum value of traffic flow, is necessary. The link capacity depends on road geometry, flow composition, control strategy at the junction. In urban area, road link capacity is highly influenced from the control strategy at the junction. Link capacity in the final section of the link (junction) is calculated as:

$$f_C = s \bullet g / c \tag{1}$$

where
- s is the saturation flow, defined as the link capacity when the traffic signal plan gives always green to the link; it does not depend on the control strategy at link junction, in particular it does not depend on the cycle and on green length;
- g is the effective green time; it is equal to the green and amber length minus the lost time;
- c is the cycle length.

In the examined case, when the cycle length changes, the green sequence and the ratio between g and c are fixed. For this reason, in each link, the capacity does not depend on the cycle length (c) because it is the product between two variables (s and g/c) independent from the cycle length.

In this context, the road capacity may be estimated by means of the whole available traffic data, independently from the cycle length relating to each interval. In this work, it is assumed that the capacity is the 98 percentile of all observed flow values.

3.2 Two variables analysis at link level

In the second step, the relationship φ between flow, f, and density, k, is specified and calibrated at link level:

$$f = \varphi(\beta, k) \tag{2}$$

with β weights to be calibrated, with a pre-calibrated value of capacity.

All traffic data observed on the link during the different cycle lengths plans are considered as data eligible for the calibration of eq. (2).

As reported in section 3.1, the value of road capacity, f_c, is independent from the cycle length in the case examined and, in this step, it is considered as exogenous value, obtained as output of the first step.

The comparison of eq (2) with different cycle lengths is done in terms of values of calibrated parameters. In relation to the available traffic data, several specifications of eq. (2) have been considered and tested. The specification that gives the best statistical results is (Drake et al., 1967):

$$f = \varphi(k) = v_0 \bullet k \bullet e^{-(k / k_0)^2 / 2} \tag{3}$$

where the parameters to be calibrated are free-flow speed (v_0) and density at the capacity (k_0).
According to eq. (3), the link capacity is equal to:

$$f_c = v_0 \bullet k_0 / e^{0,5} \tag{4}$$

The parameters (v_0, k_0) are calibrated according to a weighted least square method for each cycle length. Different weights are associated to the distances between observed flow data and estimated ones and between the value of capacity, as evaluated in the first step, and the estimated one according to eq. 4.

The comparison of the values of the calibrated parameters of eq. (2) could provide some evidences about the variation (or not) of the link flow-density diagram according to the cycle length.

3.3 Two variables analysis at network level

In the third step two variables of flow (TTD) and density (TNV) are estimated at network level for all the links i of the (sub-)network:

$$TTD = \Sigma_i \; f_i \; l_i \hspace{6cm} (5)$$

$$TNV = \Sigma_i \; k_i \; l_i \hspace{6cm} (6)$$

with TTD, Total Travelled Distance (TTD) on the (sub-)network; TNV, Total Number of Vehicles on the (sub-)network; f_i, observed flow on link i; k_i, observed density on link i; l_i, length of the link i.

The NFD diagrams are built for each cycle length operating in the traffic signals of the network.

The comparison of the NFD diagrams gives information about the variation respect the cycle length.

4. Test case

The methodology described in section 3 is tested on a zone of Santander urban area. The objective is to apply the feasibility of methodology on a real test case and to obtain some empirical evidences about the influence of the cycle length on the NFD profile.

The study is based on traffic data collected in the city of Santander, in Northern Spain. The population of Santander is about 180,000 inhabitants with a surface area of 33.9 square kilometers. The city has a linear structure, with a well developed commercial centre and several residential zones in the periphery. The west-east linear configuration of Santander channelizes the traffic along longitudinal roads, the most important of which is the central corridor which passes through the entire CBD and varies from two-three lanes in each direction. At rush hour, the origin/destination matrix registers about 40,000 car trips and 4,500 trips using public transport.

The city has a centralized traffic light control system overseeing 263 controlled intersections, which operate on a fixed timing system. According to the urban morphology, the system is subdivided into 15 control sub-areas, each of which is programmed according to the cycle length, the phases and their distribution. However, one peculiarity of this system is that the length of time spent on green is kept constant at most of the traffic lights.

A sub-area has been selected (see Fig 1) as zone for the methodology testing. The zone contains the central corridor and most conflictive junctions in the city and the main administrative services of the city (town hall, regional government and national administration offices). There are many parking spaces (five underground car parking areas) and most of the longitudinal and transversal mobility passes through this area. According to traffic assignment data of the city transportation model, around 12% of the total demand for private transport travels along the part of the central axis located in the study zone and more than 60% of the trips made on public transport.

This zone has 15 traffic light controlled junctions, all of which are centrally controlled. The length of the cycle evolves according to the travel demand (period of the day), oscillating from 80 seconds during periods of free-flow traffic to 110 seconds at peak period.

The distribution of traffic density during a sample day, detected by a traffic counter located along the central corridor, is shown in the plot of Fig. 1. The distribution (solid line) presents three main peak periods: in the morning, at mid-day and in the evening. The profile of the cycle time (dashed line) changes in order to adapt the signal junction control to the within-day oscillations of travel demand.

Finally, there are several traffic counters installed for the collection and analysis of the data (flow, occupancy, speed, …). Eight specific counting sections are selected in the study, which provide aggregated data every five minutes. The counters provide values of vehicular flow and occupation (data are not disaggregated per lane).

The section is subdivided into three sub-sections, one for each step of the methodology reported in section 3.

Fig 1- Road network of Santander: main sub-areas with traffic light controls and a focus on the examined zone

4.1 Single variable analysis at link level

The first step regards the analysis of individual traffic variables.
Starting from observed traffic data associated to cycle lengths of 80 sec and 110 sec, individual traffic variables analyzed are density (veh/km) and traffic flow (veh/h).
The frequency distribution for each individual variable is estimated, taking into account all monitored links and all periods in which each cycle length is active.
The frequency distribution of density, in relation to cycle lengths of 80 sec and 110 sec, is plotted in Fig. 2. During cycle length of 80 sec, the value of density is inside the range 0-8 (veh/km) in the great part of observed data (more than 75%). During cycle length of 110 sec, the density has values inside the range 0-55 (veh/h) in the great part of observed data (more than 85%).
The two frequency distributions are quite different, because they relate to periods of the day having high different levels of travel demand. The first period (80 sec of cycle length) is from 23:00 p.m. to 00:00 a.m., while the second period (110 sec of cycle length) is from 08:00 a.m. to 08:30 a.m**.**
The frequency distribution of traffic flow, in relation to cycle lengths of 80 sec and 110 sec, is plotted in Fig. 3.
During cycle length of 80 sec, the value of traffic flow is inside the range 0-100 (veh/h), in the great part of observed data (more than 80%). During cycle length of 110 sec, the values of the variable are inside the range 600-1200 (veh/h) in the great part of observed data (more than 80%).
As in the case of density, the two frequency distributions of traffic flow are quite different.
Considering the macroscopic differences in the distributions of the two variables, it is not necessary to compare them by means of Kolmogorov-Smirnov test.
From observed traffic flows, capacity value is 1.600 veh/h, according to the 98 percentile of all observed data.

4.2 Two variables at link level

The second step regards the two-variables analysis (flow, density) at link level.
Several link flow-density models existing in literature (Greenshields, Drew., …) are calibrated. At this stage of the research, the model that gives the more encouraging results is the one of Drake (eq. 3), where parameters are free-flow speed and, v_0, critical density, k_0, and flow capacity, f_c. In the case examined, the capacity is independent from the cycle length (see par. 3.1) and it is calculated by means of eq. 4.

Observed traffic data on selected links related to different cycle lengths plans of an average working day are used for the calibration of model (eq. 3).

Cycle length 80 sec
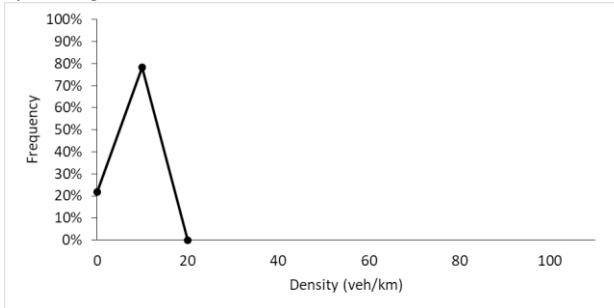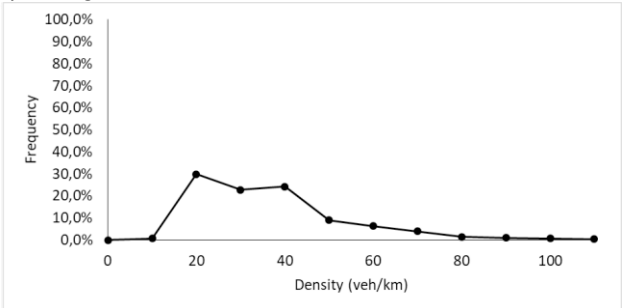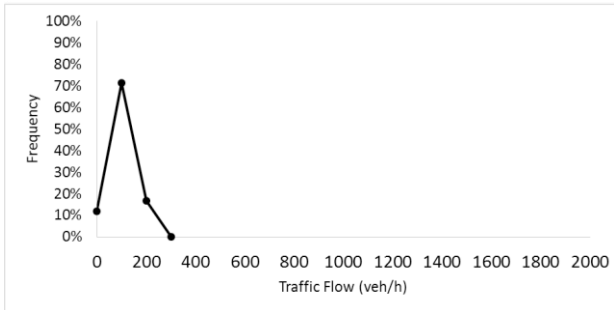
Cycle length 110 sec

Fig. 2. Frequency distribution of the density (veh/km) in the two examined cycle lengths.
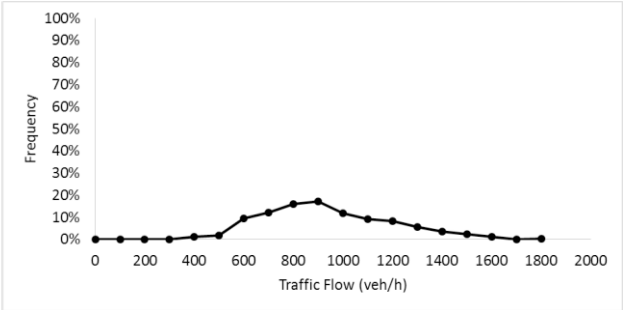
Cycle length 80 sec

Cycle length 110 sec

Fig. 3. Frequency distribution of traffic flow (veh/h) in the two examined cycle lengths

The parameters (v_0, k_0, f_c) of eq. 4 are calibrated according to a weighted Least Square Method, where a higher weight is associated to the distance between the value of capacity, as evaluated in the first step of the methodology (par. 3.1), and the value of capacity estimated according to eq. 4.

The preliminary results of model calibration using three aggregations of traffic data (all cycle, 80 sec cycle, 110 sec cycle) are reported in the following. In the first case (all cycles), the calibrated value of v_0 is close to 40 (km/h) and the value of k_0 close to 60 (veh/km). In the second (80 sec) and third (110 sec) cases, the calibrated values of v_0 and k_0 are similar to the ones obtained in the first case. Further calibrations are necessary to confirm these preliminary results.

Figure 4 shows the observed scatterplot and the calibrated model (eq. 3) of respectively flow-density (Fig. 4.a) and speed-density (Fig. 4.b) variables for the first case (all cycles). Figure 5 depicts the observed scatterplot and the calibrated model of flow-density variables for the second (80 sec, Fig. 5.a) and for the third case (110 sec, Fig. 5.b).

4.3 Two variables at network level

The third step regards the analysis of couple of traffic variables at network level.

Following the description provided in par. 4.2 and moving from a link scale to a network scale, fig. 6 shows the NFD estimated for the examined zone for an entire day.

The diagram can be seen to always remain on the stable region, without passing the critical TNV threshold. Just as was expected, the locations corresponding to the shortest cycles used during the periods of lowest traffic, are found at the lower end of the curve, while the high points of the cycle (110 sec) are concentrated in the high zone close to the maximum TTD value, as they correspond to the highest traffic flows.

By analysing the evolution throughout the entire day in greater detail and considering the current traffic light cycles being used during each time period, the state of the network can be followed during 5 minute periods according to its NFD. Thus, at the start of the day, with low flows and 80 sec cycles, the network is practically at free-flow state.

From 7:00, although it happens gradually the network starts to register more traffic. This is reflected in the progressive scale of the NFD towards higher values of TTD and TNV. However, when the first rush hour appears between 8:00 and 9:00 the network values start to oscillate among the maximum zones. This phenomenon is repeated during the other two peak periods from 13:00 to 15:00 and from 19:00 to 20:00, all of which have 110 second cycles, other regions further away during the late morning/mid-day off-peak period between 10:00 and 13:00 have a slightly shorter cycle (100 sec) and the traffic is moderate, although relatively constant. Finally, during the last period of the day, once rush hour has passed, the network unloading process takes a relatively linear form. These quasi-linear processes of loading and unloading and the oscillating behaviour in the near network capacity zone can be seen in an average flow-average occupancy diagram (figure 6.b).
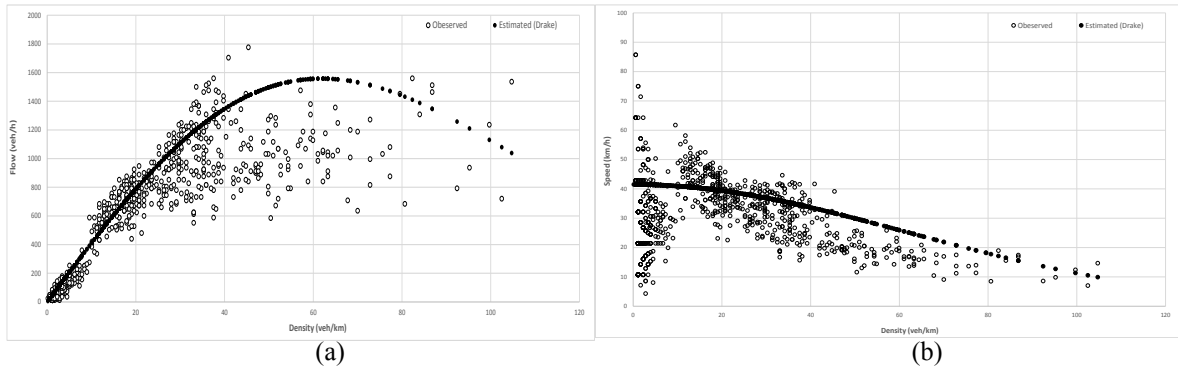

Fig.4. Flow-density (a) and speed-density (b) diagrams: observed and estimated values (Drake) for all cycles length.
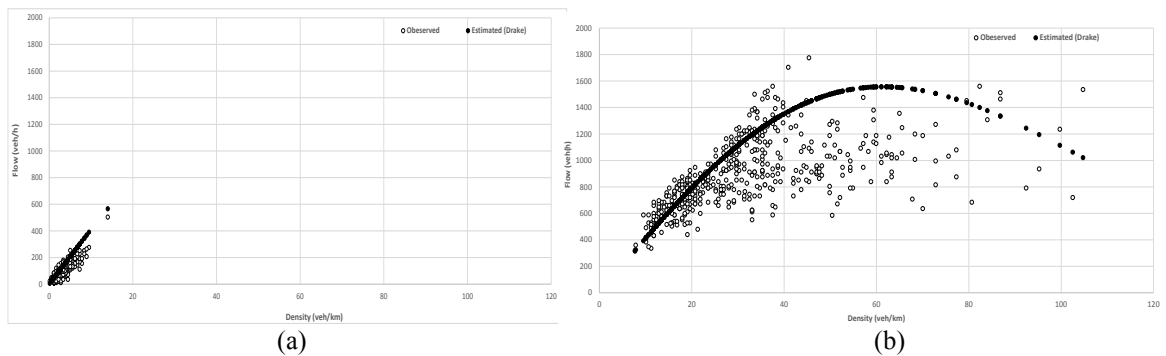

Fig. 5. Flow-density diagrams: observed and estimated values (Drake) for cycles length of 80 sec (a) and 110 sec (b).

5. Research perspectives

The objective of the research is to investigate if and in which measure the NFD profile (estimated by means of observed traffic data) changes according to the control strategy adopted for junction signals in urban network.

The first empirical evidences presented in this paper concern the city of Santander, where a specific zone has been identified according to traffic characteristics and land uses. The relationship between traffic variables (flow, density) and cycle length operating during the day are investigated at link and network levels. At link level, the analysis regarded individual variables and flow-density diagrams, while at network level the analysis has been conducted by means of the NFD.

Some preliminary considerations relating to the results are reported. Considering the traffic variables at link level, the calibrated parameters of the (Drake) flow-density model are very similar from one cycle length to another. At network level, the observed traffic values present a quasi-linear trend in relation to the cycle length. These results cannot be considered as general due to the following reasons: (1) they are influenced by the available data, (2) there is a fixed junction control in term of ratio green-cycle lengths, and (3) the traffic data for the observed period (day) cover only the stable region of the flow-density diagram. Generally, the junction control could influence traffic flow

(i.e. a non-optimal junction control could generate high congestion level in a road network loaded by high values of travel demand).

The above considerations are preliminary and they must be further investigated with a broader set of traffic data that include new cycle lengths, traffic data belonging to the unstable region of the flow-density diagram, and different junction control plans. Once that the sensitivity of NFDs to traffic regulations has been verified, this could lead to important practical implications on signal setting design and traffic management procedures.
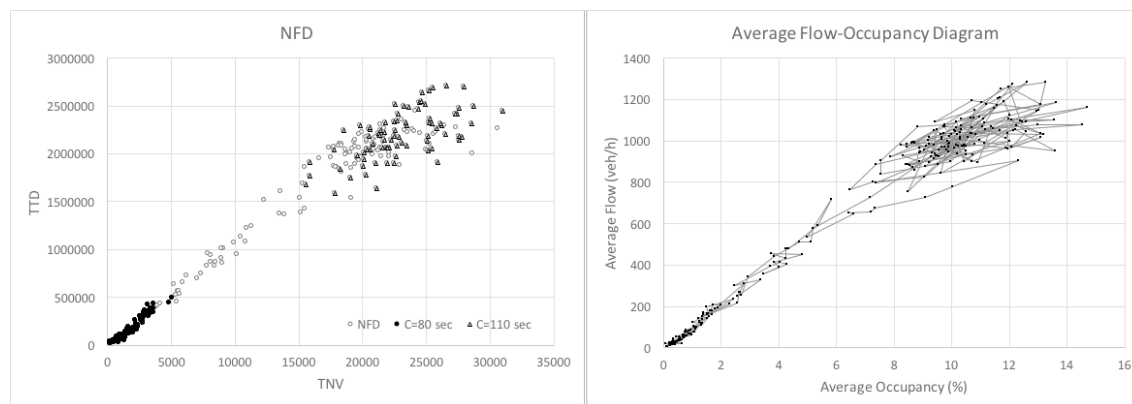

Fig 6 (a). NFD of the study area for an entire day, differentiated according to the duration of the cycle, 80s and 100s; (b) Evolution of average flow – average occupancy diagram on the network

6. Acknowledgements

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