

Estimation of travel time variation caused by transport infrastructure development

Travel time
variation

Muhammad Saadullah, Zhipeng Zhang and Hao Hu
*School of Naval Architecture, Ocean and Civil Engineering,
Shanghai Jiao Tong University, Shanghai, China*

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Abstract

Purpose – The expected benefits of newly developed transportation infrastructures are the saving of travel time and further promoted transport economics. There is a need for a methodology of travel time estimation with acceptable robustness and practicability. Macroscopic fundamental diagram (MFD) represents the overall traffic performance at a network level by linking average flow, speed and density. MFD can be used to estimate network state and to describe various traffic management strategies. This study aims to describe the effect of new infrastructure development on the network performance using the MFD framework.

Design/methodology/approach – The scenarios of Islamabad Road network before and after the infrastructure construction were simulated, in which the floating car data set (FCD) for multiple modes was extracted. MFD has been formed for the whole region and partitioned region, which was divided on the basis of infrastructural changes. Moreover, this study has been extended to calculate travel time for multiple modes using the MFD results and the Bureau of Public Roads (BPR) function at a neighborhood level.

Findings – MFD results for the whole network showed that the speed of traffic improves after the construction of new infrastructure. The travel time estimates using MFD results were dependent on the speed estimates, whereas the estimates obtained using the BPR function were found to be dependent on the traffic volume variation during different intervals of the day. By using the FCD for multiple modes, travel time estimates for multiple modes were obtained. The BPR function method was found valid for estimating travel time of traffic stream only.

Originality/value – This paper innovatively investigates the change in network performance for pre-construction and post-construction scenarios using the MFD framework. In practice, the approach presented can be used by transportation agencies to evaluate the effect of different traffic management strategies and infrastructural changes.

Keywords Macroscopic fundamental diagram, Network performance, Travel time, Travel delay, Infrastructure development

Paper type Research paper

1. Introduction

Urban population around the world is growing each passing year, and 50% of the population lives in urban areas (World Bank, 2020). In the past two decades, the urban population in Pakistan has increased by 12%, and about 37% of the population now resides

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in urban areas (World Bank, 2021). Road infrastructure not only connects different areas but also plays an important role in socio economic development of cities. Increase in urban development has increased the road transportation in Pakistan, and in the past five years, the motor vehicle registration has escalated by 40% (Ministry of Finance, Pakistan, 2021). Due to lack of good and reliable public transport in the cities of Pakistan, the existing road infrastructure is subjected to traffic congestion that increases the travel time of commuters, vehicle emission and vehicle operating cost. To ease the traffic flow in urban areas, the city administrators have initiated the construction of various infrastructure projects. On the basis of improvements, the infrastructure projects can be classified into two different categories. Improvements such as construction of a bridge or expansion of an intersection to increase the capacity can be termed as microscopic improvement, it can be analyzed using different methodologies stated by the Highway Capacity Manual (HCM). Construction of a new road or improvement of an existing freeway section can be categorized as macroscopic improvement. In Pakistan, for the microscopic improvement projects the traffic agencies require capacity analysis. On contrary to this, macroscopic improvement projects require capacity analysis, travel time study and travel demand modeling of the new project.

This study focuses on the macroscopic analysis of the impact of construction activity on the network traffic performance using the macroscopic fundamental diagram (MFD), which relates the average flow and density of the network. According to Daganzo and Geroliminis (2008), MFD is the property of the network and is independent of traffic demand. The idea of MFD was verified by using the loop detector data and floating car data set (FCD) of taxis for Yokohama, Japan (Geroliminis and Daganzo, 2008). Analytical and experimental methods for the estimation of MFD were presented by Leclercq *et al.* (2014). The effect of distance of loop detectors from the traffic signal on the MFD formation was examined by Buisson and Cyril (2009). In the same work, MFD for different road types was obtained, and it was observed that hysteresis in MFD is because of heterogeneous congestion in the network. Shape of MFD using simulation output from Verkehr In Städten – SIMulationsmodell was investigated by Ji *et al.* (2010), and the results exhibited that altering traffic demand rapidly affects the shape of MFD. Earlier MFD research mostly focused on single mode of transportation but later studies have integrated multiple modes in MFD framework. Zheng and Geroliminis (2013) developed MFD model, which represented traffic dynamics of multimodal transport system. Three-dimensional MFD (3D-MFD) concept was proposed by Geroliminis *et al.* (2014); it links the average flow of buses and cars with the average network density. In the same study, 3D passenger MFD was proposed. To evaluate the effect of different mode ratio the concept of passenger MFD was introduced by Chiabaut (2015). After the introduction of 3D-MFD, multiple studies were conducted by using the empirical traffic data from Shenzhen (Huang *et al.*, 2019), Zurich and San Francisco (Ortigosa, *et al.*, 2015). The concept of MFD has been extended to include no-motorized modes such as pedestrians (Hoogendoorn, *et al.*, 2017) and bicycle (Huang, *et al.*, 2021).

Different transportation planning applications have used MFD for analysis. Simoni *et al.* (2015) analyzed the congestion pricing policy using the MFD and developed marginal cost pricing model. This model was implemented using traffic simulation software MATSIM for the city of Zurich. The macroscopic effect of non-local vehicle plate policy for the city of Shanghai using MFD was done by Huang *et al.* (2018). The effect of driver's route choice behavior on network performance using MFD was studied by Tsubota *et al.* (2013). Different routing strategies were compared by Knoop *et al.* (2012) based on the results obtained by MFD. Using the 3D-MFD framework, London's congestion pricing policy was evaluated by Ambühl *et al.* (2018).

In addition to the relations to the speed, average flow and average density on a network level, another macroscopic factors which can be linked with MFD is the travel time.

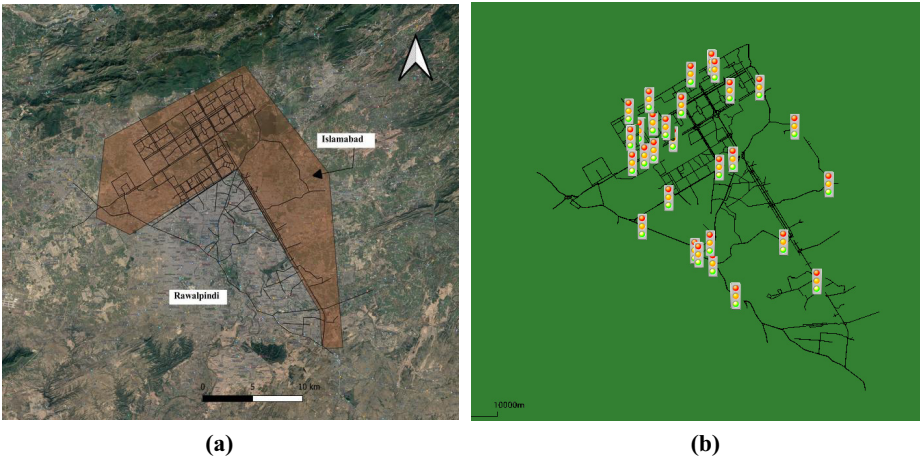
Kachroo *et al.* (2001) presented algorithm for estimation of travel time for highway network using the macroscopic modeling. It also highlighted the implementation of the proposed algorithm on incident management and traffic control strategies. Wang (2004) used the FCD from the USA freeway network and estimated the travel time delay. Zhang *et al.* (2019) used the Bureau of Public Roads (BPR) to estimate the link level travel time in the transportation network. Maass *et al.* (2020) used the Uber data to estimate the street-level travel time. Kukkapalli and Pulugurtha (2021) studied the influence of freeway road construction on link travel time. The results indicated that the travel time observed was different from BPR function estimates. Some of the studies have tried to relate travel time with the MFD framework. Tu *et al.* (2013) proposed relating travel time reliability with the network accumulation calculated using MFD and coined the term of macroscopic travel time reliability diagram. It states that the travel time reliability is a function network accumulation. Mahmassani *et al.* (2013) extended the concept of travel time reliability from link base to network level, and a relationship was established between travel time variability, average density and flow. A gap lies in linking travel time and MFD parameters. This paper initially investigates the change in network performance for pre-construction and post-construction scenario using the MFD framework. For this purpose, the road network of Islamabad has been considered and traffic simulation has been done for the existing scenario and after construction scenario. Second, this paper explores a methodology to calculate travel time using speed estimates from MFD results. The objective of the study is to evaluate the effect on network performance after an intervention based on MFD model and to estimate travel time of vehicle in a neighborhood.

The remainder of the paper is structured as follows. Study area, traffic data collection and infrastructure improvement are described in Section 2. The estimation of macroscopic parameters along with the travel time estimation for the road network is explained in Section 3. Travel time estimation by using a case study from both MFD results and BPR function are discussed in Section 4. Conclusions and a brief discussion on the results are presented in Section 5 which is followed by future recommendations in Section 6.

2. Data collection and study area

Islamabad is the capital city of Pakistan with a population of about 2 million, whereas Rawalpindi has a population of about 4 million people. The road network considered in the study with both cities are indicated in Figure 1. Due to the lack of good and reliable public transportation service, the majority of the commute takes place using cars and motorbikes. Islamabad had an industrial sector at the periphery of the city; however, owing to urban sprawl and continuous increase in population, the sector is now inside both the cities. Major highways and arterial roads act as feeder routes for the industrial zone and major proportion of truck traffic traverses through the city. Movement of slow-moving heavy trucks through the city is responsible for the deterioration of road network, and it is a safety concern for other road users. During the morning and evening peak hours, the trucks are not allowed to enter in the urban road network. For the study, the traffic count data was collected manually for three major arterials of the city, details of these arterials are presented in Table 1. To identify major origin and destination of the city, an origin–destination (OD) survey was conducted. Individuals were asked about mode of travel, time of the day, origin and destinations of the trips. Based on the OD survey, the city was divided into 55 traffic analysis zones and time-based origin and destination tables were obtained. Traffic simulation software simulation of urban mobility (SUMO) (Lopez *et al.*, 2018) was used for

Figure 1.
Study area and road
network data set in
SUMO



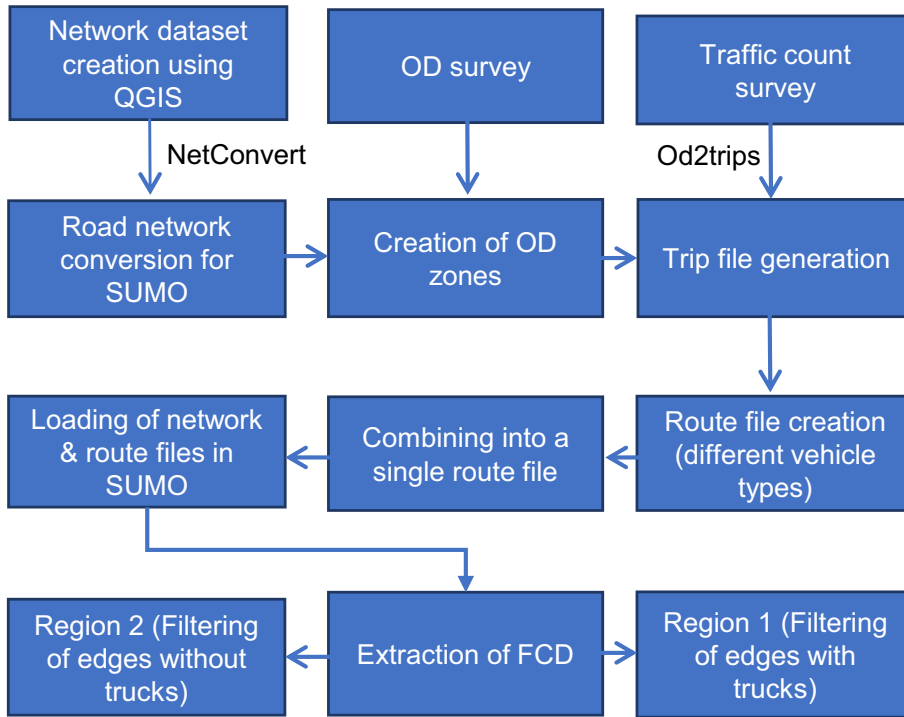


Figure 2. Flowchart of steps followed for SUMO simulation

3. Methodology with macroscopic fundamental diagram estimation

MFD shows the relation between density, flow and speed of traffic flow on a macroscopic scale. Vehicle trajectory of every vehicle was recorded in the FCD data set, [Leclercq et al. \(2014\)](#) indicated that an accurate MFD can be formed if the vehicle trajectories are available for the whole network. Average flow (Q_i) and density (K_i) are calculated using the FCD data set by the following equations:

$$K = \left(\frac{\sum_i^n T_i}{LT} \right) \quad (1)$$

$$Q = \left(\frac{\sum_i^n D_i}{LT} \right) \quad (2)$$

$$V_i = \frac{Q}{K} \quad (3)$$

Where $\sum_i^n D$ and $\sum_i^n T$ represent the total traveled distance and total travelled time by the vehicles, respectively. Whereas, L and T represent the length of the total road network and the time interval for which FCD was extracted, respectively. MFD for the whole day

represents the average density and average flow for an interval of 120 s. The data for the whole day has been divided into six-time intervals (21:00–06:00, 06:00–09:00, 09:00–12:00, 12:00–15:00, 15:00–18:00, 18:00–21:00). The later sections describe the MFD formation of pre-construction and post-construction for the whole network and partitioned network. The speed, average density and average flow have been considered to assess the macroscopic network performance of both the scenarios.

3.1 Macroscopic fundamental diagram of the whole network

MFD for the whole network for both pre-construction and post-construction scenarios are illustrated in [Figure 3\(a\)](#); the MFD curve for the pre-construction is lower than the post construction scenario. For the pre-construction scenario, the maximum flow is achieved by 08:45 hours, and the critical accumulation is 372 veh-ln/km, whereas for the post-construction scenario, maximum flow was observed at 15:30 hours and the critical accumulation attained was 318.22 veh-ln/km. The speed–MFD curves for the whole network are illustrated in [Figure 3\(b\)](#). After the expansion and rehabilitation of existing road network, the average speed observed was increased and it attains the range between 40 kmph and 50 kmph. However, for the pre-construction scenario, the average speed obtained was between 20 kmph and 35 kmph.

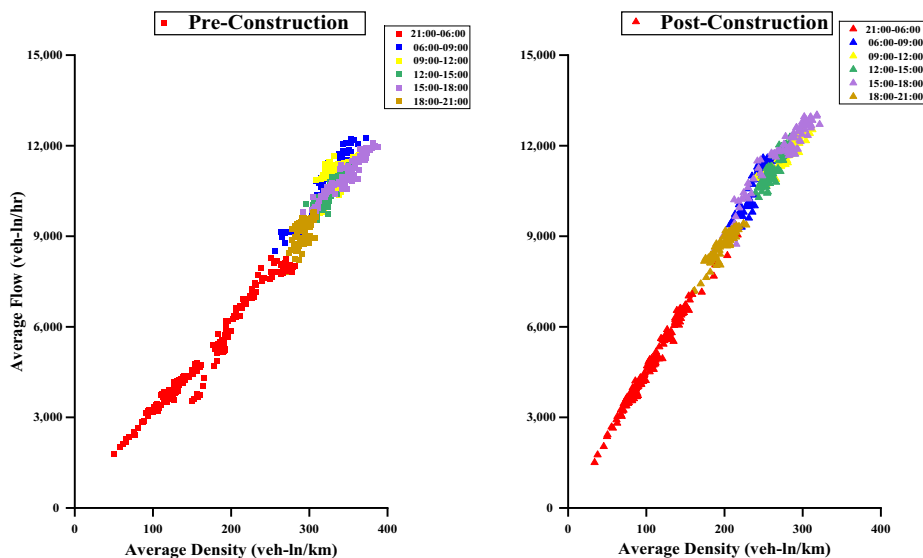
3.2 Network partitioning

To further investigate the effect of construction activity on the MFD, network partitioning is done on the basis of network improvement. Region 1 consists of roads on which construction activity has been planned and the adjacent road network, whereas the rest of the network has been included in Region 2, which is formed by two disconnected areas, but the characteristic of the roads are the same, i.e. no rehabilitation work has been done. Both of these regions are presented in [Figure 4](#).

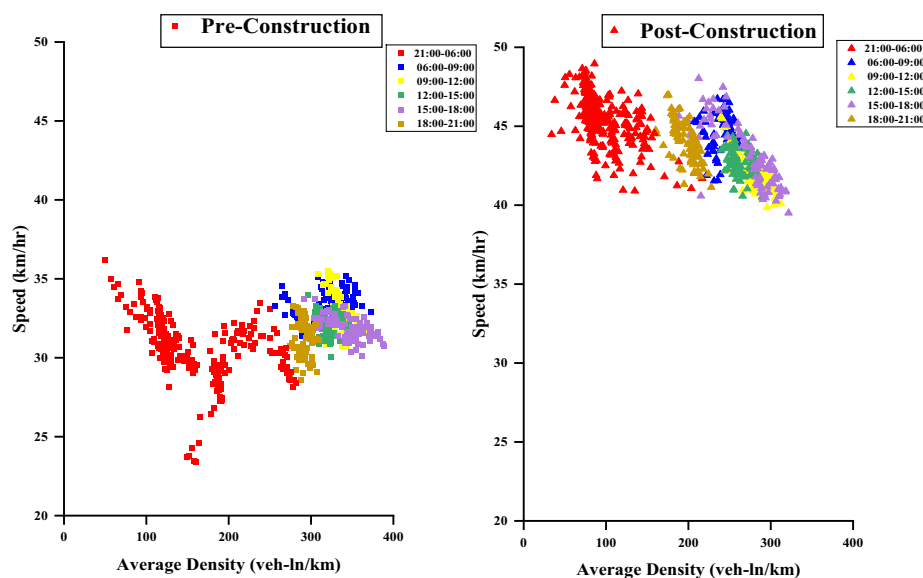
Majority of the slow-moving truck traffic traverses through the road network in Region 1. MFD for Regions 1 and 2 for both scenarios are illustrated in [Figure 5](#). The average density observed for the pre-construction scenario is higher than the post-construction scenario; this is due to removal of bottlenecks and improvement in road condition in Region 1. Close investigation of post construction scenario reveals that the maximum average flow achieved is higher than the pre-construction scenario. For Region 2, MFD curves for both scenarios overlap each other. For pre-construction scenario, the maximum average flow is observed in the morning peak hours at 08:45 hours., whereas for the post-construction scenario, the maximum average flow is observed at 15:40 hours. With the improvement in road condition in Region 1, a shift in the macroscopic parameters in Region 2 has been observed.

Macroscopic parameters for Regions 1 and 2 after the improved road network conditions are presented in [Tables 1](#) and [2](#), respectively. For better investigation in the change of network parameters, whole day has been classified into eight-time intervals and each represents 3 h of the day.

For Region 1, pre-construction scenario results show that maximum average flow of 5179 veh-ln/h was observed between 15:00 and 18:00 time interval with critical density of 216.128 and average speed was 24 km/h. Similarly, for the post-construction scenario, the maximum flow of 5513 veh-ln/h was observed between 15:00 and 18:00 time interval with critical density of 120.02 veh-ln/h and the speed reported was 46 km/h. For Region 2, the pre-construction results show that maximum average flow of 7853 veh-ln/h was observed between 06:00 and 09:00 time interval with critical density of 215 veh-ln/km and average speed was 37 km/h. However, for the post-construction scenario the maximum flow of 7592



(a)

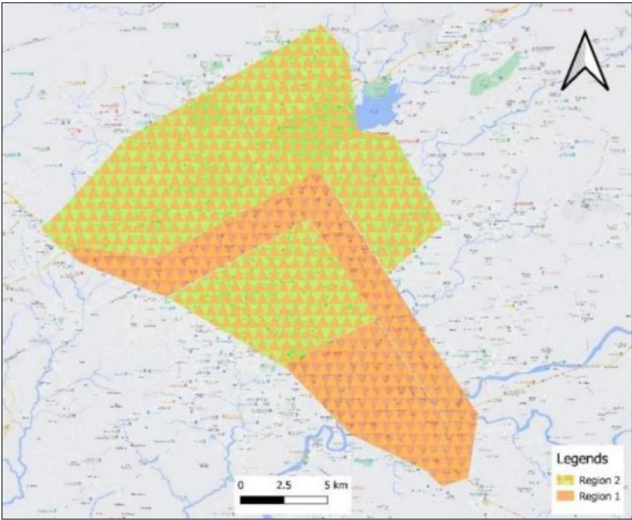


(b)

Notes: (a) MDF for whole network; (b) speed MDF for whole network

Figure 3.
MFD and speed MFD
for whole network

Figure 4.
Network partitioning
based on construction
activity



veh-ln/h was observed between 06:00 and 09:00 time interval with critical density of 179 veh-ln/h and the speed reported was 42 km/h (Table 3).

3.3 Travel time estimation

Mostly in Pakistan, the travel time studies are conducted by recording the journey time incurred to drive between two different points. By using the traveled distance and journey travel time, the speed is estimated. The travel delay at different intervals of the day is calculated by comparing it with free flow travel time. According to HCM 2016, the travel time can be calculated by using the following equations:

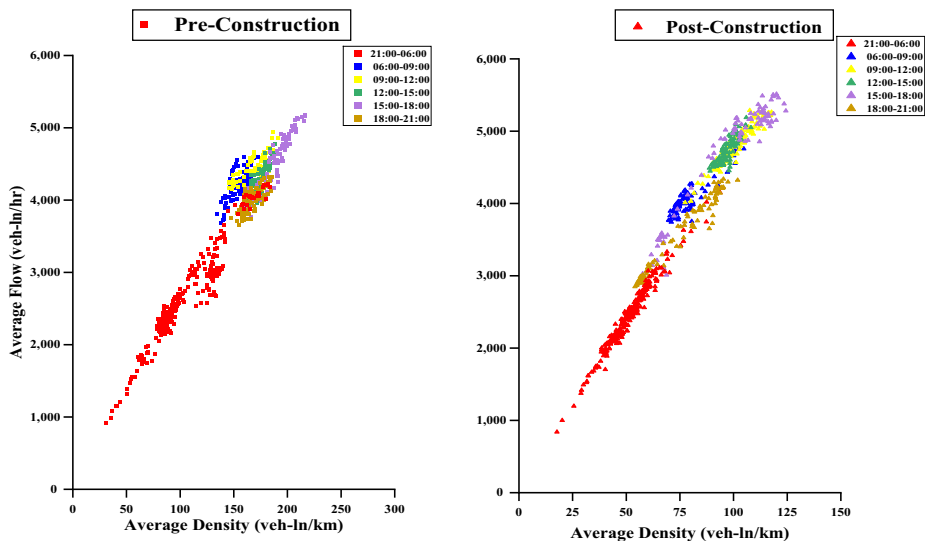
$$TR = \Delta_{US} + \Delta_{OS} + TR_{FF} \tag{4}$$

$$TT = TR * L \tag{5}$$

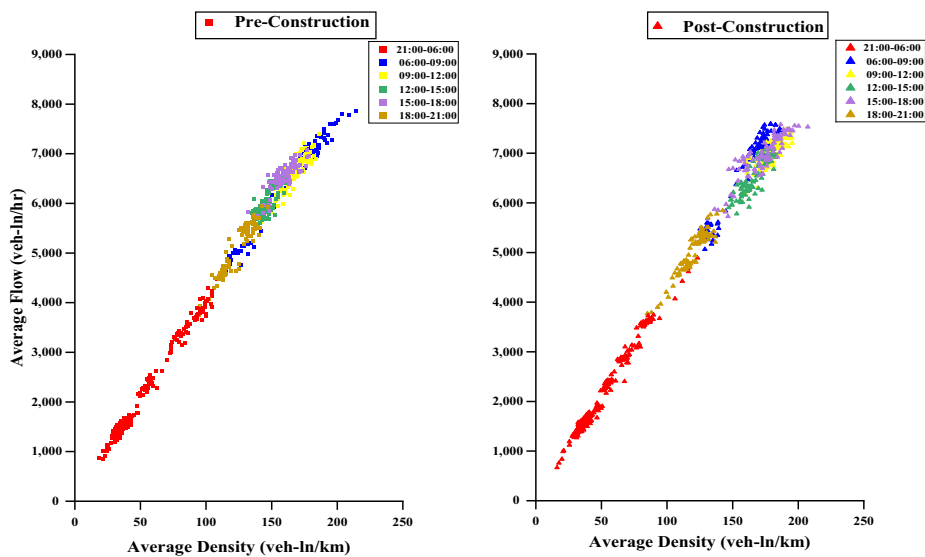
Using the HCM methodology, travel time (TT) for a road section at a specific interval of day can be calculated using equation (5). TT depends on the travel rate (TR) and the length (L) of the road section. The TR is the sum of free flow TR (minutes per kilometer), travel delay rate (minutes per kilometer) for over saturated (Δ_{OS}) and for undersaturated (Δ_{US}) traffic conditions as depicted in equation (4). The methodology proposed in this work calculates TT using the MFD results, which are then compared with the TT estimation using by BPR function, it is presented in the subsequent section.

3.4 Travel time estimation using macroscopic fundamental diagram

According to Mariotte (2018), the average flow and density can be extended to calculate accumulation and production of the vehicles in the network. Accumulation



(a)



(b)

Notes: (a) MFD for Region 1; (b) MFD for Region 2

Figure 5.
MFD for partitioned
network

Table 2.
Macroscopic
parameters for
Region 1

Time interval	Maximum average flow (veh-ln/h)		Critical density (veh-ln/km)		Speed (km/h)	
	Pre- construction	Post- construction	Pre- construction	Post- construction	Pre- construction	Post- construction
00:00–03:00	2,552	2,569	92	54	28	48
03:00–06:00	3,726	4,152	140	94	27	44
06:00–09:00	4,600	4,756	159	105	29	45
09:00–12:00	4,936	5,288	187	108	26	49
12:00–15:00	4,770	5,190	189	105	25	49
15:00–18:00	5,179	5,513	216	120	24	46
18:00–21:00	4,323	4,338	186	95	23	46
21:00–00:00	4,219	3,331	182	69	23	48

Table 3.
Macroscopic
parameters for
Region 2

Time interval	Maximum average flow (veh-ln/h)		Critical density (veh-ln/km)		Speed (km/h)	
	Pre- construction	Post- construction	Pre- construction	Post- construction	Pre- construction	Post- construction
00:00–03:00	1,735	1,772	42	44	42	40
03:00–06:00	4,570	4,892	111	123	41	40
06:00–09:00	7,853	7,592	215	179	37	42
09:00–12:00	7,406	7,486	186	192	40	39
12:00–15:00	6,601	7,099	161	176	41	40
15:00–18:00	7,077	7,577	177	187	40	41
18:00–21:00	5,947	5,847	142	142	42	41
21:00–00:00	4,236	3,742	104	90	40	42

represents the number of vehicles circulating or present in the network, whereas production represents the number of trips served by the network at a particular interval of time. Both accumulation and production can be calculated using the following equations:

$$A = K_i L = \left(\frac{\sum_i^n T_i}{LT} \right) L \tag{6}$$

$$P = Q_i L = \left(\frac{\sum_i^n D_i}{LT} \right) L \tag{7}$$

$$V_i = \frac{\sum_i^n D_i}{\sum_i^n T_i} \tag{8}$$

For the travel time estimation, consider a neighborhood with hypothetical 3×3 grid network having a unidirectional flow as illustrated in [Figure 6](#).

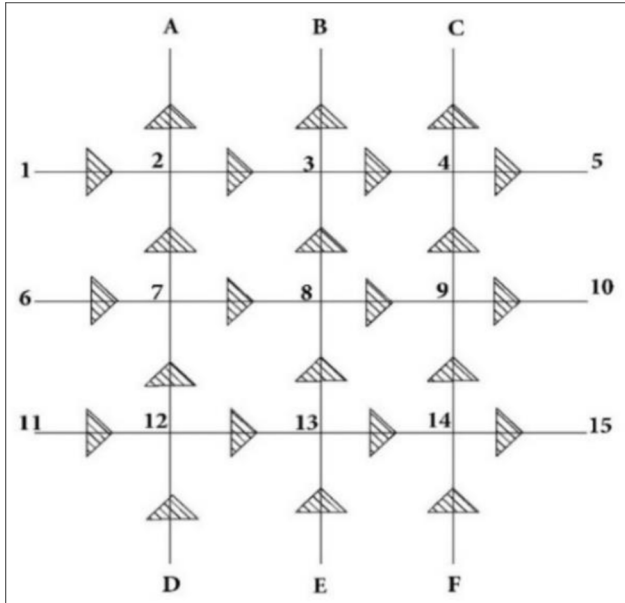


Figure 6.
Hypothetical 3×3
grid network

Distance between each node is considered to be x meters. Different variables used for the travel time estimation using the MFD framework are as follows:

- m represents multiple modes in neighborhood;
- N_{mi} Accumulation of vehicles for internal trips;
- N_{mc} Accumulation of vehicles crossing the neighborhood;
- P_{mi} Production of vehicles for internal trips;
- P_{mc} Production of vehicles crossing the neighborhood;
- V_{ff} Observed speed in free flow conditions;
- D_{mi} Distance travelled by a mode for internal trips in a neighborhood;
- D_{mc} Distance travelled by a mode crossing the neighborhood;
- V average speed of vehicles in neighborhood;
- P Production of all vehicles in the neighborhood; and
- N Accumulation of all vehicles in the neighborhood.

Following equations can be used for the calculation of travel time and speed of the vehicles in the neighborhood:

$$P = \sum_{i=0}^n P_{mi} + \sum_{i=0}^n P_{mc} \quad (9)$$

$$N = \sum_{i=0}^n N_{mi} + \sum_{i=0}^n N_{mc} \quad (10)$$

$$V = \frac{P}{N} \quad (11)$$

$$TT_{mi} = \frac{\sum_{i=0}^n D_{mi}}{V} \tag{12}$$

$$TT_{mc} = \frac{\sum_{i=0}^n D_{mc}}{V} \tag{13}$$

The travel time for a vehicle traversing in a neighborhood depends on the distance travelled, traffic congestion on the links in the neighborhood and the road pavement condition. Consider a vehicle in neighborhood traversing from 6 to 5, it can have three routes with different travelled distance and different TT as presented below in [Table 4](#).

4. Case study results and discussions

For the travel time estimation, the neighborhood selected in this work is indicated in [Figure 7](#), it is selected in such a way that the impact of construction activity on the travel time is also assessed. Presently, from Rawat T-Intersection to Korang bridge, the road rehabilitation and expansion of the existing infrastructure is being carried out, and the length of the road between both these nodes is about 10.2 km. The average free flow speed for the vehicles to traverse from Rawat T-intersection to Korang bridge for pre-construction

Table 4.
Travel time for
different alternates

Links followed	Travelled distance	Travel time
6,7,8,9,4,5	250 m	$\frac{250m}{V}$
6,7,2,3,4,5	250 m	$\frac{250m}{V}$
6,7,12,13,14,9,4,5	350 m	$\frac{350m}{V}$

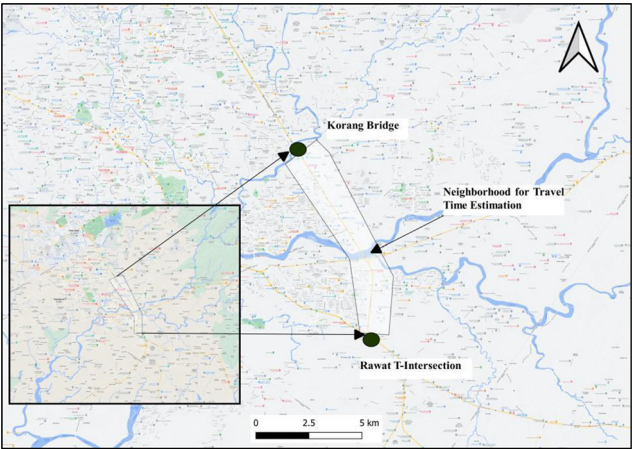


Figure 7.
Neighborhood for
travel time estimation

scenario considered was 40 kmph, whereas the speed after the improvement in network is assumed to be 80 kmph.

For traffic simulation of post-construction scenario Duarouter with Duaiterate.py was used. This allowed the Dynamic User Assignment of traffic vehicles and the traffic demand generated due to infrastructural improvement was also written in the route files.

4.1 Travel time estimation using macroscopic fundamental diagram

The MFD of the neighborhood considered in this section for both pre-construction and post-construction scenario are presented in Figure 8. Maximum production of 1,430,575 veh/h for the post-construction scenario was achieved by 16:00 hours and the critical accumulation achieved was 35,462 veh. For the pre-construction scenario, maximum number of trips, i.e. 1,255,992 veh/h were generated at 11:00 hours and the critical accumulation was 67,902 veh.

The speed estimation from MFD for both scenarios is presented in Figure 9. For the pre-construction scenario, the speed of the vehicles remains below 20 kmph. However, after the improvement of the road network average traveling speed of the vehicles lie between 40 and 60 kmph. The fall of speed for trucks to zero at 09:00 hours indicate that for post-construction scenario the trucks leave the network. The nodes indicated in Figure 7 are at the periphery of the neighborhood, thus TT_{mc} is used to calculate travel time. The results for travel time for both pre-construction and post-construction scenarios are presented in Figure 10.

The travel time of the vehicles to cross the neighborhood for the pre-construction scenario was estimated between 30 and 40 min, whereas, the travel time for the post-construction scenario to traverse through the neighborhood was a little above 10 min. As mentioned in the earlier sections, the trucks are not allowed to enter the system in the morning and evening peak hours. The TT curves for the pre-construction scenario show that the trucks cannot leave the system because of slow traveling speed, but for the post-construction scenario due to improved network, the trucks leave the system in the morning peak hours. The difference in the travel time estimates for both the scenarios represents the net travel time savings.

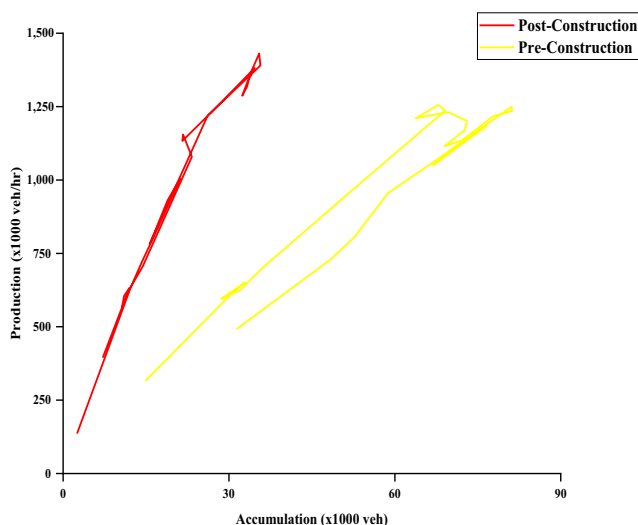


Figure 8.
MFD for
neighborhood

Figure 9.
Speed estimation
from MFD

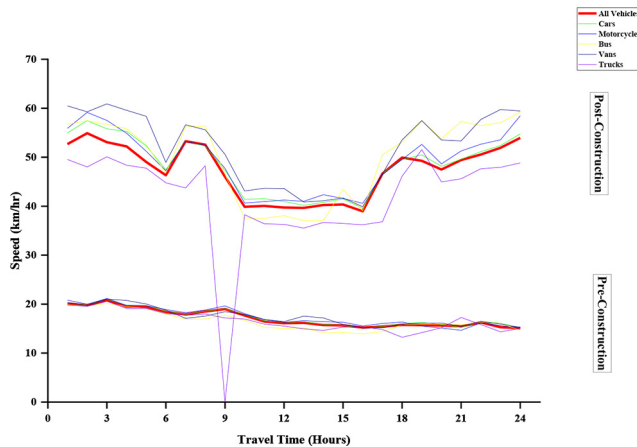
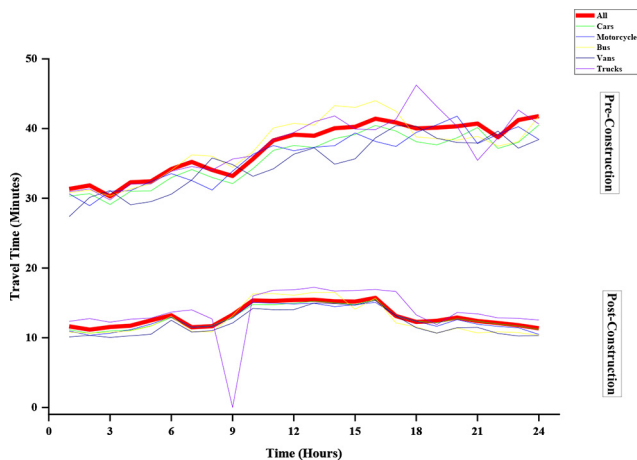


Figure 10.
Travel time
estimation by MFD
methodology



4.2 Travel time estimation using Bureau of Public Roads function

For the estimation of travel time using the BPR function, the road network in consideration was further sub-divided into multiple sections, the mathematical equation for BPR function is as follows:

$$TT = TT_{FF} \left(1 + \alpha \left(\frac{V_{FR}}{C} \right)^n \right) \quad (14)$$

Where TT_{FF} represents free flow travel time, volume on different link is shown by V_{FR} and C depicts the capacity of the link. The constants α and n were assumed to be 0.15 and 2 for the travel time calculation. For the TT calculations, the capacity of the links is assumed to be 1,800 vehicles per hour per lane. FCD data set was transformed into traffic flow (q), which was estimated using the Edie's flow measurement (Edie, 1965) by the following:

$$q = \frac{XL}{T} \quad (15)$$

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Where X is the distance of the vehicles travelled in the section, L is the length of the section and T is the time interval. The TT_{FF} calculated was dependent on the free flow speed of each sub-section. TT for the given section has been calculated using the BPR function the estimates for both the scenarios under consideration with TT using MFD results are presented in Figure 11.

The travel time estimates using the BPR function depends on the volume which varies during different hours of the day. The maximum travel time of 44 min was reported between 08:00 and 09:00 hours interval for the post-construction scenario. The travel time estimates using the BPR function are slightly higher than the MFD travel time estimates. The MFD travel time estimates are dependent on the speed of the vehicles, in the pre-construction scenario, as the slow-moving truck traffic increases after 21:00 hours, the travel time reported is much higher as identified in Figure 10, whereas for the same time interval, the volume of the vehicles reported is less which results in lower estimates of travel time using BPR function. For the post-construction scenario, the calculated travel time using the BPR function follows the change in traffic volume, and the estimates are bit higher than the MFD travel time estimates. BPR method was unable to capture the change in speed for the road network, where 5 lanes merged into 2 lanes. Moreover, the change of travel time for multiple modes was also not estimated using the BPR function which can be calculated using the MFD travel time approach.

5. Conclusions

This study aimed to determine the effect of construction activity on the network performance using the MFD framework. For this purpose, Islamabad's Road network was

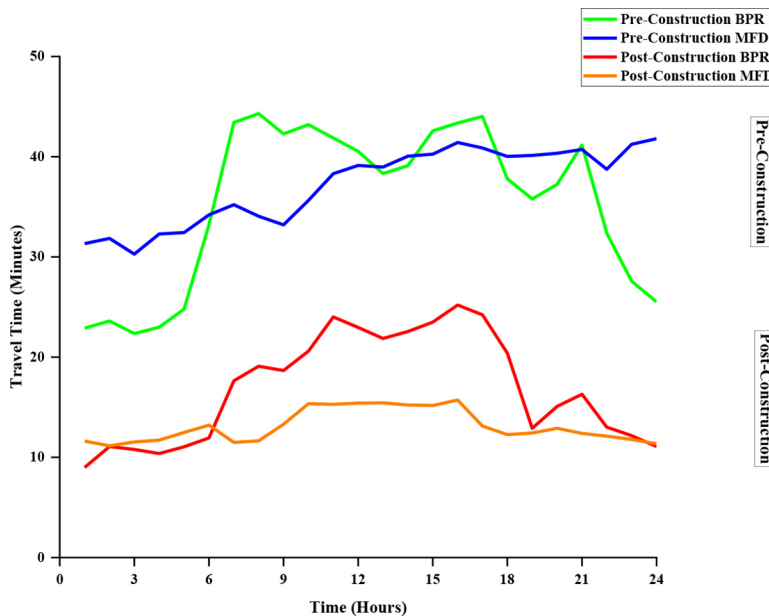


Figure 11.
Travel time
estimation using BPR
methodology

considered and MFD for two different scenarios, i.e. pre-construction and post-construction were generated. The MFD results indicate that the traffic flow speed increases after the infrastructural improvement. Network was divided into two regions based on the construction activity. The overall network performance increases in Region 1 as compared to Region 2. Average speed of vehicles increases in Region 1, which resulted in increased number of trips served by the region, and the vehicle accumulation on the road network is decreased for the post-construction scenario. The macroscopic parameters for Region 2 were largely unaffected as majority of the construction activity was being carried out in Region 1. For a neighborhood, the speed predicted by MFD has been extended to estimate the travel time for vehicles in the neighborhood. This study proposes methodology for estimating travel time for the vehicles either crossing or for internal trips in the neighborhood. The results of travel time estimate from MFD are then compared with the BPR function travel time model. The BPR function predicts travel time for a particular traffic stream for a specific road section. Thus, it was not able to predict the travel time for individual modes. This deficiency of BPR function was overcome by MFD method as it allowed travel time estimation for individual modes. Based on the results from this study, it was concluded that the infrastructural improvement in a network result in the improvement in macroscopic traffic flow parameters. Travel time calculations show that the volume of the road section plays a significant role in the BPR model travel time estimation. Meanwhile, the network speed at a particular interval is important for MFD travel time estimation.

6. Future work

This research work presents travel time estimation while using the MFD. This work can further be extended to estimate the travel time reliability using the travel time calculated from MFD results. Researchers can also develop a complete MFD based framework for evaluating an intervention in the transportation network. Different parameters such as vehicle operating costs, travel time cost and vehicle emissions cost can be estimated based on the MFD results. The results can be applied by transportation agencies particularly in Pakistan to estimate travel time at different intervals of the day and to evaluate alternate transport networks.

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Corresponding author

Zhipeng Zhang can be contacted at: zp.zhang@sjtu.edu.cn

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