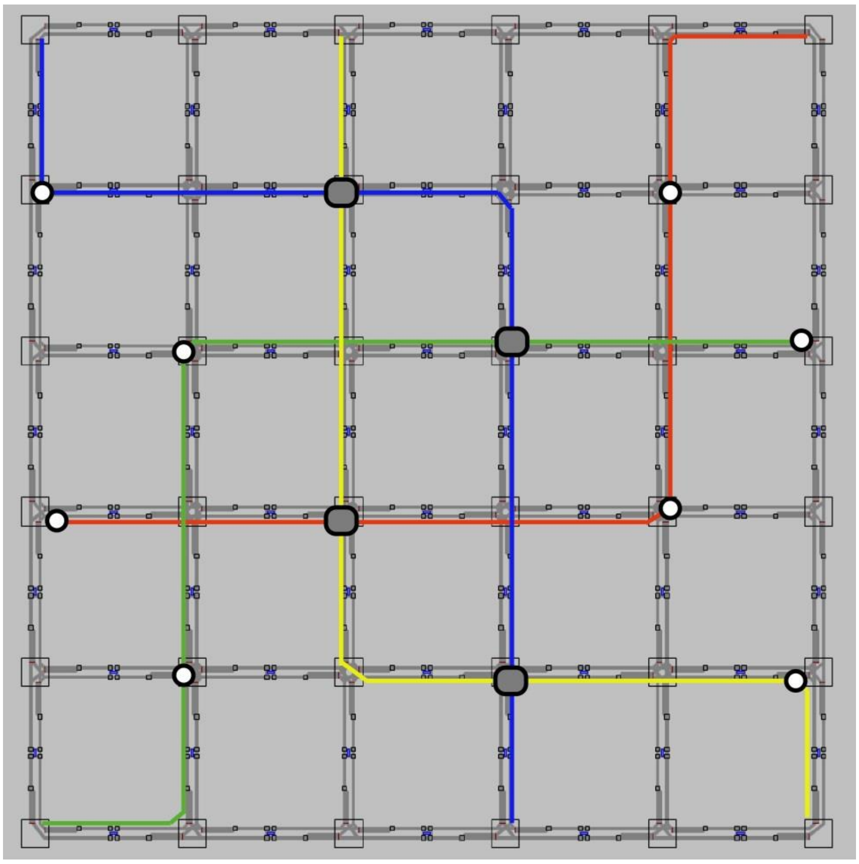

Effects of Bus Operations on Urban Networks

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Abbreviations

AI: Bus Stops located downstream of Intersections (after intersections)

BI: Bus Stops located upstream of Intersections (before intersections)

DTA: Dynamic Traffic Assignment

IBL: Intermittent Bus Lanes

MFD: Macroscopic Fundamental Diagram

MSA: Method of Successive Averages

N/A: Not Applicable

NEF: Network Exit Function

O-D: Origin – Destination

Symbols

“Downstream”: Bus network with the bus stops located downstream of intersections

“New Network”: New bus network (other configuration) with stops upstream of intersections

“Middle of road”: Bus network with bus stops located in the middle of the road links

“Upstream”: Bus network with the bus stops located upstream of intersections

Master Thesis Department of Civil Engineering

Effects of Bus Operations on Urban Networks

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Abstract

Project goal is the bus operational effect identification on urban networks with macroscopic simulation procedures and dynamic traffic assignment implementation. Infrastructural consistency regarding arterial size and traffic-signal allocation allows the influence-level determination for various headways, bus-line networks and bus-stop location configurations. Simulation results illustrated higher capacity decrease for the bus-stop location downstream of intersections and for the dense radial network in contrast to their upstream default settlement. Bus simulations present initially close-to-the-no-buses capacity results for 10-Min headways but they reach up to 27% capacity decrease for 2-Min headways. Linear correlation is noticed between the capacity decrease and the bus courses per hour. Reduced vehicle output due to bus operations can be compensated by the passenger output with the higher bus-passenger full factor. Easiness of passenger-requirement satisfaction depends on the selected headway and the network accessibility. The latter relies upon the travel time, the required transfer numbers and the transfer time. Partial network accessibility comparison elucidates beneficial results for the radial network compared to the uniformly-distributed bus network for 5-Min-headway operations.

Key Words

Bus operational effects; bus simulations; passenger capacity; bus network accessibility;

Preferred Citation

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1 Introduction

Public transportation is an integral part of urbanism and it is responsible for citizen’s movement either for business or for leisure activities. Therefore it is an almost 20-hour daily available service for the majority of urban regions. It is divided into rail and road transport with the first category including subways, city trains and trams and the second one including buses and trolleys. Rail transport is principally allocated separately from network vehicles, for instance cars and trucks and only trams share partially the same road space with the remaining traffic. This ensures their unobstructed operation with delay elimination and potential reliability increase. On the contrary, road transports mainly involve with the cars and the trucks and the obstructed operation is only limited to arterials with dedicated bus lanes. However, this is not completely provided and it is inevitable that road space is allocated both for private and public transport. This road space sharing causes bi-directional effects. Buses cause delays to the cars and trucks due to dwell times at the bus stops and due to the reduced travelling speeds at a microscopic level. On the other side, traffic demands exceed the infrastructural capacities especially at peak hours and congestion is generated across the whole network which affects also the bus operations that stick to the traffic jams.

A bus operation is an argumentative issue and is vital at urban regions for the passenger satisfaction. However, the aforementioned delays due to dwell times and reduced speeds are influential for overall traffic performance at a macroscopic level. It is crucial to approach the bus operational effects macroscopically and to investigate the reduced vehicle output due to bus network incorporation. Simulation process is the implemented tool and technique to visualize network behaviour when infrastructure is loaded with vehicles and subsequently also with buses. Full bus operational effect comprehension can be achieved only when certain parameters remain constant. Initial decision for the project identification is the urban network determination and configuration which is maintained for all the simulation procedures. Investigation goal is to identify the bus operational effects on the simulated network for various bus headways, for modifications in the bus network design and for alterations of the bus-stop position. All these configurations are realistic applications at urban public-transport networks. To be more specific, it is always necessary to increase bus frequencies especially during peak hours in order to satisfy the passenger demands. Moreover, it is a routine for the transport agencies to adjust the bus lines based on the passengers’ preferences and necessities. One additional contemporary tendency is the bus-stop construction close to intersections for transfer-point generation. In total, it is useful for the traffic operations to understand the network “reactions” after these adjustments from a macroscopic point of view.

As discussed above, network traffic performance is awaited to be negatively affected from the bus operations and overall vehicle output is expected to decrease. Despite this, bus operations are characterized as beneficial which relies on the bus passenger capacity and the ability of public transport to accommodate much more users than the “private” ones. This issue extends the topic from the vehicular to the passenger output and the passenger requirements which balance the bus operational capacity drops. Passenger-demand topic raises the argument about easiness of buses to transport the aforementioned passengers dependent also on the implemented bus headway.

Passenger demand requirements can only be satisfied based on the available bus-network accessibility. The latter depends mainly on the required passenger travel time, the necessary public-transport transfers and the transfer-point waiting times. More analytically, there are some passengers that select their route based on the door-to-door travel time; others prefer travelling with one means of transport despite a slightly longer travel time. There is a third category that searches for their optimal combination. Various simulated bus-line networks, following raster and radial design, are compared for their accessibility. Equilibrium introduction is provided between the accessibility and the vehicle output from the simulations.

2 Background

This chapter presents analytically the previous implemented researches related to the current survey. First, there are surveys that verify the MFD existence and its representation of the network traffic behaviour. Second, surveys with infrastructural similarities to this analysis based on simulation applications are presented. Moreover, bus operations and space allocation is shown analytically. In addition, discussion is provided about capacity decrease due to bus operations.

An issue that derives from the ongoing simulation implementation is the existence of Macroscopic Fundamental Diagram and its correlation with the Fundamental Diagram, in which the flow and the density are related. Experiments in the city of Yokohama approve the existence of the MFD (Geroliminis & Daganzo, 2008). Data has been collected both from fixed detectors inside the urban area and from real taxi drivers' routes. Regarding the detector data collection, data verifies flow fluctuations and congestion during weekdays. This evidence certifies the MFD existence for the network portion equipped with detectors. MFD shows a non-monotonic relation between the flow and the speed. As for taxi drivers' collected data, it is identified once again that the MFD exists. Use of the Network Exit Function[1] instead of flow and density for the MFD has been approved. The MFD existence is suggested to be the tool for the network traffic-condition identification and for the road-management-strategy implementations. Suggestions for traffic improvement behaviour via routing strategies with the MFD use are also presented by Knoop, Hoogendoorn, and Van Lint (2012).

Research continuation of Geroliminis and Daganzo (2008) is the survey of N. Geroliminis and J. Sun (2011). They focused on the property identification for the MFD satisfaction through loop-detector real data in Yokohama and Minnesota. Spatial distribution of vehicle density affects the MFD scatter and shape and therefore analytical derivation of spatial distribution is implemented. The implementation result is that MFD is non-representative for the traffic operations only at freeways due to hysteresis effects. This has been, first, extracted only from loop detectors in Minnesota (Nikolas Geroliminis & Jie Sun, 2011) and then it has also been confirmed from the detectors in Yokohama (N. Geroliminis & J. Sun, 2011). This outcome proves that the MFD application at an urban area is well-defined and representative. Additional survey, which accomplishes the basic experimental analysis of Geroliminis and Daganzo (2008) in Yokohama, has been implemented with real-data loop-detector collection

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[1] Network Exit Function: See analytically in section 4.1.1.

in Toulouse, France (Buisson & Ladier, 2009). The basic analysis in Yokohama has been undertaken at a homogenous network whereas research target in Toulouse is the heterogeneous infrastructure examination (freeways and urban streets). Buisson and Ladier (2009) conclude that zone homogeneity and congestion onset and offset are crucial factors for a representative MFD. All these factors are considered for the current analysis with organization of a grid homogeneous network and with the smooth demand increase during simulation (Ji, Daamen, Hoogendoorn, Hoogendoorn-Lanser, & Qian, 2010).

After the examination of the existence of the MFD diagram (Geroliminis & Daganzo, 2008), Carlos F. Daganzo and Geroliminis (2008) approximate analytically the MFD of urban traffic with expressions of the shortest path recipe. These approximations are based on the already collected real data from San Francisco and Yokohama from the previous publications.

Parallel to real data collection, additional simulation-based research for the MFD existence is fulfilled by Ji et al. (2010). The simulation process is based on the same simulation tool named “Vissim”. It focuses on a central urban region in Amsterdam which consists of both freeways and urban arterials. Factors affecting the MFD have been investigated for instance the demand and the ramp-metering. Useful analysis result is the MFD dependence on the selected demand. Abrupt demand decrease does not lead to congestion resolution due to inefficient use of the links. Therefore it is selected for the current survey to increase the network demand smoothly and to sustain the network loading for the whole simulation period. The analysis of Ji et al. (2010) does not maintain, though, the Dynamic Traffic Assignment (DTA) strategy and does not focus on the bus operational effects.

Despite MFD existence, jam-density and bifurcation instabilities can be noticed especially at the congested MFD part (Carlos F. Daganzo, Gayah, & Gonzales, 2011). Networks with overlapping streets reach their jam density at a fraction of the overall average jam density. This instability is also noticed, at a lower rate, for homogeneous spatial networks with evenly distributed flows and densities and with adapted to-the-traffic-conditions re-routing. Empirical data from Yokohama, Nairobi and San Francisco show the MFD consistency for low densities (uncongested part) and presents the bifurcation when the network gets loaded until the jam density is reached. This output is crucial for the following simulation procedures and explains the potential instabilities and bifurcations at the congested MFD parts.

Infrastructural basis for the implemented simulation process is the analysis of Ortigosa, Menendez, and Gayah (2014). This execution focuses on the macroscopic urban network behaviour for various infrastructural configurations. The overall concept of the current research is supplementary to aforementioned one with bus implementation. One-way and two-way streets with prohibited and protected left turns have been simulated to examine the MFD existence and to show the gridlock-approaching level for each configuration. The output for the MFD design was the NEF which correlates the flow and the density with the number of completed trips and the active network vehicles respectively. This correlation together with the Dynamic Traffic Assignment (DTA) implementation and the Method of Successive Averages (MSA) are also sustained in the current analysis. DTA provides more realistic users' approaches considering the drivers' experienced travel times and it is analytically explained in section 3.2.1. It is derives from this paper that the uncongested MFD part is similar for all configurations and differences are noticed only at the congested part. Regarding the results, the configuration with the protected left-turns has a limited capacity compared to the others and gridlock is reached quicker. This was an envisioning that vehicle demand limitations may also rise in the current implemented simulation.

The differentiation of the current analysis and the research of Ortigosa et al. (2014) is the public-transport non-existence. Bus operational capacity disturbances are the investigation target of the current research, which mainly sustains the remaining external parameters in order bus operational effects to be determined.

Similar approach shows the research implemented by Gayah and Daganzo (2012). Project goal is capacity-level definition for both one- and two-way network configurations. Various configurations, with overlapping and non-overlapping left lanes, with left-turn pockets, with pre-signals, with single-lane approaches, with banned left turns and one-way directions are simulated. Results show that the traffic signal reduction for the through-moving vehicles does not show reduced capacity results when the average trip length is low. The reason for capacity sustainability is the direct movement at the two-way network and the circuity avoidance due to left-turn pockets. This research is evidence that operational efficiency with liveability can co-exist harmonically in a network.

The results of the aforementioned research are complementary to the ones of Ortigosa et al. (2014). The latter extracted that one-way networks guarantee similar results with the two-way networks with prohibited left turns and higher results than the two-way network with protected left turns. Difference between them derives from the average trip length. Ortigosa et al. (2014) simulate a large network with long average trips whereas Gayah and Daganzo (2012) relate the network capacity with the average trip length. As a result, the simulated network in the current analysis is a two-way network with smaller size in order to better fulfil the short trip-length criteria of Gayah and Daganzo (2012).

Emphasis is given generally on the space allocation between private and public transportation. Urban-area space is always limited and there is a strong controversy for the appropriate allocation based on the diverse government policies. Space allocation between public and private transport throughout a weekday in Seoul is the topic of Black, Lim, and Kim (1992). Black et al. (1992) work with users' costs to identify the optimal lane allocation between various lane types (mixed, transit, bus and truck lanes). They conclude that bus lanes are the most efficient peak-hour implementation especially if they are also used as HOV lanes. Same space allocation for the morning peak hour is analysed by Gonzales and Daganzo (2012). Temporal equilibrium is their analysis basis considering the user equilibrium, the system optimum and tolls and fares for both implementation and dismissal of dedicated bus lanes.

Later on, Guler and Cassidy (2012) identify the fully dedicated bus-lane inefficiency for large network proportion. This research deals with the phenomenon of underutilized space usage of dedicated bus lanes at low public-transport rates. It additionally presents alternative compromising strategies for bus-delay limitation and vehicle-decrease avoidance. For instance, Intermittent Bus Lanes (IBL) is a dynamic method that switches a shared to a dedicated bus lane only during the bus approach. This application is efficient for low bus rates and high vehicle demands with simultaneous bus-delay minimizations. Additional example is provided for bottlenecks, in which the exclusive bus-lane allocation can underutilize the space effectiveness. Therefore appropriate alternatives are examined. Special analysis focuses on signalized intersections for the proper bus route selection that guarantees bus-delay avoidance. The analysis of Guler and Cassidy (2012) is an incentive for the current survey that the dedicated bus- lane application at the whole grid network would substantially decrease the network vehicle efficiency.

Another more recent reference to the space allocation is the analysis of Zheng and Geroliminis (2013). Goal of this project is the multimodal MFD analyses and travelled passenger-hour minimization due to demand redistribution in-between transport modes. Simulation-based analysis copes with space allocation between public and private transportation with consideration of the pricing effects as a network management strategy. Network has been divided into mainly two areas, an urban central with changes between dedicated and shared lanes and a suburban one. Regarding the lane types, there is a division between static allocation (always dedicated bus lanes), dynamic allocation (switching from dedicated to shared) and dynamic allocation with pricing. Outcome is that the most efficient implementation is the 10% dedicated bus-lane existence for dynamic allocation with car-capacity limitations and higher passenger numbers. Static and pricing are not as successive as the dynamic allocation due to the space allocation inflexibility and due to the extremely high public transport preference respectively. This research connects space allocation with passenger travelling fulfilment and expands the current survey potentials to the passenger output. This means that the higher bus-passenger number outweighs the capacity decrease of the bus operations and analysis about this topic would be useful.

Parallel to the separate analysis of the MFD existence and the space allocation, there is a research that combines both implementations (Gonzales, Geroliminis, Cassidy, & Daganzo, 2010). Network monitoring and control through the MFD existence with existing real data from San Francisco was the survey objective of Gonzales et al. (2010). Additionally, evidence was provided for the interactions of multiple transportation modes and their MFD incorporation. The researchers found out that city-access restriction improves the overall traffic behaviour and mobility. Moreover they concluded that dedicated space is advantageous even for the network users whose space was taken away. This research enters the issue of users' accessibility, explains the controversy of road users' space and allocates this space to the corresponding users, for instance with HOV lanes.

Last but not least, there are various researches focusing on the bus operational impediments caused to traffic performance. Average bus-stop delay located upstream of intersections was the analysis topic of Wong, Yang, Yeung, Cheuk, and Lo (1998). They simulated microscopically various upstream bus-stop configurations with several factors to identify the delay. Their findings conclude that the delay decreases rapidly when the bus stop is next to the intersections and it is not so highly affected by the dwell time, the green time and the traffic cycle. Another crucial factor is the bus frequency. Similarities exist only for the investigation of bus operational effects but the network investigation level differs among them (macroscopic vs microscopic). Additional differences derive from the aforementioned parameters (dwell time, green time and traffic cycle). They are taken for granted in the current analysis compared to the fluctuating ones in the survey of Wong et al. (1998).

The most similar goal to the current analysis illustrates the research of Boyaci and Geroliminis (2011). They searched for the network capacity decrease regarding the bus operation. This paper shows network capacity decrease that reaches the level of 30% considering all modal shifts as separate vehicles. Additional information is provided about the vehicular and the passenger-capacity difference taking into account the diverse multimodal full factors. Despite vehicular capacity decrease, passenger capacity increases up to 164% depending on the passenger number, the traffic cycle and the lane number per direction. Significant difference between these two analyses arises from the data collection mechanism. Boyaci and Geroliminis (2011) simulated the network and gathered the information from moving observers' trajectories. Additional difference derives from the bus-stop location. The aforementioned research allocates the bus stops only in the middle of the network links whereas the current research considers more realistic configurations with close-to-intersections bus stops. Reference to the vehicular and passenger capacities is executed also in this analysis.

3 Methodology

This chapter focuses on the presentation of the simulation infrastructural characteristics, sets the simulation parameters and explains the bus route and bus-stop decision.

3.1 Network Configuration

Physical infrastructural network properties will be presented in this section regarding the network size and type, the length of the links and the left turns.

3.1.1 Network Type & Size

The selected network is a 6 X 6 two-way street grid network with left turns and with one lane per direction. The network shape with the entire infrastructural configuration is shown in Figure 1.

The choice of a two-way street network with left turns entrenches to the real ones. It mainly allows more direct movement in the network and shortens the travelling distance. The majority of the urban streets is structured either with permitted or with protected left turns. An additional green phase is incorporated into this simulation[2] despite the capacity decrease for the remainder. As a consequence, left-turn pockets are configured and used for the left-turn vehicle accumulation.

Concerning the size of the network, the 36 intersections are selected as the balance between the macroscopic approximation of a real urban network and the required computational load. Infrastructural reference survey of Ortigosa et al. (2014) provides that the 100-intersection network demands long simulation periods.

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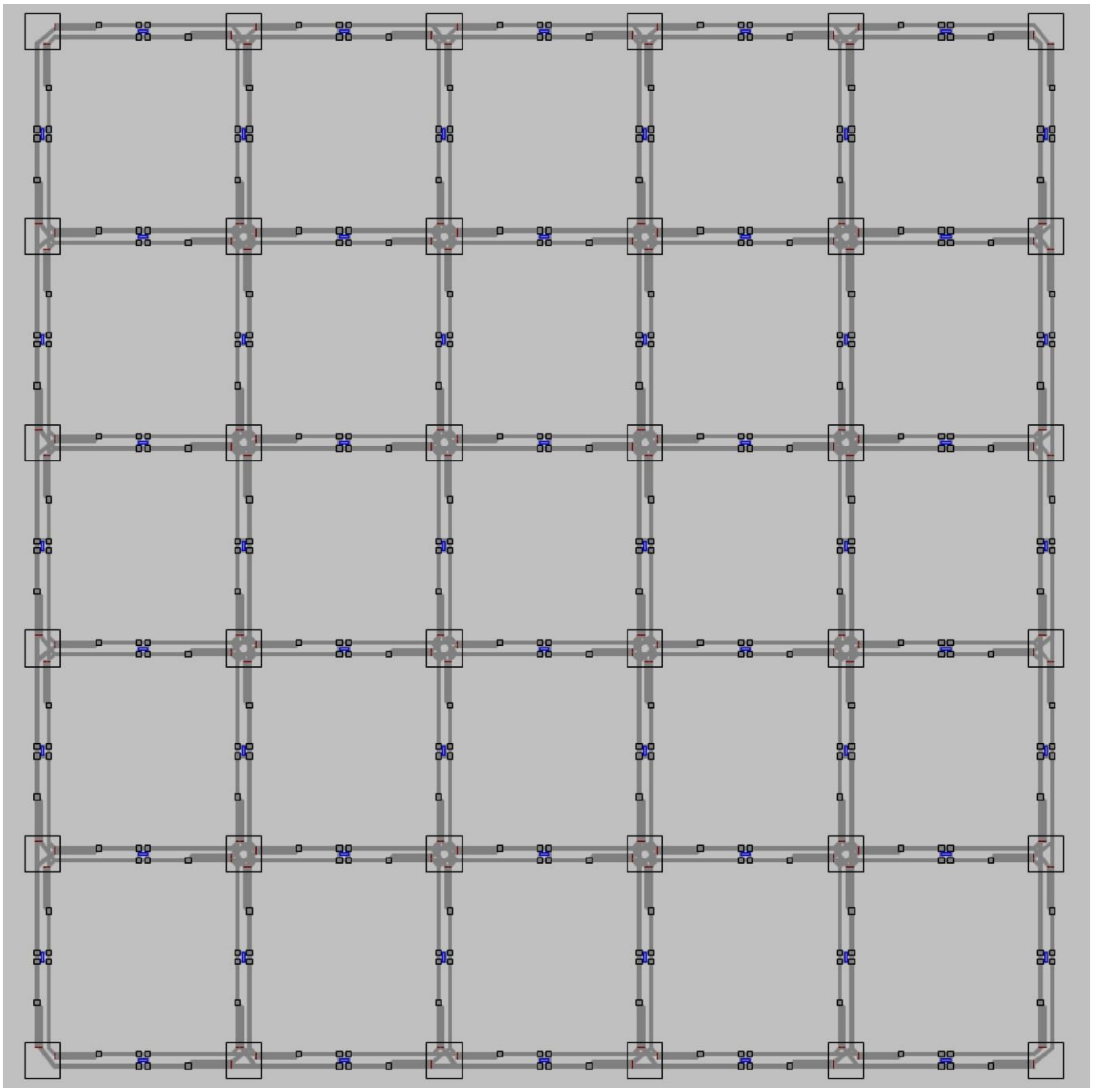
[2] Protected left turns selected

Figure 1 6 X 6 two-way street grid network with left turns and one lane per direction

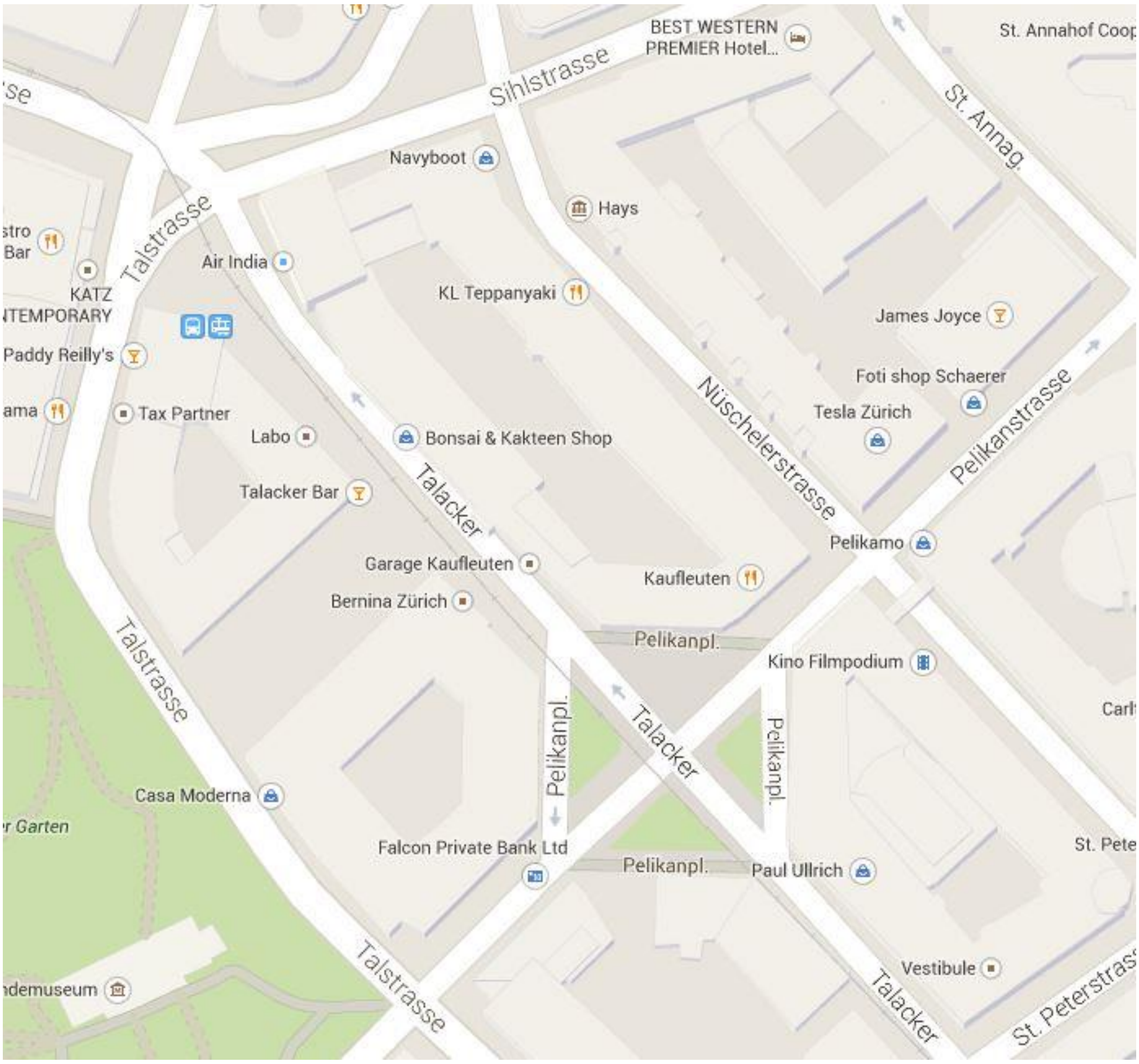


Source: Vissim 6 (2014), Own Configuration

3.1.2 Length of Links

The length of each link is 150 m. This creates an overall network of 0.56 km^2 (750m X 750m). The length of the links is chosen to notch that observed at real networks, mainly in the city of Zurich (Stadt Zurich, 2014), considering the distances between the traffic lights within the network. Random measurements at several intersections and locations in the city of Zurich show that the distance between two signalized intersections varies between 70 and more than 200 m. Frequent scenario in the city of Zurich is the existence of parallel central arterials, which have signalization every more than 200 m along their length but their in-between distance does not exceed 100 m.

Figure 2 Example of Traffic Signal Distance in the city of Zurich



Source: ("Google Maps," 2014)

In Figure 2, for instance, “Talstrasse”, “Talacker” and “Nueschelerstrasse” are three main signalized central arterials in the city of Zurich. The distance between the signals at these links is longer than 200 m whereas at the crossing street named “Pelikanstrasse” the traffic light distances are 90 m and 70 m respectively. Taking this variability into consideration, it is assumed that the 150m-length is an average value that represents the traffic-light distances in Zurich.

3.1.3 Left-turn Length

Zhang and Tong (2008) approached the road blocking due to spill-back effects of the short left-turn bays for the through-moving vehicles. In addition, they examined the effects of left-turn disturbance due to spill-back effects at the through-moving drivers. Based on their simulations, blocking depends on the traffic volumes for left-turn- and through-moving vehicles, the traffic cycle length and the left-turn-to-through-arrival ratio. In principle, large left-turn bays protect intersections from spill-back effects. It can be derived from Zhang and Tong (2008) that the spill-back probability reaches almost zero when the left-turn bay is long enough for ten vehicles. Therefore the length of the left-turn lanes is selected to be 40 m. This enables queueing of the left-turn vehicles at these special lanes and prevents from blocking the through- and right-moving vehicles. As a result, the maximum link density is higher and the network is prohibited from gridlock[3] for longer. Analogous to the left-turn length is the green phase exclusively for the left-turn vehicles as seen in section 3.2.4.

3.2 Network Operations

After the infrastructural introduction, information of the dynamic traffic assignment implementation, the origin-destination matrices, the network parking zones, the traffic signal operation and the conflict area determination are provided.

3.2.1 Dynamic Traffic Assignment

Attainment of the simulation processes is the application of the dynamic traffic assignment (DTA) regarding the users’ travel times (Transport Research Circular, 2011) & (Ortigosa et al., 2014). Algorithm for route optimization (users’ equilibrium) is already analysed by Jiang et al. (2011), who propose a user-optimal model based on various finite volume and element methods.

Various already implemented simulations were established on several static traffic assignments with instantaneous travel time routes. This route choice is elucidated as:

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[3] Gridlock: Traffic state in which vehicles are congested at most of the links in the network (less than 10% trip completion rate compared the trip completion rate at the capacity)

- Shortest travel time route is supplied to the network users at the departure from the origin point.
- Network users select their travel time route considering the provided traffic information and ignoring the experienced travel times.

Static assignment is rather unrealistic and does not correspond to the network users' real behaviour. In reality, drivers seek to minimize their travel time route dependent on their previous experience. Therefore their selected route is contingent to their experienced travel time route (from previous iterations) and does not rely only on the information at the departure time. This choice continues until the network users identify their shortest route or in other words they reach their equilibrium. As a result, DTA algorithm runs regarding the following parameters until convergence criterion is attained:

- Different departure times are assigned with different routes.
- Vehicles with common departure time and common O-D pair would pick such a route that guarantees same travel time due to user equilibrium.

In total, the DTA inserts to the simulation a more realistic approach with the consideration of the experienced travel times for the achievement of the user equilibrium (Transport Research Circular, 2011). Input for the DTA implementation are the O-D matrices presented in section 3.2.2.

3.2.2 Origin Destination Matrices

Vehicle input in the simulation process can be completed either manually through the settings or as an external source through the origin-destination matrices. Regarding this method, the vehicle demand is inserted in the network through external files, which include the time interval of the demand input, the scaling factor, the number of network zones and the number of trips between the zones ("Vissim 6 Manual," 2014). After the time-interval determination, the number of zones is provided so that all possible trips are generated. The scaling factor is used for the multiplication (demand increase) of the whole matrix and number of trips enables heterogeneity in the trip generation between the various O-D pairs. For instance, referring to large metropolitan cities, trips between suburbs are not as usual as movements from the suburbs to the city centre and this can be manually modified in the external file.

This grid network is a homogeneous network with same number and size of arterials and it can be regarded as a city centre with homogeneously distributed trips. Therefore, the matrix consists only of “1” values for all the possible O-D trips which ensures this homogeneity. As a result, the scaling factor is modified regarding the time interval and thus the demand is analogous to the selected factor.

3.2.3 Parking Zones

The parking lots or parking zones exist either for the modelling of the roadside parking and the pick-up/drop-off lanes or for the configuration of the origin-destination trips. The former is used mainly for the static and dynamic assignment whereas the latter is solely used for the dynamic assignment (see chapter 3.2.1). There are three alternatives for the parking zones:

- **Zone connector**: Vehicles enter and exit the network without inducing deceleration and delays. This alternative only matches to origin-destination trips.
- **Abstract parking lots**: Vehicles decelerate when they reach the parking lot and they are deleted after the parking process.
- **Real parking spaces**: Limited number of parking spaces and real simulation of the overall parking procedure is provided. ("Vissim 6 Manual," 2014)

Zone connector is selected for these simulations mainly for two reasons:

- It is the singular method that combines the implementation of the dynamic assignment with origin-destination trips.
- Network traffic is not influenced from the parking manoeuvres and external factors affecting the bus operations are evaded.

The length of the zone connectors is determined to be 10 m so as to only allow vehicles to enter the network one by one.

3.2.4 Network Traffic Signals

The selection of the traffic signal operation is based on the successive parameters:

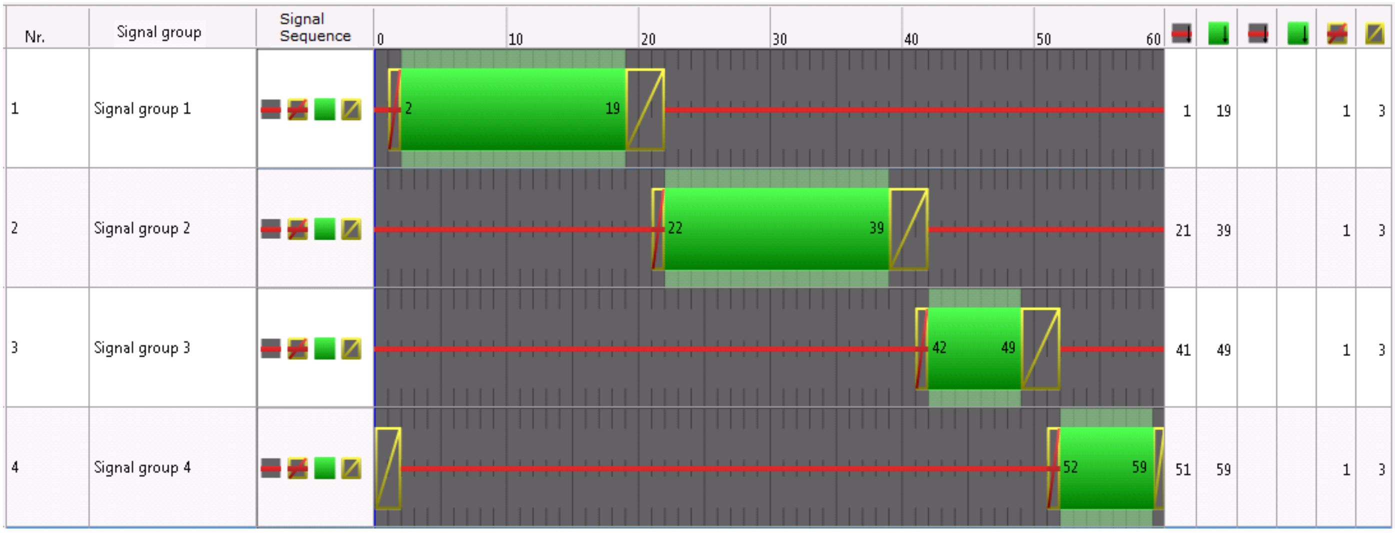
- Travel paths are modified among the iterations based on the dynamic assignment and vehicle demand, subsequently, fluctuates in-between the links.
- Immense computational load is required to adjust actuated traffic signals and it does not counterpart to the application of the dynamic traffic assignment.

- Application of the green wave at centralized arterials is not feasible due to uniform grid network (no central arterials).

Taking all the aforementioned parameters into consideration, it has been decided that fixed time signals with certain allocation of traffic green times along the whole network and no off-set time are applied at the network.

As mentioned above, the network consists of two-way streets with separated left turns which indicate that four green phases are required for each intersection, two for the through- and right-moving vehicles and two for the left-turn vehicles. The latter are proportionally appointed to have enough green time to release the yielding vehicles in the 40m left-turn lanes. Therefore the green time allocated to the left turn phases is 7 seconds. Assuming that the lost intergreen time is 3 seconds (Total lost time: 12 seconds) it results that the green time for the through- and right-moving vehicles is 17 seconds. The allocation of the green time phases between the signal groups is presented in Figure 3.

Figure 3 Green Phase Time Allocation among Signal Groups



Nr.	Signal group	Signal Sequence	0 10 20 30 40 50 60	🟥	🟩	🟥	🟩	▨	▨
1	Signal group 1	🟥 ▨ 🟩 ▨	2 19	1	19			1	3
2	Signal group 2	🟥 ▨ 🟩 ▨	22 39	21	39			1	3
3	Signal group 3	🟥 ▨ 🟩 ▨	42 49	41	49			1	3
4	Signal group 4	🟥 ▨ 🟩 ▨	52 59	51	59			1	3

Source: Vissim 6 (2014), Own Configuration

3.2.5 Network Conflict Areas

Conflict areas are regarded those in which traffic flow from various directions coincide among themselves. The grid network contains the following conflict-area categories:

- Traffic signal intersections
- Parking lots
- Left-turn diverge points

It is noticed in the simulation implementation that by congestion creation the traffic spills back to the following links. The vehicle queue blocking the intersection, however, was not an obstacle for the cross direction and vehicles were “overtaking”. This unreal occurrence was hindering queue creation and vehicle loss of green time due to bus operations especially close to intersections. Consequently, the initial results were misleading and it is decided to restrict this “overtaking” behaviour. It is selected to set the status of the conflict areas to “undetermined”. This means that there is no right of way and vehicles follow their original sequence ("Vissim 6 Manual," 2014). This determination guarantees that occupied conflict areas cannot be used from other-directional vehicles when intersections are blocked.

3.3 Simulation Parameters

This section presents the simulation assumptions and parameters. Information is provided about the simulation period, the vehicle demand and composition distributed in the network and the dynamic assignment parameters.

3.3.1 Simulation Period

Each iteration lasts for a 3-hour real time simulation. This 3-hour procedure can be correlated with the real morning peak period, in which the network gets steadily loaded until the demand exceeds the network capacity. The selection of this simulation duration outweighs the computational load required for the dynamic assignment with reliable and reasonable simulation results. Several simulations that gridlock during the 3-hour period are selected to be simulated for 3 hours and 40 minutes (see also section 3.3.3).

3.3.2 Vehicle Composition

Urban networks consist mainly of private cars and motorcycles. The percentage of trucks is generally low due to use of suburban corridors to avoid urban congestions. Therefore, 98% of the network vehicles are private cars and only 2% are trucks. Input of motorcycles in Vissim is evaded due to their reduced width, their movement flexibility and their congestion avoidance through overtaking.

3.3.3 Vehicle Demand

Vehicle demand selection insinuates the relation with the supply of the network which has a saturation flow of 1800 vehicles/hour. Optimizing the network demand is vital for the simulation processes in order to identify the suitable one reaching the link capacity. Substantial is the fact that the existing network is a grid network with homogenous characteristics, same arterials and lack of local streets, in which the traffic congestion dissipates. This implies that the limited urban simulated network leads to unavoidable gridlock effects when spill backs are created.

Various tests are implemented to identify the appropriate network demand. The procedure of the demand selection concludes to the following required demands for this network.

Table 1 Vehicle Demands for Simulation Processes

Simulation Period (Hours:Minutes)	Vehicle Demand (Vehicles per O-D pair)
00:00 – 00:20	0.40
00:20 – 00:40	0.70
00:40 – 01:00	0.85
01:00 – 01:40	1.80[4]
01:40 – 02:20	1.90
02:20 – 03:00	2.00
03:00 – 03:40[5]	2.00

Source: Vissim 6 (2014), Own Configuration

Goal of the demand selection is to visualize the morning peak period of the network with gradual network loading from the early morning hours with limited demand to the peak-hour period. As shown in Table 1, the loading of the network is steady and smooth. Abrupt network loading is avoided in order to refrain from stepping from really uncongested to extremely congested traffic states. As shown before, it leads to inefficient use of the links (Ji et al., 2010). This ensures that network capacity levels can be extracted from the simulation processes.

---

[4] Demand is proportional to the simulated period and this is the explanation for the demand inequalities.

[5] Additional simulation period is used only when the simulation does not reach gridlock. Bus network input leads quicker to congestion especially for high bus frequencies. Therefore, the simulation period for no buses and for low-frequency buses is extended to extract also the congested MFD diagram.

3.3.4 Dynamic Assignment Parameters

As mentioned above, dynamic traffic assignment is implemented at the simulation processes, in which the travel time routes are calculated contingent to the experienced travel time routes of previous iterations. There are two alternatives for the consideration of these iterations:

- **Exponential smoothing of the travel times**: All iterations are considered for the calculation of the travel time routes with the most recent ones having a larger weight.

- **Method of Successive Averages**: Certain number of iterations is considered for the calculation of the travel time routes with equal weights for each iteration ("Vissim 6 Manual," 2014).

Method of Successive Averages (MSA) is applied at these simulation processes with the last 5 iterations being accounted until the convergence criterion[6] is satisfied. This evaluation with a limited iteration number has mainly two advantages:

- First simulations with lack of experienced travel times lead to artificial gridlocks which disappear when the users reach their equilibrium.

- Computational load is smaller due to reduced evaluation number.

Convergence criterion is achieved due to re-routing dependent on the drivers' experienced travel times. After each iteration, the simulation program collects all the possible paths between each O-D pair. It calculates a probability for each of the pairs dependent on the utility of the path and the travel time[7]. The probabilities derive from the Kirchoff equation as below:

$$P^{r}_{i,j} = \frac{{U^{r}_{i,j}}^{k}}{\sum_{s=1}^{N} {U^{n}_{i,j}}^{k}}$$

Kirchoff parameter k is the crucial factor for the route choice. Increase in this parameter conveys to higher probability that the shortest route will be selected. For instance, a Kichoff parameter of 20 results in 99.97% choice of the least duration path[8] (Ortigosa et al., 2014).

A default value of 3.5 is selected for the simulations, which indicates that there are a significant percentage of users which do not choose the shortest route. Referring to aforementioned

---

[6] Convergence Criterion: Travel time on paths of the last iteration is smaller or equal to 5% compared to corresponding ones of the previous 5 iterations. (see chapter 3.3.6)

[7] Path utility is the inverse value of the travel time.

[8] Three alternative path durations: 10 min, 15 min and 20 min

example, 75% of the users would pick the shortest route, 18% the second shortest and 7% would prefer the longest one. This approach is more feasible to the reality, in which the traffic state normally fluctuates among the days and other conditions (see weather conditions). Therefore users do not always know in advance the shortest route.

3.3.5 Additional Simulation Parameters

Two additional parameters need to be explained regarding the simulation processes: the simulation resolution and the random seed.

The simulation resolution identifies the frequency of the vehicle positions within a simulation second. Ten steps will be positioned for each vehicle at this period. This value is regarded as an average value which smooths the vehicle movements within a simulation second and is recommended also from the PTV Group ("Vissim 6 Manual," 2014).

Random seed initializes a random number generator and stochastic functions of Vissim. This results in different traffic flow distributions. It is recommended for an DTA application to keep this value constant for avoiding see-saw effect ("Vissim 6 Manual," 2014). Randomly it is selected to keep the value of 42 for this parameter for the first random seed and the values 17 and 65 for the second and the third respectively.

3.3.6 Simulation Completion

DTA is applied as mentioned above and users re-route to shorten their travel time routes. Parallel to DTA, the considered re-routing travel times are the last five, each of which weighs identically for the route selection based on the MSA. The simulation criterion is fulfilled when the travel times on paths of the last five iterations do not vary more than 5% among themselves. Simulation process is completed when this convergence criterion is satisfied.

3.4 Bus Network Design

This section analyses the bus input in the network. Analytical details referring to the bus-line sizes and types, the bus network selection, the bus-stop determination and various bus-stop parameters are provided.

3.4.1 Bus-Line Types

The urban simulated network is represented as a city centre, in which a moderate number of bus lines occupy its central streets. Considering the city of Zurich ("ZVV," 2014), it can be noticed that the central part of the city is the main railway station (Zurich HB). Numerous bus and tram lines cross the station, the size of which is so large that three stops are required at its periphery to cover the passenger demands.

In addition, the network consists mainly of diameter lines[9], which are the combination of two radial lines, cross the city centre and connect two city suburb areas at different directions. For instance, the bus line 31 in Zurich is a diameter line that connects the east north-east city suburbs with the south west city-centre part.

Advantages and Drawbacks of Diameter Lines

The advantages of the diameter lines are:

1. The central breakpoint of the line (The central station in the aforementioned example) is operated as a passage point with bus waiting times that do not exceed two minutes. As a result, the layovers of the buses at central locations in comparison to radial lines are avoided and buses do not occupy the congested city central links for a long period.

2. It is feasible to create different large-scale corridors without transfers. Higher flexibility is provided to the network users when the bus connects two juxtaposed suburban neighbourhoods (Weidmann, 2012).

Diameter lines contain one main drawback that derives from demand criteria:

1. Symmetry between the combined radial lines is required to prevent heterogeneously loaded bus courses (Weidmann, 2012).

Considering the aforementioned benefits of diameter lines, similar lines are established in the grid network in order to connect distinct urban regions.

---

[9] Diameter Line: (German Definition: Durchmesserlinie) Combined line which connects two separated radial lines. This is a line that initiates from a city suburb, ends to another suburban area mainly at the opposite direction. It crosses the city center, in which the bus does not stop for long time. Therefore, long waiting times and layovers in the congested central area are avoided.

3.4.2 Bus-Line Configurations & Selection

Bus network design can be a hub and spoke system, in which there is only one transfer point in the network and a whole bus grid network[10]. The latter consists of various radial, tangential and diameter lines that allow transfers at every network stop. The grid system permits higher flexibility to the public transport users. It provides transits at non-centralized locations with respective reduction to the passengers' travelling distance. On the contrary, it has two main drawbacks:

- Grid system necessitates more route-kilometres to satisfy the overall bus-line demand.
- Coordination between the lines is infeasible (C. F. Daganzo, 2010).

Analysis in the lecture script of Daganzo (2010) short systems with few stops and long lengths compared to the service perimeter do not compel transfers whereas longer systems are assisted from transit points. It is also mentioned regarding practical applications that the bus grid-network goal is to cross the city centre with sustainability of a ring-radial concept. This implies that concept continuity of the diameter lines would be the design of a ring line that develops new transfers between the existing lines.

Consideration of the preceding strategies is the incentive for the creation of various bus network scenarios. It should be noticed that all the consecutive scenarios consist of two-direction bus lines. This is common implemented strategy at central urban regions which enables easier adaptability for the users to the bus network system. To be more specific, it is more user-friendly to create bus stops for both directions at the opposite points than detour the opposite-direction lines to different arterials, forcing non-regular users to search for the bus stops.

Scenario 1

Scenario 1 is determined as a raster non-symmetrical network in terms of this network size. There are several transit areas in the network that guarantee connections among all the existing lines but the required travel route is inefficient at several transfer points. To be more specific, a passenger that travels from south west to north west needs to change from the yellow to the red line at the north east side of the centre.

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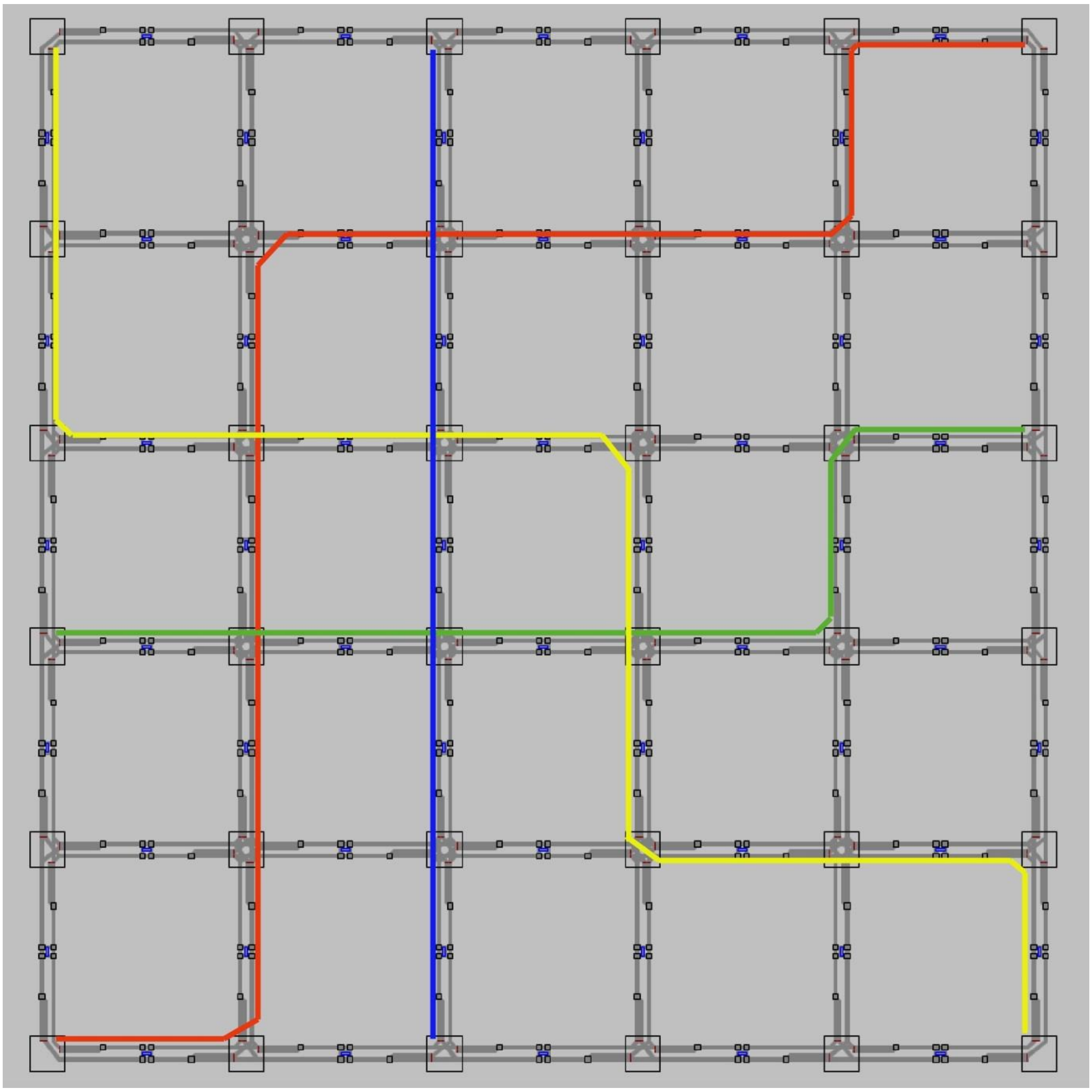
[10] Bus grid Network: It is a network form mainly used in polycentric regions. It can either be a city network or a rural region or a large city distinct. The average network density is almost identical among the regions and numerous interchanges are available between the public transport at various positions and directions of the network. (Weidmann, 2012)

Figure 4 Bus Network Scenario 1

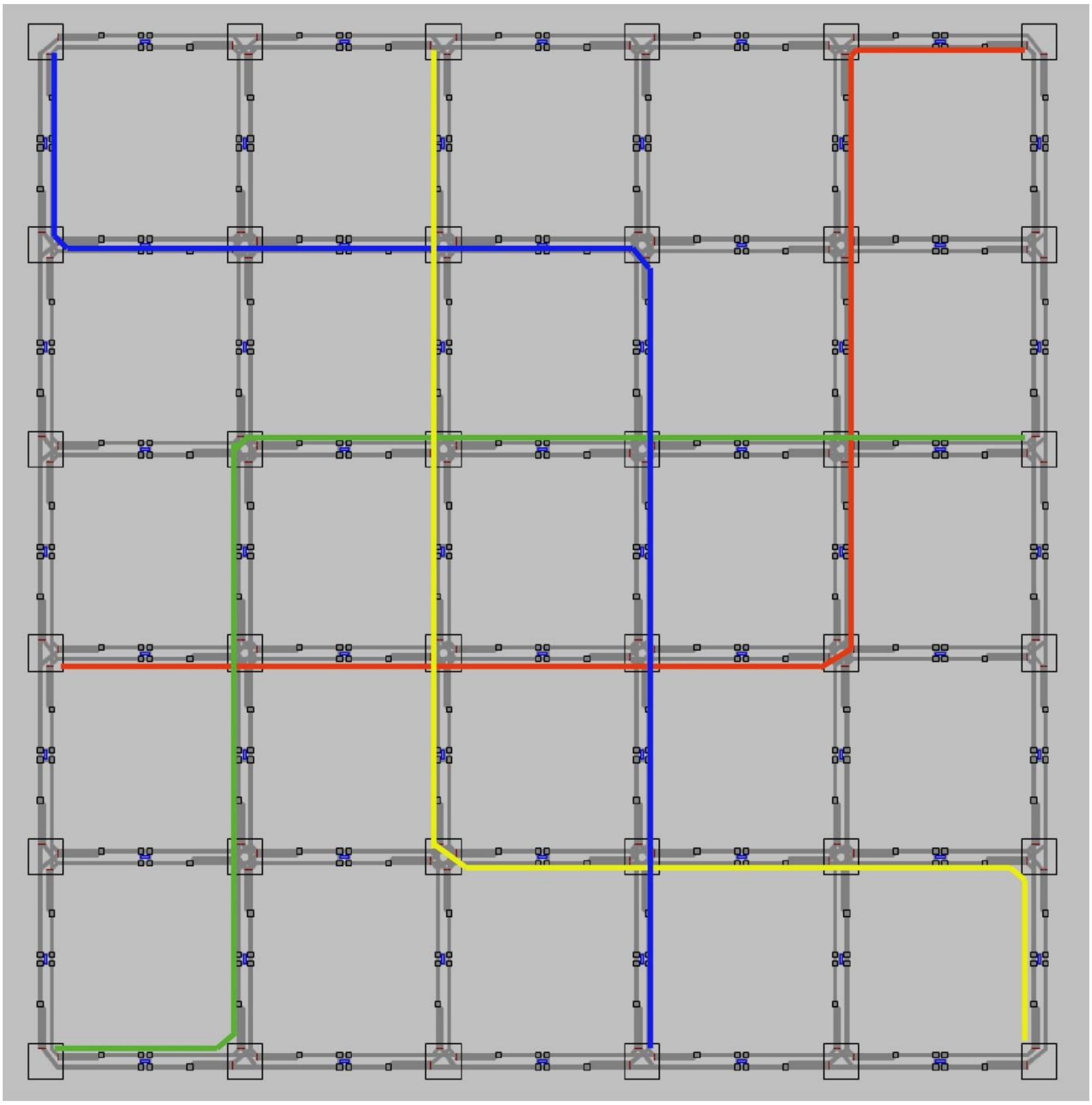


Source: Vissim 6 (2014), Own Configuration

Scenario 2

Scenario 2 is also a raster but symmetrical network; each bus travel route contains 1200 m and the direction of the lines is rather “diagonal” maintaining the advantages of the diameter lines. The transfer points are noticed in the four central nodes resulting in users’ travel distance reduction. Symmetry guarantees the uncomplicated homogeneous bus-stop distribution in the network. Regarding the passenger accessibility to the bus lines (considering walking distances from the links without bus lines to the corresponding ones with bus lines), scenario 2 covers more uniformly the entire network in comparison to the previous scenario especially in the south –west region.

Figure 5 Bus Network Scenario 2

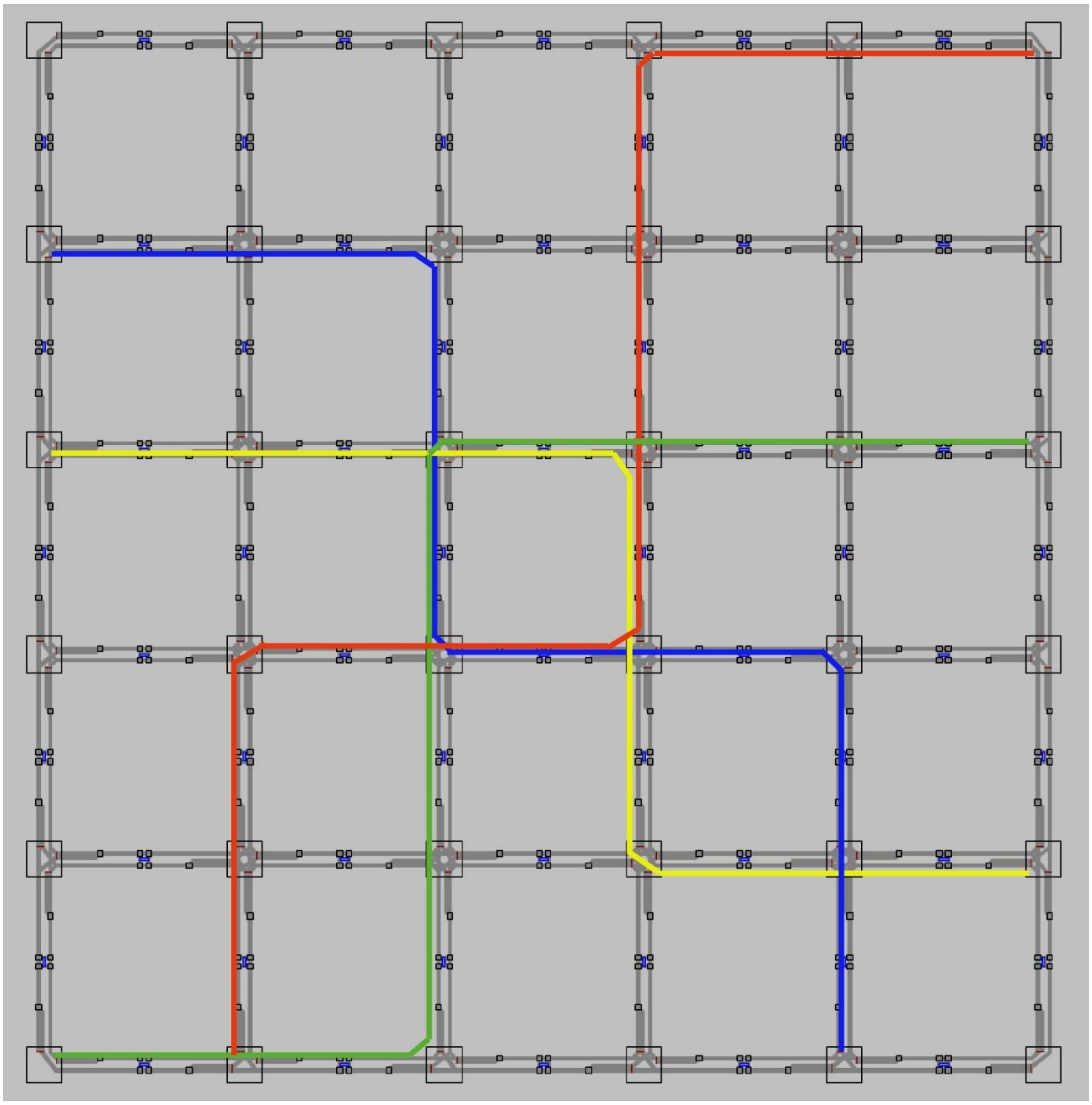


Source: Vissim 6 (2014), Own Configuration

Scenario 3

Scenario 3 can be described as a radial non-symmetrical network. All the bus lines convene mainly at 4 streets in the network centre. One special characteristic which differentiates this network from the previous is the crossing of two bus lines on each of the four central links. This results in transit points at these locations from three distinct lines.

Figure 6 Bus Network Scenario 3

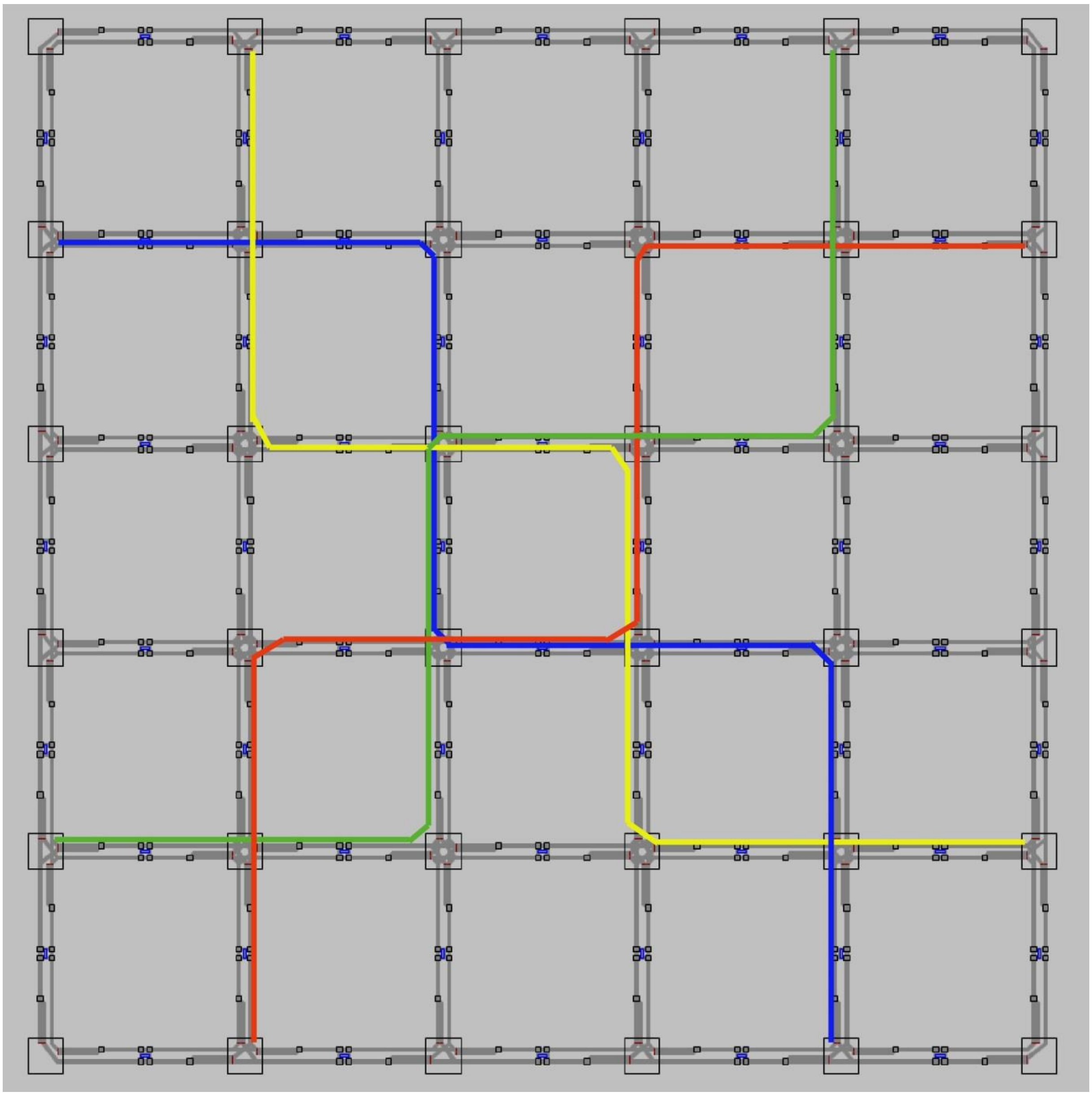


Source: Vissim 6 (2014), Own Configuration

Scenario 4

Scenario 4 is also a radial but symmetrical network. Principal characteristics from scenario 3 remain constant but higher accessibility is provided to the users throughout the whole network due to homogeneous bus-line distribution.

Figure 7 Bus Network Scenario 4

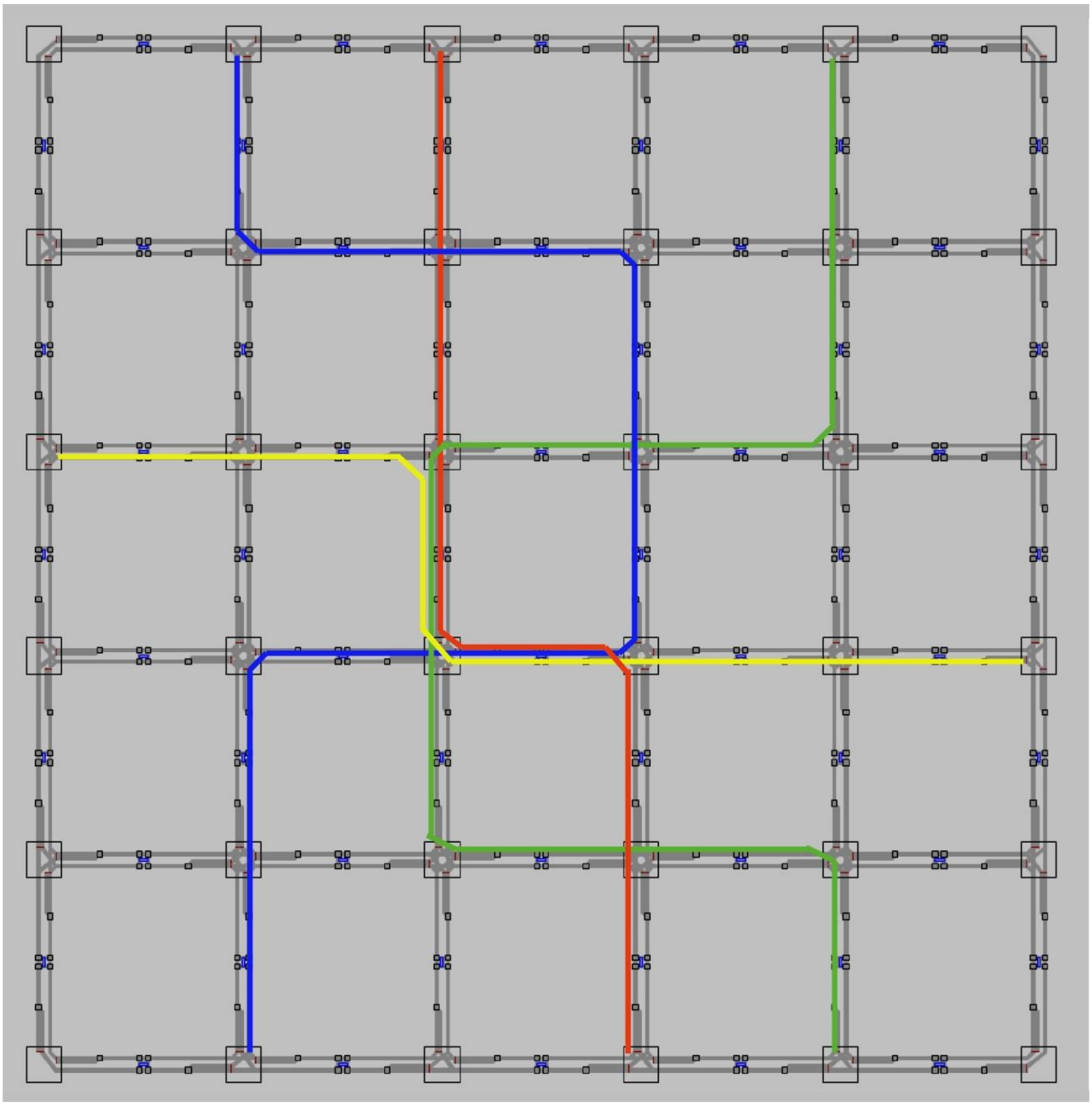


Source: Vissim 6 (2014), Own Configuration

Scenario 5

Scenario 5 is an additional radial symmetrical configuration. Its goal deepens in the convergence of three of the bus lines inside two links. Symmetry is identified in pairs; the green and the blue different from the red and the yellow line.

Figure 8 Bus Network Scenario 5



Source: Vissim 6 (2014), Own Configuration

Scenario Selection

The scenario principles proceed from less centralized bus lines to more congested-with-buses streets. Scenario 2 is selected as the basis for the bus network configuration. It provides a balance between high accessibility of the bus lines from all the network locations and uniform distribution of the lines between the central links. Scenario 4 appears to be more realistic due to the higher bus-line concentration at central links. However this encloses the possibility of re-routing of experienced users to the peripheral streets and congestion may be created on the outskirts of the network. Scenario 2 indicates higher uniform congestion distribution among the network. Result comparison of scenarios 2 and 4 is undertaken in the final simulation procedure.

3.4.3 Bus-Stop Distance & Location

Subsequent assignment is the bus-stop distance and location determination with reference to the existing two-directional bus lines.

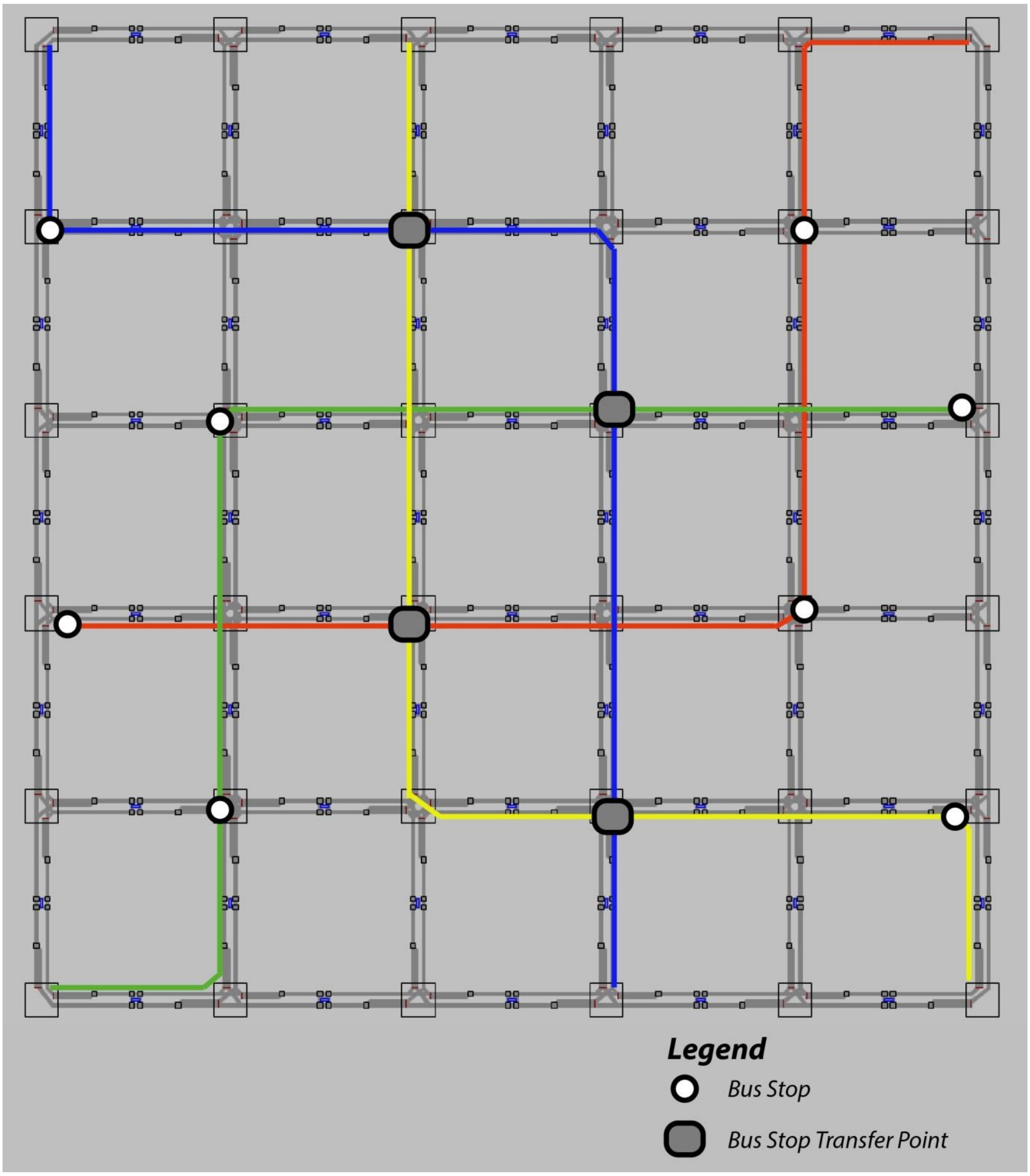
Decisive is the range of the acceptable standards for the bus-stop distance regarding urban central regions. Bus and tram stops are, commonly, conceived every 400 – 600 m referring to large cities. At central urban locations, specifically, bus stops can be organised denser, every 200 – 300 m (Weidmann, 2012). Another research from Furth, Rahbee, and Trb; Trb (2000) showed that the optimal bus-stop distance should be 400 m although it is, now, 200 m. All network configurations and bus stop-distance information considered, there should be a bus stop at every 300 m (two grid network links) for the default network configuration. Simulation of scarcer bus-stop distribution will be implemented for comparison purposes with the in-between bus-stop distance being 450 m.

Additional issue is the bus stop location. Contemporary tendency at real networks is the bus-stop settlement upstream or downstream of the intersections to enable transferability. This existence, however, burdens the traffic flow. Various scenarios are simulated to compare the traffic effects of the bus stops being either in the middle of the streets or downstream or upstream of the intersections.

3.4.4 Default Bus Network Configuration

As discussed above, the default bus network contains four stops per line and direction. This means that there is a bus stop every 300 m. Regarding the default bus-stop location, it is selected to set them upstream of the intersections. The existence of the stops downstream of the traffic lights seems to highly influential because the traffic from all the directions to this certain link is blocked.

Figure 9 Default Bus Network Configuration with 4 Stops per Line & Direction upstream of Intersections



Source: Vissim 6 (2014), Own Configuration

On the contrary, the bus stop before the intersections blocks only the through- and right-moving vehicles upstream of the traffic signal. The default bus network configuration is presented in Figure 9, in which the grey rectangles represent the transfer points and the white circles refer to the single two-directional bus stops.

The transfer points, as shown in Figure 9, are mainly settled in the central grid-network area to enable easier transferability and to reduce the users’ travel distance.

Important to be noticed is the fact that the bus stops at the turning points have been established before the diverge point for the left-turn movements.

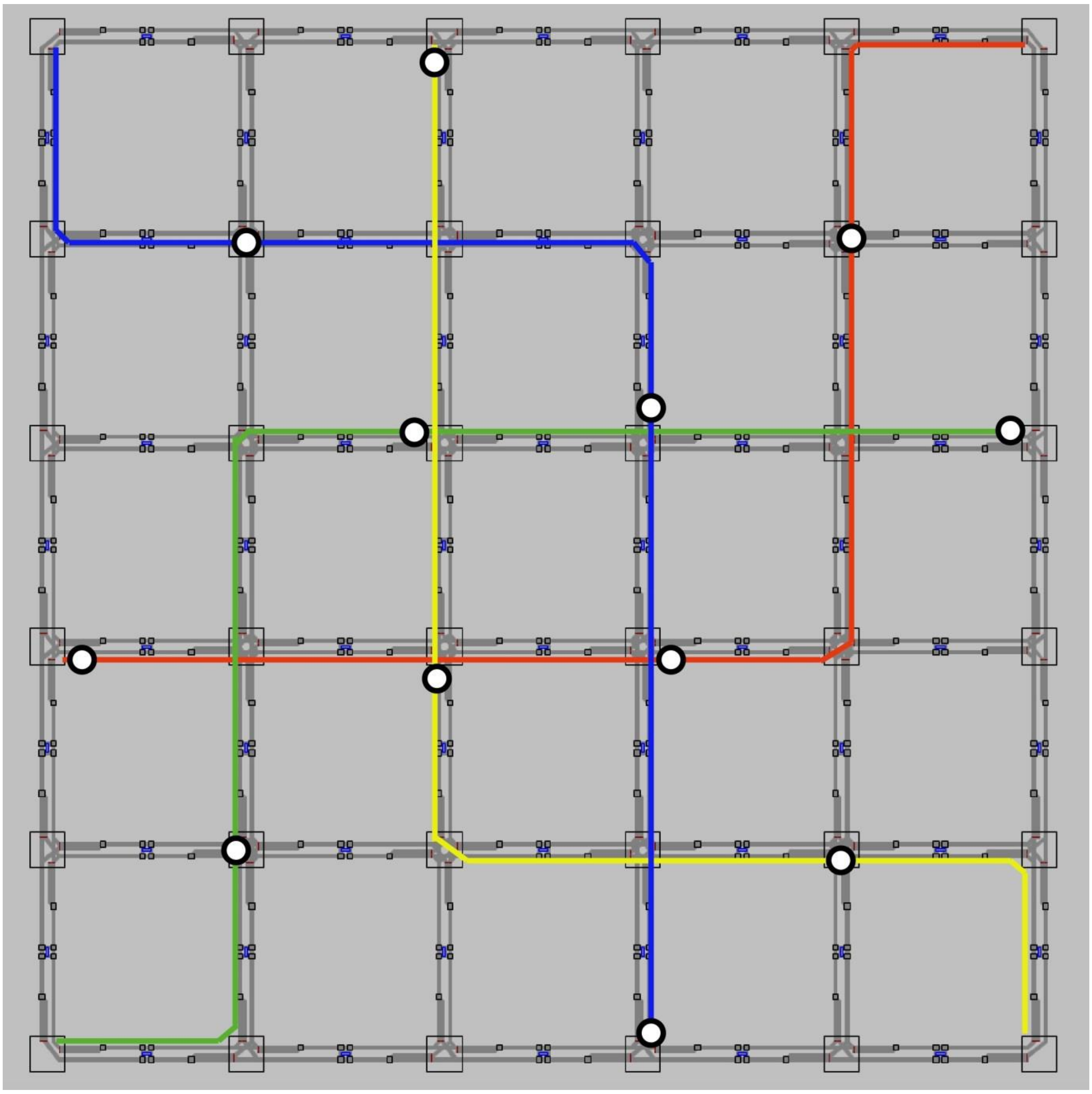
3.4.5 Sensitivity Analysis

Referring to the aforementioned default network, various simulations with different parameter settings are implemented to estimate the network sensitivity. Factors, for instance the bus-stop number, the bus-stop location, the network configuration and the bus headway are altered for the sensitivity-analysis implementation.

Fewer Bus-Stop Configuration

The default network consists of four two-directional lines and four bus stops per line and direction. In total, there are 32 stops in the network. A new configuration is based on the concept of the network bus-stop reduction. Taking the bus-stop distance from the chapter 3.4.3 into consideration, bus stops are mostly established at distances between 400-600 m when referring to urban networks. Therefore it is selected to ground three bus stops per line and direction, the distance of which is 450 m. Once again, there are 24 upstream-intersection bus stops in this new configuration as shown in Figure 10.

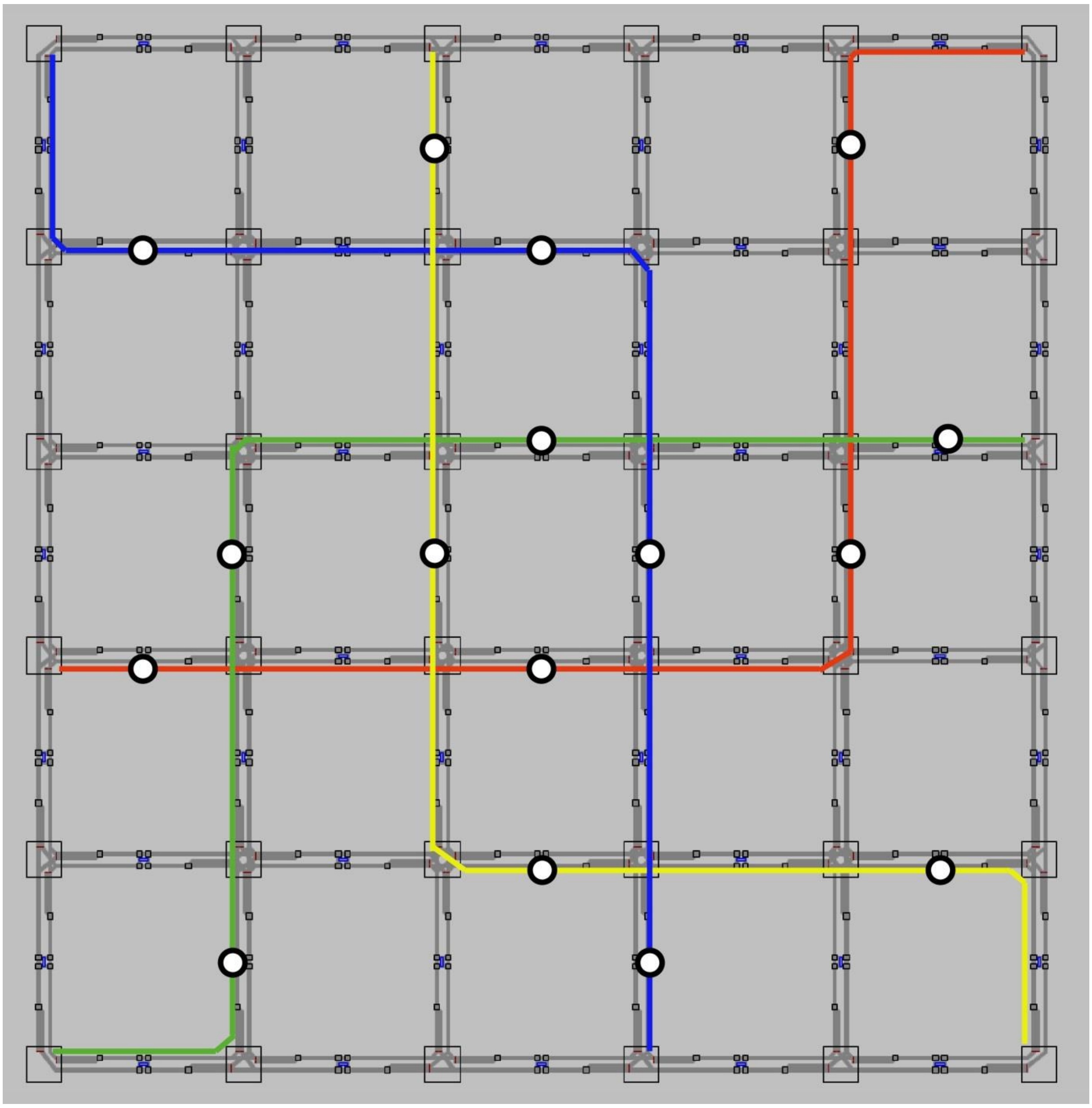
Figure 10 Bus Network with fewer (3) Stops per Line & Direction upstream of Intersections



Source: Vissim 6 (2014), Own Configuration

Bus-Stop Location Modification

Figure 11 Bus Network with 4 Stops per Line & Direction in Middle of Intersections



Source: Vissim 6 (2014), Own Configuration

Regarding the bus stop location, there are two different configurations that need to be investigated and compared to the initial default model.

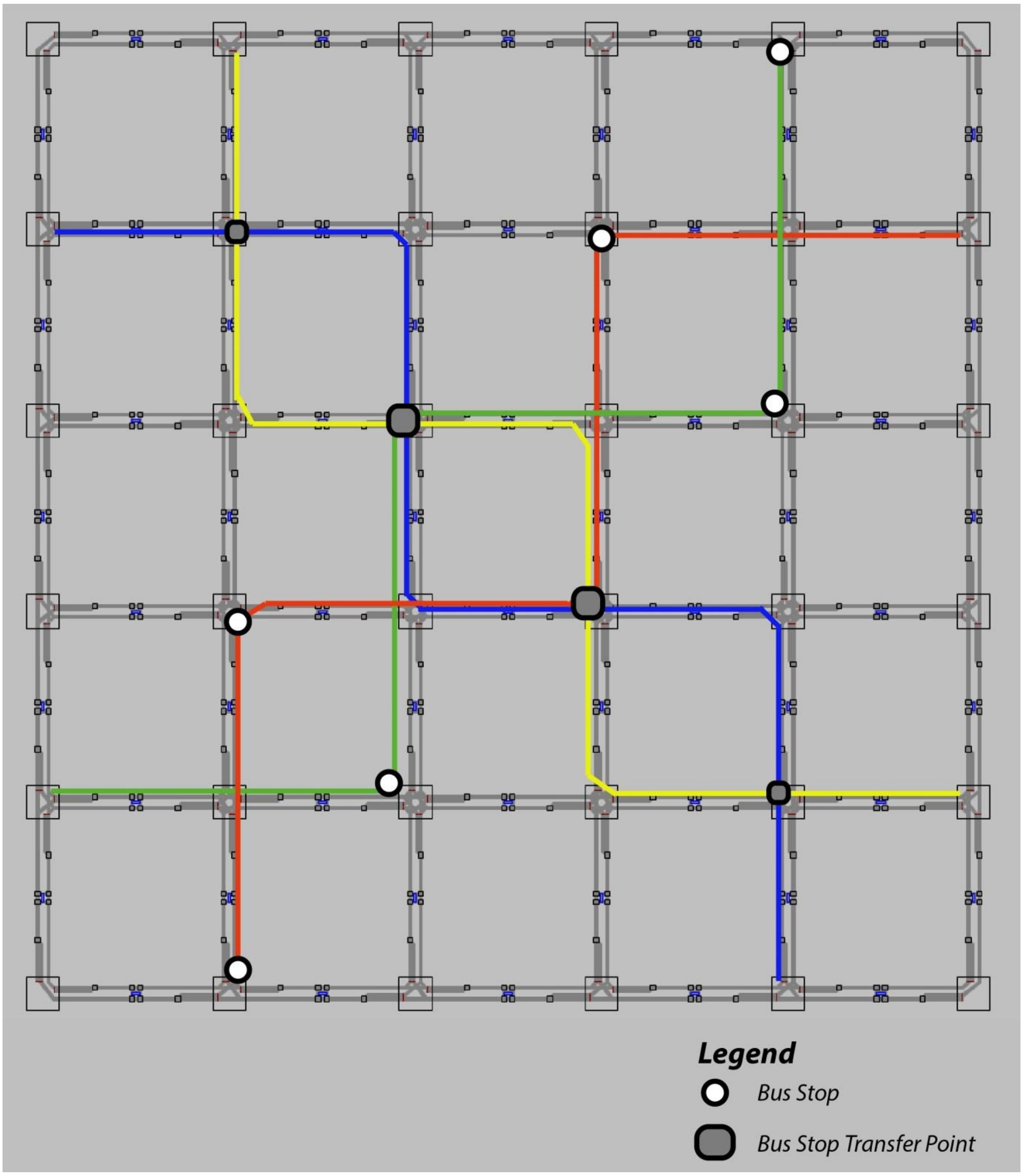
The first one is associated with the transition of the bus stop downstream of the intersections. This implementation becomes an obstacle for all the directions reaching the corresponding link when the bus stops, whereas the default configuration burdens only the through- and right moving vehicles. As for the bus-stop location this is exactly the same with the default network which is presented in Figure 9.

Additional analysis derives from the bus-stop movement in the middle of the links. The spill – back effects of the “downstream” implementation are avoided in this case due to the longer available storage space. The location of the stops is shown in Figure 11. It should be noticed that the transferability at this network is not as efficient as the previous configuration due to longer required walking distances.

New Network Configuration

Another configuration implemented for sensitivity analysis is the overall network alteration. The concept of the four two-directional lines with 4 stops per line and direction is sustained. New are the bus routes, the target of which is to organize a denser central region with more bus lines crossing the intermediate urban links. The new configuration is visible in Figure 12. It is noticed that the four central links are occupied with two separate lines each. This increases the transferability because transfer points in-between three lines are provided at the two main centrally-located bus stops.

Figure 12 New Bus Network Configuration with 4 Stops per Line & Direction upstream of Intersections



Source: Vissim 6 (2014), Own Configuration

Bus-Line Headway

Important factor that fluctuates and affects the network operations is the bus frequency. All the aforementioned configurations are simulated for 2-Min, 5-Min and 10-Min headways in order to fully understand the proper headway effects. Selective representative network configurations are also simulated for 3-Min and 4-Min headways.

3.4.6 Various Bus Network Parameters

Three additional bus network parameters need to be identified, the bus-stop length, the bus-stop duration and the offset of bus-line initialization.

Bus-stop length is assumed to be 5 m. Lack of common bus stops does not demand longer platforms for two consecutive buses in a row. Only the bus stops at the central transfer points of the new network provide longer bus stops. These are the only stops, in which more than one bus lines stop there. Therefore longer platforms of 15m are selected to allow two buses to stop there simultaneously.

Bus stop duration is assumed to be 20 seconds. This is the default value that is selected from the simulation program and is maintained also for the simulation processes provided that it is reasonable especially for central stops.

Bus initiations on different lines are staggered (i.e. they do not to initiate simultaneously). The reasons for this choice are the following:

- Avoidance of simultaneous network loading
- Avoidance of stops at transfer points in the same time.

Offset of bus-line initiation guarantees the uniform loading of the network and enables potential transfers without long waiting times.

4 Simulation Results

This chapter focuses mainly on the simulation-result presentation. Introductory issues regarding the data collection and the capacity determination and overview of the implemented simulations are provided. Simulation result presentation and comparisons between the headways and the networks is the basic issue of this chapter.

4.1 Simulation Introduction

Simulation result presentation should be accompanied by various introductory topics crucial for the result presentation. This section introduces the mechanism for the data collection with the network exit function presentation and the capacity determination procedure.

4.1.1 Simulation Data Collection with Network Exit Function (NEF)

Overall research goal is the macroscopic analysis of the network behaviour and the effects of the bus operations on an urban network. For this visualization it is important to create the MFD before and after the bus-network implementation. The MFD is the macroscopic representation of the Fundamental diagram, in which the flow and density of an urban area instead of a road link are correlated.

The simulation program named “Vissim” does not guarantee the direct output of the required for the MFD flow and density. Therefore the NEFs are used for the representation of the network performance instead (Ortigosa et al., 2014). The NEF correlates the completed network-vehicle trips with the active network vehicles. The number of completed trips corresponds to the network flow and the number of active vehicles to the network density.

Regarding the time-interval collection points, results are collected every 30 seconds. Basis for the MFD representation points is a 5 minute-period, which means that each MFD result-point contains ten 30-second intervals. Referring to the trip completion rate, data is summed throughout the 5-min period providing the overall completed trips. As for the active network vehicles, data is averaged for the corresponding time intervals (Ortigosa et al., 2014). This average eliminates the heterogeneous loading errors of the 30-second intervals deriving from the selected random seed. Parallel to this, various random seeds for the most representative simulations are executed in order this loading error to be fully eliminated.

4.1.2 Capacity Determination

It is additionally crucial at this step to explain how the network capacity level at the simulation processes is calculated. In the majority of the simulations it is noticed that the network is sensitive and inconsistent from the capacity level until the jam density (congested MFD part). Consequently, there is a point scatter close to capacity level and therefore it is selected to calculate the capacity with percentage use. More analytically, the highest-capacity point per simulation is identified. Then it is determined that all the points with 6%[11] deviation from the highest one will be taken into account for the capacity calculation. However, there are some outliers so high that there are no other points included in the 6% deviation. For these cases it is selected to add the second point to the calculation to avoid outlier effects even though the deviation increases.

4.2 Overall Simulation Processes

This section provides briefly and visually all the implemented simulations before the result presentation.

Table 2 summarizes all the simulation procedures for all random-seeds in this analysis.

Table 2 Overall Simulation Processes with various Random Seeds

Description	10-Min Headway	5-Min Headway	4-Min Headway	3-Min Headway	2-Min Headway
No Buses	3				
Buses Upstream of Intersections (Default)	1	3	3	1	3
Buses Downstream of Intersections	1	3	1	1	3
Buses Upstream of Intersections (3 Stops)	1	1	0	0	1
Buses Middle of Intersections	1	1	0	0	1
New Network Upstream of Intersections	1	3	1	1	3

Source: Own Configuration

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[11] 6% Deviation: This deviation is selected based on various application attempts for the capacity calculation. Initial capacity deviation was 5% but the outcome provided many simulation processes with fewer-than-necessary significant points. This was risky due to outlier issues and therefore 5% deviation was avoided. On the contrary, 7% deviation affected negatively the capacity results due to the high number of capacity points included in the calculations. Therefore the best compromise for the capacity calculation was the 6% deviation from the highest point.

Main reason of the selective additional random-seed simulation is the required computational load for each simulation.

Regarding the default bus network, the various-random-seed simulation process is selected based on the initial results from the first random seed. The 10-min-headway results do not differ highly from the no-buses ones and it is not a usual urban peak-hour frequency. Therefore various random seeds are avoided. 5-Min and 4-Min headways are simulated for three random seeds because they are representative for the peak-hour headways and they provided reasonable capacity effects. Result similarity between the 4-Min and the 3-Min Headway indicates that there is no necessity for additional 3-Min-headway simulations with various random seeds. 2-Min headway is another frequency which would provide useful results with additional random-seed implementations.

Priority for the additional random seed implementations is also given to the “downstream” and the new network configuration. They both present the highest bus operational effects. For this reason, it would be beneficial to examine if the initial results are also verified in the second and the third simulation. Apart from that, they both represent realistic bus network designs with advantageous transfer points and beneficial accessibility. The “upstream” with the 3 stops and the “middle of links” networks suffer from unattractive transfer points, long bus-stop distances and accessibility difficulties. They are not as realistic as the previous ones and as a result they are not additionally simulated (only one random seed).

4.3 Default Simulation Results

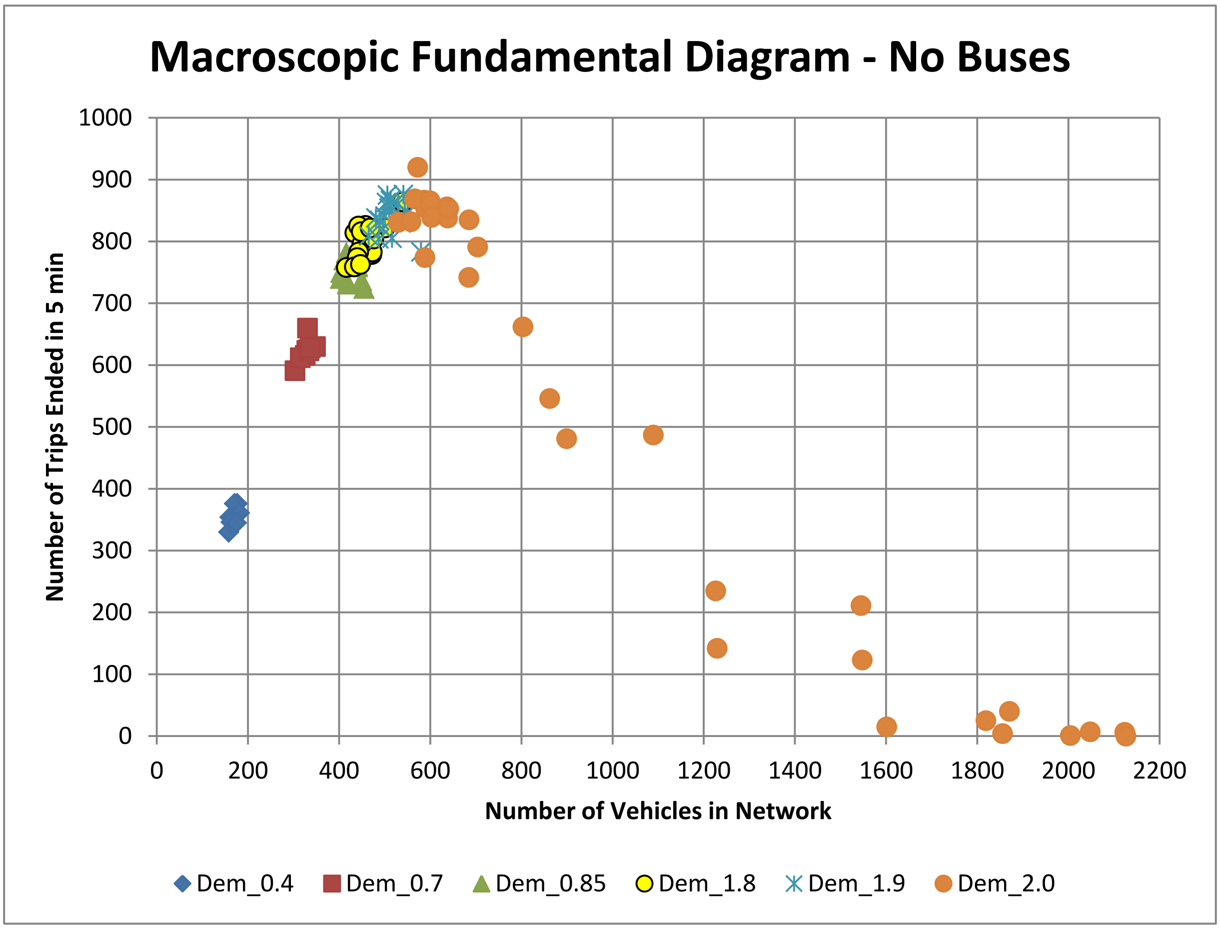
This section presents the simulation results both including and excluding the bus operations from the networks. NEF use gives the corresponding MFDs and discussion about the capacity level and the MFD shape is provided.

4.3.1 Final MFD (NEF) without Bus Input

Basis for project goal satisfaction is the network-operation presentation without the bus implementation. This is the reference performance for the bus-result comparison.

Figure 13 presents the network MFD shape throughout the whole simulation period when the network gets loaded. As mentioned before, each point represents a 5-min interval. Different symbols are used to distinguish the wished demand levels, the number of which is shown in the legend below. Analytical details concerning the network demand are presented in section 3.3.3.

Figure 13 Final MFD (NEF) without Bus Input



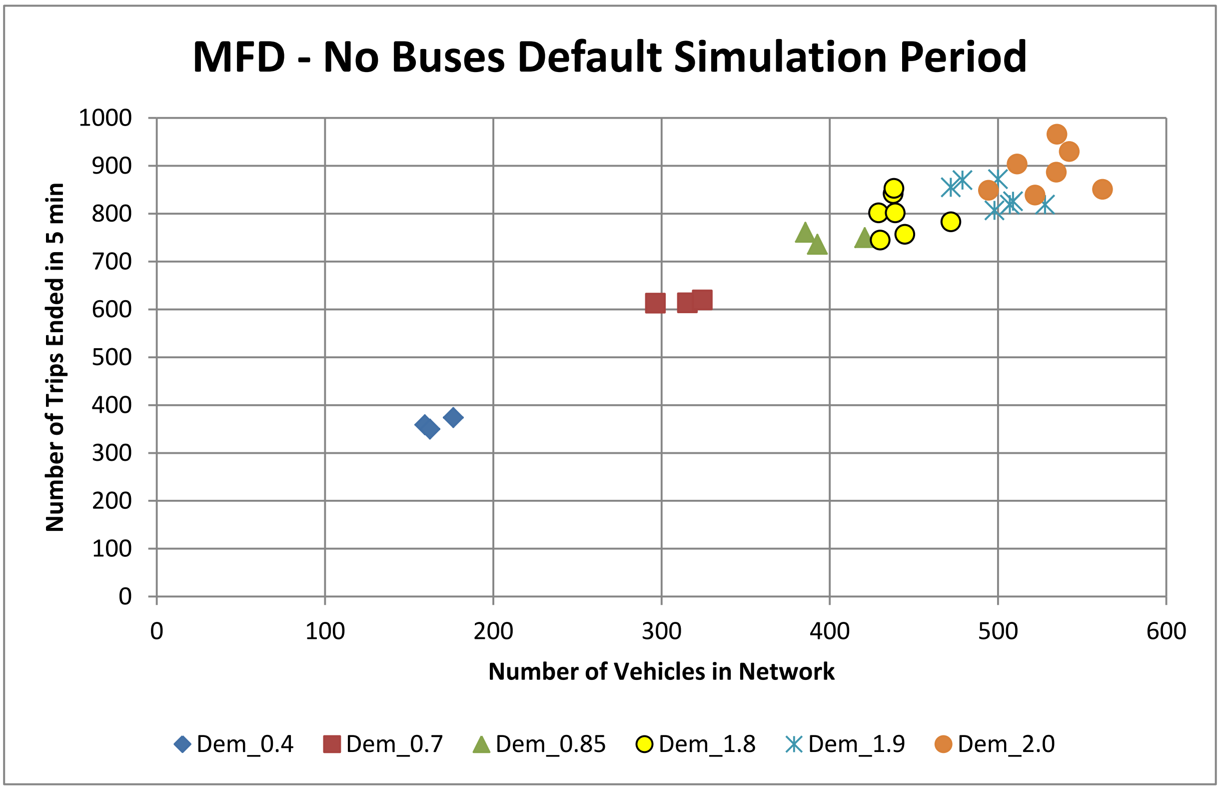
Source: Vissim 6 (2014), Own Configuration

As for the simulation results, it is noticed that the network performance follows the MFD shape. Once again the MFD existence through the simulation process is verified. Both the uncongested and the congested part can clearly be identified in the diagram. It is obvious that the higher the network demand is, the more unstable the results are. To be more specific, the traffic is stable for the low demands (0.4, 0.7 and 0.85) and almost identical points have been extracted from the simulation. However, as the network gets loaded, the flow and the density become more sensitive and scatter between these points can be recognized. The highest demand value of “2.0” exceeds the current network infrastructure supplies. After reaching capacity level, network congestion initiates which leads to jam density and due to network homogeneity inevitably to gridlock.

Regarding the MFD values, it can be noticed that the network capacity is identified for values between 800 and 900. This provides the number of cars and trucks that can finish their trips in the 5-min interval. There is only point that exceeds 900. For these ended trips the number of active vehicles in the network is between 500 and 600 characterizing the optimal density. As for the jam density, it results that 1800 active network vehicles gridlock the network, and these vehicles cannot finish their trips.

A misleading issue is the occupancy level of all the links and the gridlock points. The congestion begins when the queue spills back to the upstream link. This phenomenon continues to consecutives links until a certain level when all the movements in the network are restrained. This, however, does not guarantee that all the links to all the directions are “busy”. Trip generation from uncongested origins is allowed even after reaching the jam density. Despite trip generation, these users are unable to reach their destination because they select a route that is already under congestion. As a result, the number of active vehicles continues increasing whereas the number of ended trips remains almost zero.

Figure 14 MFD (NEF) without Bus Input for a 3-hour Simulation



Source: Vissim 6 (2014), Own Configuration

A factor that affects the capacity level and leads to congestion is not only the selected demand level but also the duration. Figure 14 shows the simulation results for a 3-hour simulation. This takes into account that the highest network demand (Wished demand 2.0) lasts only for 40 minutes and not for 1 hour and 20 minutes as in Figure 13. Outcome of the duration reduction is the MFD sustainability at the capacity level without congestion development. In higher bus frequencies (2-Min Headways), though, traffic congestion is attained long before the highest wished demand. Therefore, flexibility is chosen regarding the simulation duration in order to receive the overall MFD shape for all the simulation processes. The shorter simulation shows higher vehicle output (flow) than the longer one and this is explained from the re-routing of the DTA application. The drivers follow the re-routing based on their experienced travel times. When the highest demand is short, users can re-route so that the network does not get congested, does not lead to gridlock and allows higher users’ number to complete their trips. With longer period, though, even users’ re-routing is not enough and network reaches gridlock levels. This verifies the network demand sensitivity.

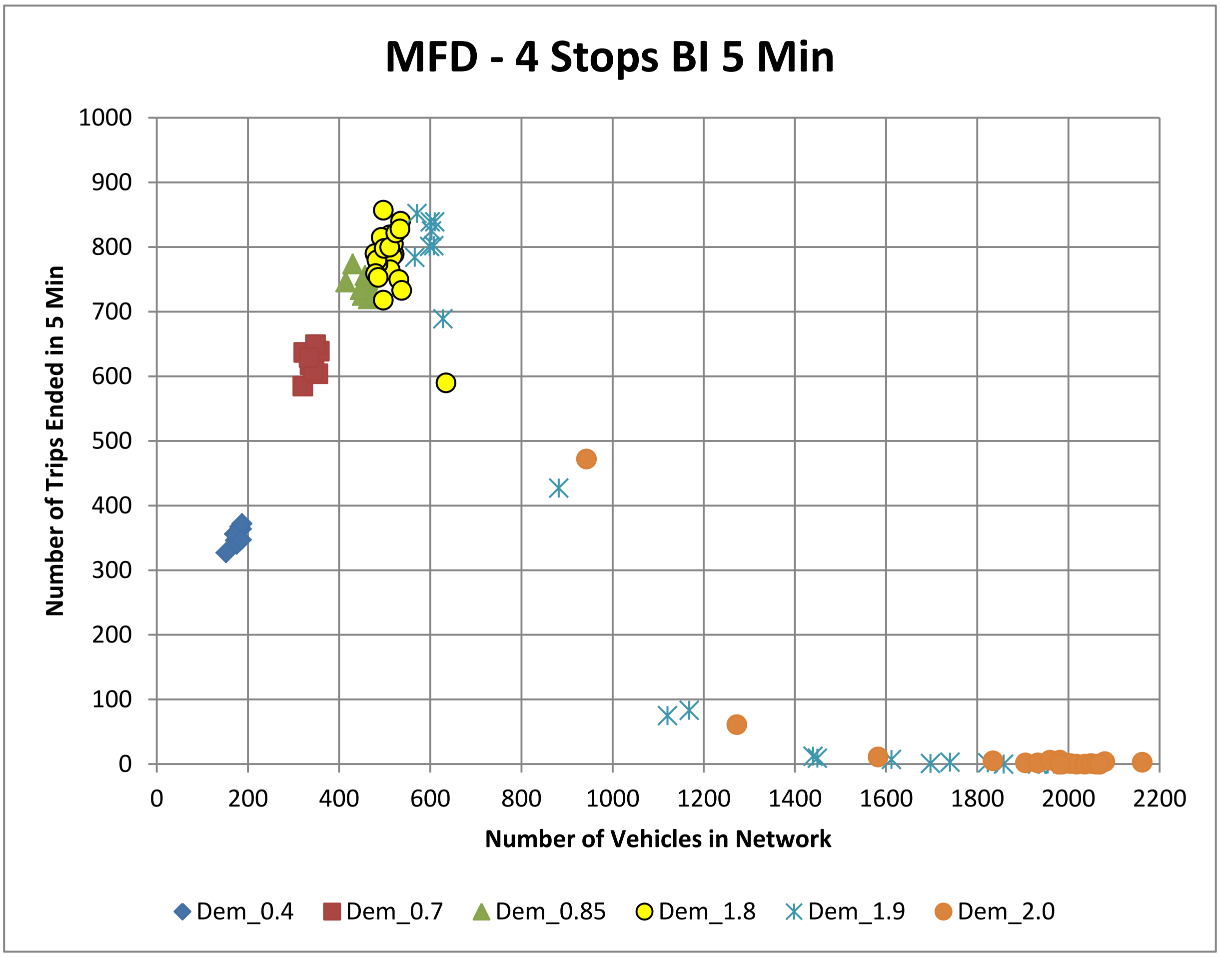
4.3.2 MFD with Default Bus Network & 5 Min Headways

Figure 15 presents the MFD shape with the default bus-network implementation and the bus stops located upstream of the intersections. Bus headway is set for this simulation to be 5 minutes per line and direction.

The MFD shape exists also for this configuration following almost the triangular shape of the fundamental diagram. The flow-density points in the uncongested segment are almost identical to the ones without bus implementation. Then a scatter at the capacity level is recognized showing once again the network sensitivity. The congestion initiation varies among the various random seeds and among the different wished demands levels. This result inconsistency among the random seeds visualizes the additional-simulation necessity for the result randomness elimination.

As for the capacity level it can be noticed that there is a slight decrease when buses insert in the simulation. There are no points in this simulation reaching or exceeding the level of 900 ended trips. Another significant result is the slight density increase at the capacity level which reaches almost 600 active vehicles. This implies a speed decrease which is reasonable considering the lower average bus speed due to dwell times and due to lower bus travelling speed. Important is the fact that the capacity level is achieved for lower wished demands than the maximum one (Demand 1.8-1.9). This shows that bus operations affect the unobstructed traffic performance of the remaining vehicles (cars and trucks).

Figure 15 MFD with Buses Upstream of Intersections & 5 Min Headway

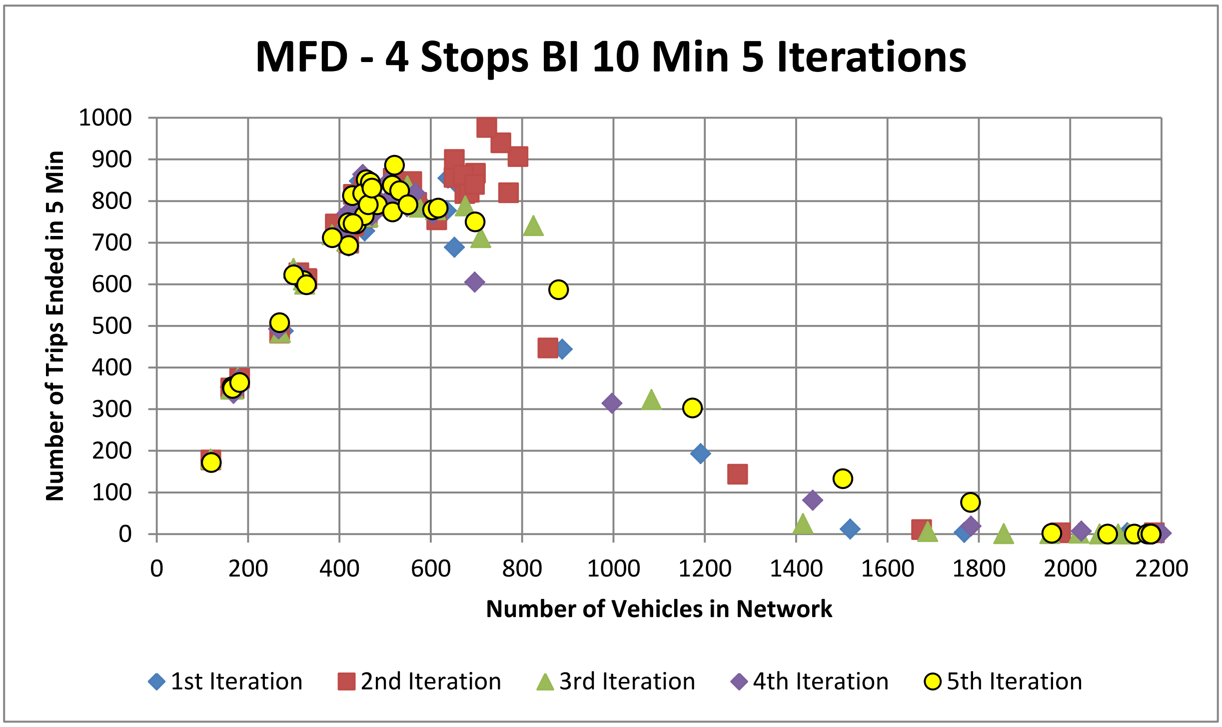


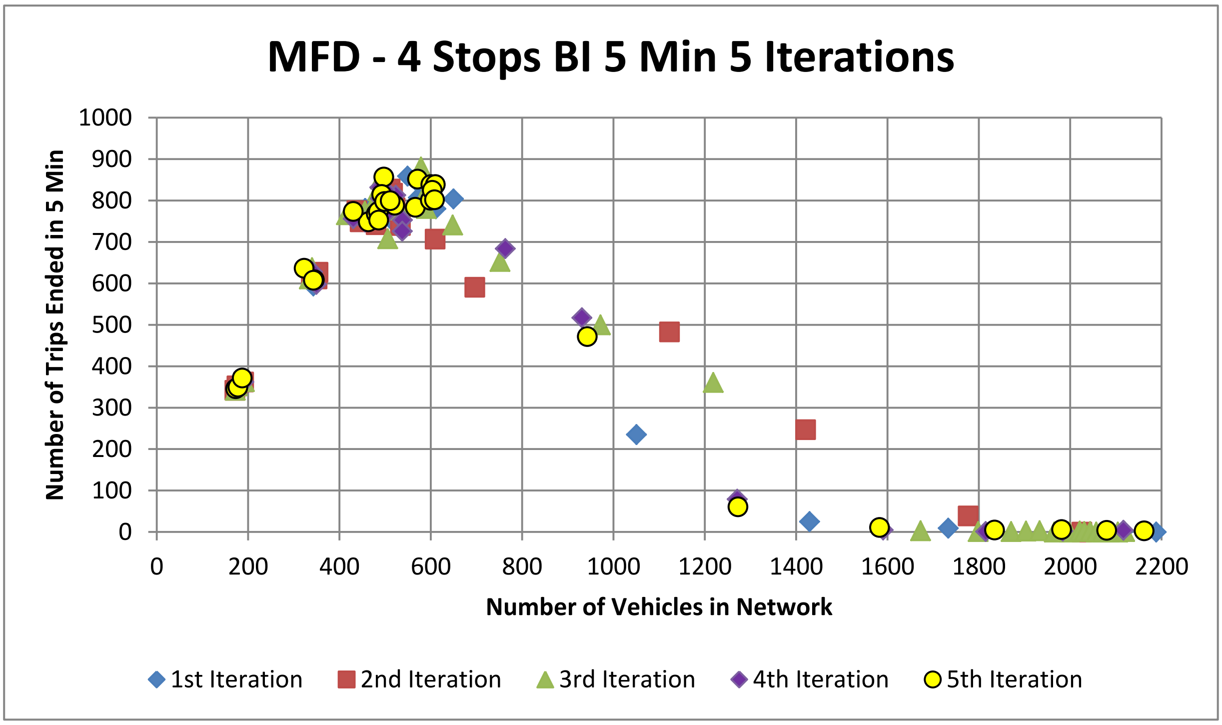
Source: Vissim 6 (2014), Own Configuration

Overall, it can be mentioned that the network capacity level is not highly affected from the bus operations with 5-min headway. This headway is a typical value for morning and evening peak-hours at centralized regions. The results show that the perturbation of the bus stoppage time and reduced speed can be recovered in-between the 5-min headway. Simulations for more rare bus frequencies (10-min headway) show that the capacity decrease is even lower compared to the aforementioned analysis.

As for the random seed differences, it can be indicated in Figure 15 that there are interval points at the congested diagram part from different wished demands. This is caused from the various random-seed implementations. Regarding the jam density, this is around 1500 active vehicles that cannot finish their trips. This is highly affected from the selected random seed, the O-D selection randomness and the last-iteration result relativity.

Figure 16 MFD bifurcation (scatter) at congested diagram part for 10-Min & 5-Min headways





Source: Vissim 6 (2014), Own Configuration

It is selected that the simulation converges when the travel time on paths for the last five iterations (MSA) do not differ more than 5%. This means that the aforementioned results are not identical and present differences among them. Figure 16 shows this result diversity of the last five iterations in-between the first random seed for the 10-Min and the 5-Min headway. Convergence criterion has been fulfilled for both of them but the result differences are clear. 5th iteration for the 10-Min headway reaches jam density for more than 1800 active vehicles whereas the 2nd iteration, for instance, shows gridlock effects for less than 1600 vehicles. On the contrary, 5-Min-headway results illustrate exactly the opposite behaviour. They provide 1600 vehicles for the fifth and 1800 vehicles for the second iteration. This means that the convergence criterion does not guarantee result equalities but it shows result similarities. Therefore the last iteration randomness can provide wide range of jam-density results which vary between 1500 and 1900 active vehicles.

4.3.3 MFD with Default Bus Network & 2 Min Headways

Referring to the bus frequencies, typical headway values for the central-area peak hours is 5-7.5 min per direction. However, there are cases, in which passenger demand necessitates higher headways or there are several bus lines sharing the same central streets and stops. As a result the bus frequency at central stops reaches up to 2 min. Simulation results of 2-min headways are presented in Figure 17.

Important simulation result is the significant capacity decrease which is lower than 800. This means that the existing capacity is 12.79% lower than the no-buses network capacity. Expected is also the density increase at the capacity level. Density, now, almost reaches 600 active vehicles. Consequently the average network speed is also lower due to the more frequent bus service. In addition, the network reaches gridlock for lower wished demand levels[12] and it is obvious that buses become the serious bottleneck for this network operation. Data points from different random seeds at the congested MFD part indicate, once again, the wished-demand diversity in-between the various random seeds. The jam density is constant at almost 1700 active vehicles. It is verified that the network jam density varies between 1500 and 1900 active vehicles depending on the randomized O-D generation and the random last iteration results. Another useful notice is the result inconsistency at the congested diagram part compared to the uncongested one. All the aforementioned simulations show almost similar outcome for the uncongested part and bifurcate at the congested because of instability and sensitivity issues (Carlos F. Daganzo et al., 2011).

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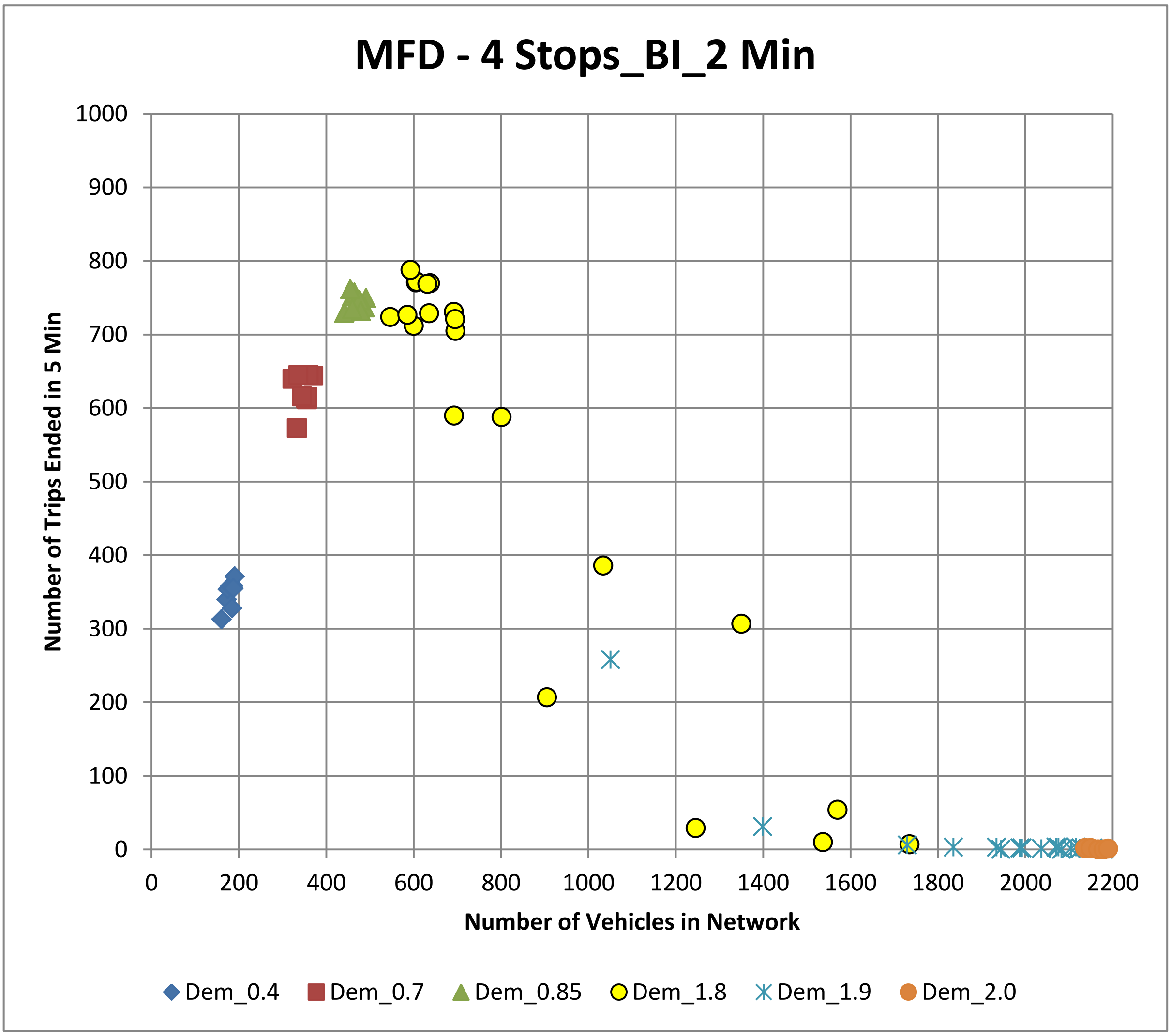
[12] Congestion initiates for “Demand 1.8” in 2-min headways and for “Demand 1.9” in 5-min headways.

Figure 17 MFD with Buses Upstream of Intersections & 2 Min Headway



Source: Vissim 6 (2014), Own Configuration

4.4 Sensitivity Analysis Results

This section analyses how different bus network configurations and headways contribute to the overall network performance. Various comparisons showing the different effects of bus operations are provided. The following results are presented below:

- Number of random seeds
- Number of significant points

- Capacity (ended trips)
- Capacity decrease from the no-buses simulation
- Optimal density (active vehicles)
- Jam density (active vehicles)

All these results are selected to fully characterize and numerically visualize the MFD shape. All the MFD diagrams of the implemented simulations are provided in the appendix.

Number of random seeds and significant points are presented to show on average the number of significant points per random seed. Significant points were useful for capacity comments, which in some cases were unexpectedly high indicating outliers. Moreover, it is an indicator for the network stability and sustainability close to the capacity level. There are many simulations with numerous points close to the capacity level showing that capacity can be sustained for longer. There are others in which the network was inevitably directed to traffic jam. Optimal density is mainly shown for the average network speed identification. Average network speed decreases after bus implementations with parallel lower capacities and higher density levels. Jam density is presented, mainly, for the bifurcation identification and the “noise” that is created at the congested MFD part (Carlos F. Daganzo et al., 2011).

4.4.1 Headway Comparisons

This section illustrates how the bus-frequency alterations affect the overall network performance for each of the different network configurations.

Default Network Configuration

In Section 4.3 simulation results of the default bus network with 5 and 2 min headways have been presented. Network-capacity, average-speed decrease and density increase have been identified but there is no significant reference to the intermediate headways. This section focuses on the presentation and the result comparison of various headways for the default bus network configuration.

Table 3 summarizes and shows briefly all the aforementioned comparisons for the default network configuration.

Table 3 Headway Comparison of Default Network Configuration

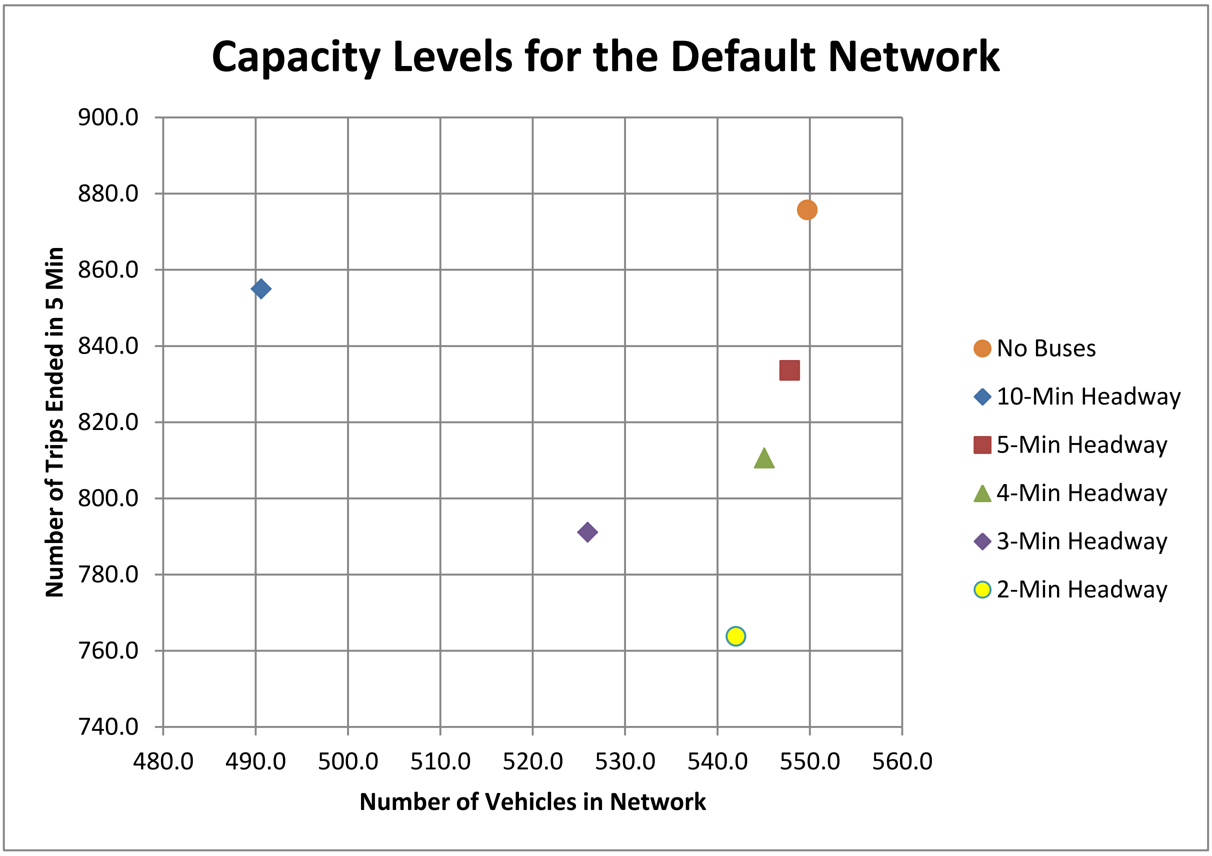
Network Description	No of Random Seeds	No of Significant Capacity Points	Capacity (Ended Trips)	Capacity Decrease (%)	Optimal Density (Active Vehicles)	Jam Density (Active Vehicles)
No Buses	3	8	875.8	-	549.7	1886.5
10-Min Headway	1	4	855.0	2.37	490.6	1871.0
5-Min Headway	3	10	833.6	4.82	547.8	1506.6
4-Min Headway	3	12	810.6	7.44	545.1	1652.4
3-Min Headway	1	10	791.1	9.67	526.0	1727.5
2-Min Headway	3	10	763.8	12.79	542.0	1614.4

Source: Own Configuration

Regarding the network performance, it can be referred that the bus-frequency increase leads to capacity decrease. More analytically the network capacity drops up to almost 13% when 2-Min-headway buses are inserted in the network. 10-Min headway buses do not influence the performance substantially and there is only 3% capacity decrease, which is accompanied by higher than the no-buses speed results. This means that the bus operations almost do not affect traffic operations. Influential become the results when the headway increases to 5 minutes. 5-Min headway shows a more substantial capacity decrease that reaches 5%. Capacity drops more when the headway increases to 4 and 3 minutes with the differences from the no-buses simulation being 7.44 and 9.67% respectively. Capacity drop is even higher for the 2-Min headway reaching up to 13% from the no-buses simulation. Outcome of the capacity result commendation is the proportional decrease in the bus implementation with the percentages increasing steadily from 2.37 to 12.79% (see section 4.7).

Important is also the output regarding the network densities among the various headways. 10-Min headway shows marginally higher capacity than the 5-Min but the density is much lower. This means that although the vehicle output (flow) is similar among them, the network is considerably affected by the bus operations. This is visible to the large density increase with obvious speed reduction caused by the frequent buses. Apparently, 10-Min headway is an almost non-influential implementation. It provides even higher average speed than the no-buses simulation despite the small capacity decrease. Linear correlation is identified between the capacities and densities among 5, 4 and 3-Min headways. Reasonable density increase (corresponding to the capacity decrease) compared to the aforementioned proportions is noticed for the 2-Min headway. This provides evidence that this most frequent bus operation is the bottleneck cause leading to unstable network which cannot satisfy the high wished demands.

Figure 18 Capacity Levels for Default-Network Simulations



Source: Own Configuration

Figure 18 provides the average network speeds. It is obvious that the 10-Min-headway speed is dramatically higher than the remaining ones. This derives mainly from the low density and this is also the reason for higher than the no-buses network speed (see also section 4.6). 5-Min, 4-Min and 2-Min headway illustrate a clear speed decrease among them and also from the no-buses simulation. Density is varying for all of them in-between 540 and 550 active vehicles with the capacity ranging from 760 to 880 ended trips. Although the 3-Min headway result provides smaller density than the no-buses, the proportional-to-the-density capacity decrease is much higher. As a result the ratio (speed) is lower than the no-buses result.

Bus Stops Downstream of Intersections

Continuation of the default network is the bus-stop transition from the location upstream of intersections to the downstream side. This is the single modification that is implemented in this network to identify the additional effects from the bus-location transfer. The network capacity is affected more because the bus dwell times create directly bottleneck on the corresponding links. Buses dwelling at “upstream” bus stops create an obstacle for the through moving vehicles until the left-turn separation points and for the whole link after these points. The default bus-stop input guarantees long space (135 m) for vehicle accumulation until the traffic spills back to the next road link. In contrast to the default network, the vehicle accumulation at this case does not exceed 2-3 vehicles. Spill-back effects appear directly after the bus stops even if the current wished demand is low.

Table 4 Headway Comparison of Bus Stops Downstream of Intersections

Network Description	No of Random Seeds	No of Significant Capacity Points	Capacity (Ended Trips)	Capacity Decrease (%)	Optimal Density (Active Vehicles)	Jam Density (Active Vehicles)
No Buses	3	8	875.8	-	549.7	1886.5
10-Min Headway	1	2	847.0	3.29	515.2	1486.1
5-Min Headway	3	8	801.5	8.48	568.4	1470.7
4-Min Headway	1	5	744.0	15.05	550.6	1707.9
3-Min Headway	1	4	748.8	14.50	571.8	1571.2
2-Min Headway	3	6	634.8	27.52	510.2	1704.9

Source: Own Configuration

The aforementioned assumptions are already verified through the simulation processes. It is obvious that the capacity decrease is high enough for this bus-location transfer reaching up to 27% for the 2-Min headway. 10-Min headway is a frequency which is not very influential even for this sensitive network. Capacity decreases only by 3.3% compared to the no-buses simulation but the remaining frequencies lead to substantial network-performance drops. The most representative headway for the peak-hours[13] (5 minutes) has a limited performance of almost 9% from the no-buses and more than 5% from the 10-Min headway. Another im-

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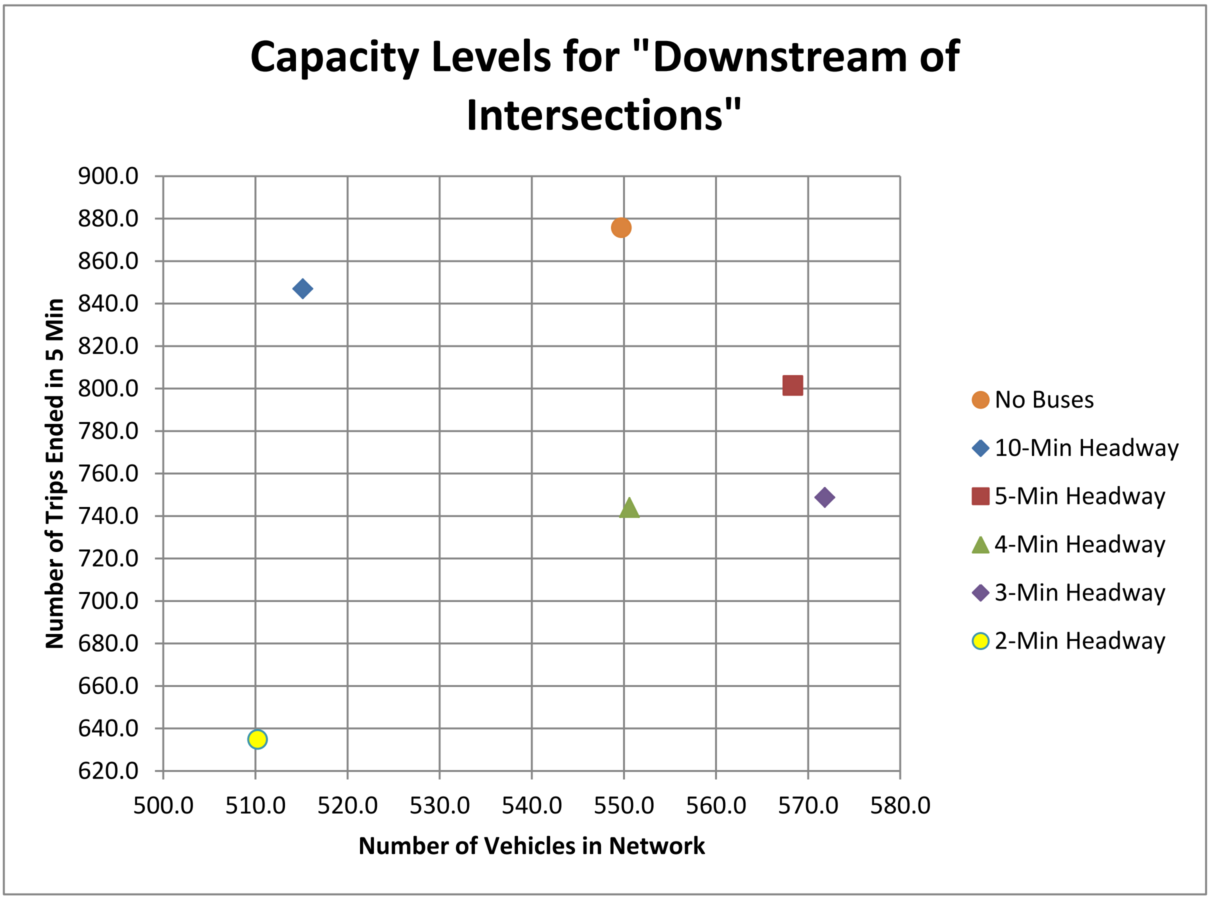
[13] This refers to the bus line existence in which there are no overlapping bus lines. 3-Min- and 2-Min headways are representative for several bus lines using the same link and as a result each line follows in total 5-Min headway.

portant output similar to the default simulation is the capacity similarities between the 4-Min- and the 3-Min headways. The latter shows larger densities and this small speed decrease verifies the more frequent bus operations. It can be summarized from both network configurations that there are no significant differences between 4-Min and 3-Min headways. Therefore, bus frequencies can be selected based on the passengers' requirements. Their adverse capacity results indicate that additional random seeds are required for the inconsistency verification. As for the highest bus frequency, it is extracted that the capacity decreases drastically showing that this bus operation severely creates a bottleneck for the remaining traffic.

Jam densities show, as before, a fluctuation between 1500 and 1900 active vehicles depending on the bifurcation of the congested MFD part (Carlos F. Daganzo et al., 2011).

Figure 19 Capacity Levels for Network Downstream of Intersections



Source: Own Configuration

Figure 19 provides the simulation capacity results for this network configuration. Once again, the scarce bus operation (10 minutes) presents a comparably low density for the current capacity level. This indicates that network speed is higher than the no-buses one. 5-Min headway shows a huge density increase and consequently speed decrease in contrast to the 10-Min headway. This explains the significant operational effects from the bus frequency increase. Another visual outcome that explains the effects of bus operations is the apparent density increase between the 4-Min and the 3-Min headways. This means that the 3-Min-headway effects are higher influential than the 4-Min ones although the 3-Min headway capacity is higher, as mentioned above. Consequently, 3-Min-headway speed is reasonably lower than the 4-Min-headway one. This probably derives from the reduced implemented random seeds for these headways. 2-Min-headway speed is also lower than the no-buses speed. Numerically this is verified from the 7%-density and the 28%-capacity decrease.

Important notice from this simulation process is the network instability. The 5-Min- and 2-Min headways, which are simulated with three random seeds, provided outliers that reduced the number of significant points. In addition, it is shown that one of random seeds in each case (different for each one) provided small capacity results. Therefore the highest points from each of these simulations are added to the calculation process despite non-inclusion to the 6% deviation (see section 4.1.2).

Bus Stops Upstream of Intersections (3 Stops per Line & Direction)

Table 5 shows the comparison results of the network configuration with 3 stops per line and direction instead of four. General output of the current simulations is the smaller bus operational effects especially for the 10-Min- and the 5-Min headways. Capacity reduction for the 10-Min headway is expected and it reaches almost 4% decrease. On the contrary, results for buses every five minutes are unexpected with the capacity being as high as the no-buses simulation. This result probably derives from the selected random seed. Verification would have been necessary with additional random-seed implementations. However, this high result implies the smaller influence on the network operation from the several bus-stop deletions. Expected is, though, the optimal density increase for the 5-Min headway illustrating how the reduced bus speeds and dwell times burden the unobstructed “private” operation. As before, bus stops create a substantial bottleneck for the network when the headway rises to 2 minutes. The capacity falls up to 12% from the no-buses implementation. Last outcome from these comparison results is the higher stability at the capacity level with 6 and 8 significant capacity points only from one simulation process. This verifies that the network is able to satisfy its users for longer period than the previous networks.

Table 5 Headway Comparison of Bus Stops Upstream of Intersections (3 Stops)

Network Description	No of Random Seeds	No of Significant Capacity Points	Capacity (Ended Trips)	Capacity Decrease (%)	Optimal Density (Active Vehicles)	Jam Density (Active Vehicles)
No Buses	3	8	875.8	-	549.7	1886.5
10-Min Headway	1	5	848.4	3.13	515.8	1897.3
5-Min Headway	1	5	879.8	-0.46	606.2	1705.8
2-Min Headway	1	8	770.0	12.08	530.8	1715.4

Source: Own Configuration

Bus Stops Middle of Road Links

Table 6 summarizes the simulation results of all the implemented headways for the network configuration with the bus stops being in the middle of the road links.

Table 6 Headway Comparison of Bus Stops Middle of Road Links

Network Description	No of Random Seeds	No of Significant Capacity Points	Capacity (Ended Trips)	Capacity Decrease (%)	Optimal Density (Active Vehicles)	Jam Density (Active Vehicles)
No Buses	3	8	875.8	-	549.7	1886.5
10-Min Headway	1	12	825.3	5.77	522.7	1832.4
5-Min Headway	1	6	796.3	9.08	513.4	1523.9
2-Min Headway	1	4	780.3	10.90	571.2	1623.9

Source: Own Configuration

As for the lower frequencies of 10-Min and 5-Min headways, it is unexpectedly extracted that the capacity decrease is high enough reaching more than 5 and 9% respectively. Explanation for this capacity reduction might be the bus location 60 meters from the intersections and the shorter accumulation space than the upstream networks. The capacity decrease of the 2-Min headway is, once again, high enough. However, it is as high as at the sensitive “downstream” configuration. The density increase in the 2-Min headway application is large providing that the bus operation leads to overall speed reduction. As for the jam densities, they remain constant at 1500 and 1900 active vehicles. Once again, the high number of significant capacity points certifies the network stability and the tendency to allow steadily high users' number to complete their trips.

New-Network Bus Stops Upstream of Intersections

After covering all the combinations and alterations for the existing network, it is crucial to see how the results are modified when the bus lines follow a central radial configuration. Table 7 summarizes the simulation results of the new radial network with the bus stops being upstream of intersections. Outcome of the results is that there is a gradual and proportional decrease among the 10, 5, 4 and 3-Min headways (see section 4.7). The decrease percentage is in almost all these headways 3% higher than the previous one. Substantial difference exists for the 2-Min Headway which shows a 25% decrease from the no-buses implementation. This explains that bus input for this frequency turns out to be highly influential creating a large bottleneck for the network performance. This comparable-to-the-"downstream" high influence means that the non-uniform bus-line distribution may create local congestions at the central region which are distributed to the whole network. Capacity outliers with only one significant point appeared at the simulations of 10-Min and 4-Min headways. As mentioned in section 4.1.2, second highest capacity point is also taken into account. Instability is the main characteristic of this configuration and it derives from the locally "inflated" central square with the two bus lines per road link.

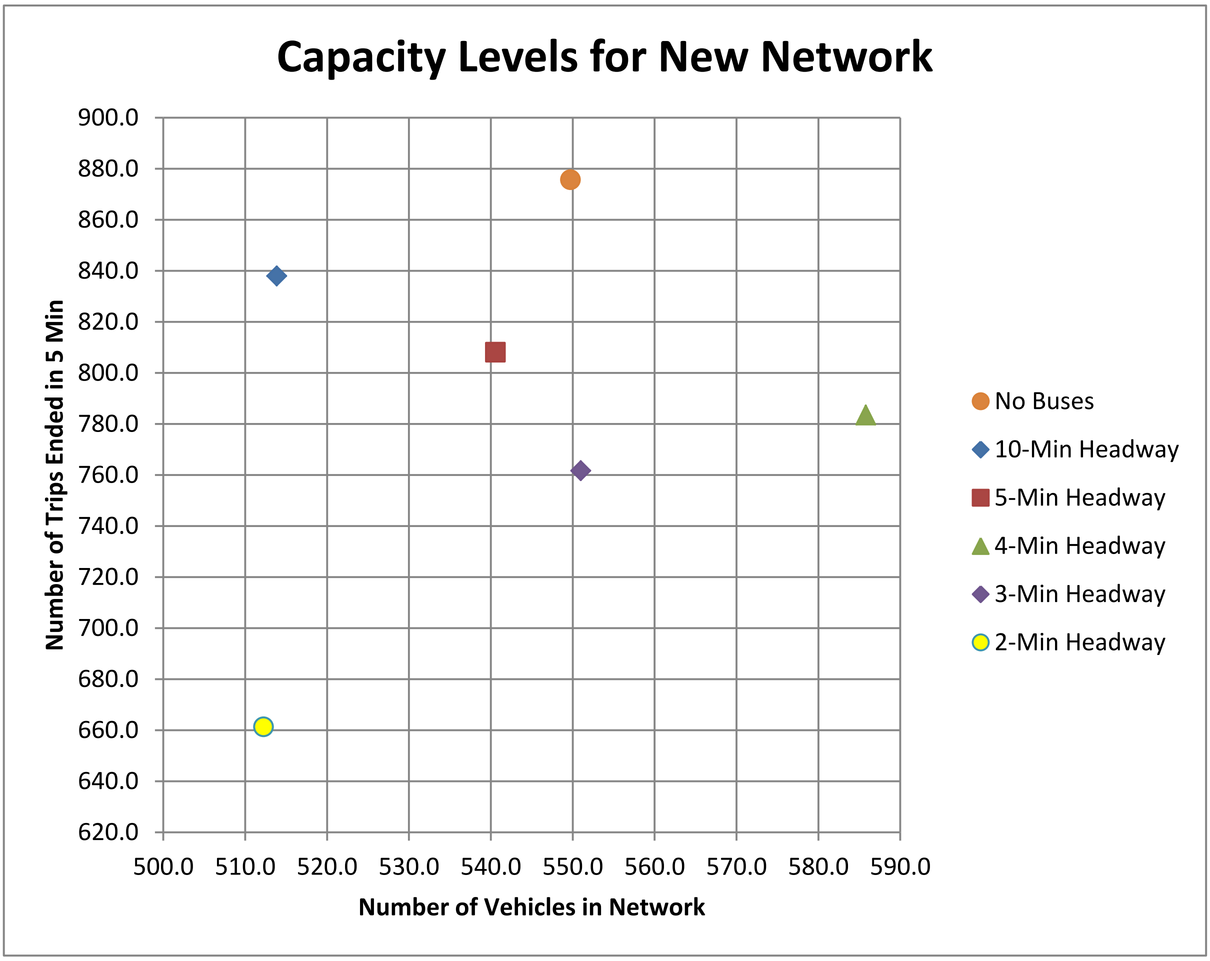
Table 7 Headway Comparison of New-Network Bus Stops Upstream of Intersections

Network Description	No of Random Seeds	No of Significant Capacity Points	Capacity (Ended Trips)	Capacity Decrease (%)	Optimal Density (Active Vehicles)	Jam Density (Active Vehicles)
No Buses	3	8	875.8	-	549.7	1886.5
10-Min Headway	1	1(2)	838	4.32	513.9	1873.1
5-Min Headway	3	7	808.1	7.73	540.6	1739.7
4-Min Headway	1	1(2)	783.5	10.54	585.8	1729.0
3-Min Headway	1	3	761.7	13.03	551.0	1695.5
2-Min Headway	3	6	661.3	24.49	512.2	1375.8

Source: Own Configuration

Figure 20 presents the capacities (flows and densities) for all the implemented headways. Its shape is similar to the "downstream" results following a proportional decrease with negative and subsequently positive slope. 10-Min, 5-Min and 4-Min headway show proportional capacity decrease which is accompanied also by density increase. All this output is expected with lower vehicle output (ended trips), higher densities and lower average network speeds. 10-Min-headway speed is the only higher than the no-buses-speed result. 5-Min and 2-Min-headway densities are lower than the no-buses one. Their density decrease, though, is not as high as their capacity decrease from the no-buses capacity with lower ratio. 4-Min and 3-Min headways provide higher-than-the-reference density (no-buses) with significantly lower capacities.

Figure 20 Capacity Levels for New Network Upstream of Intersections

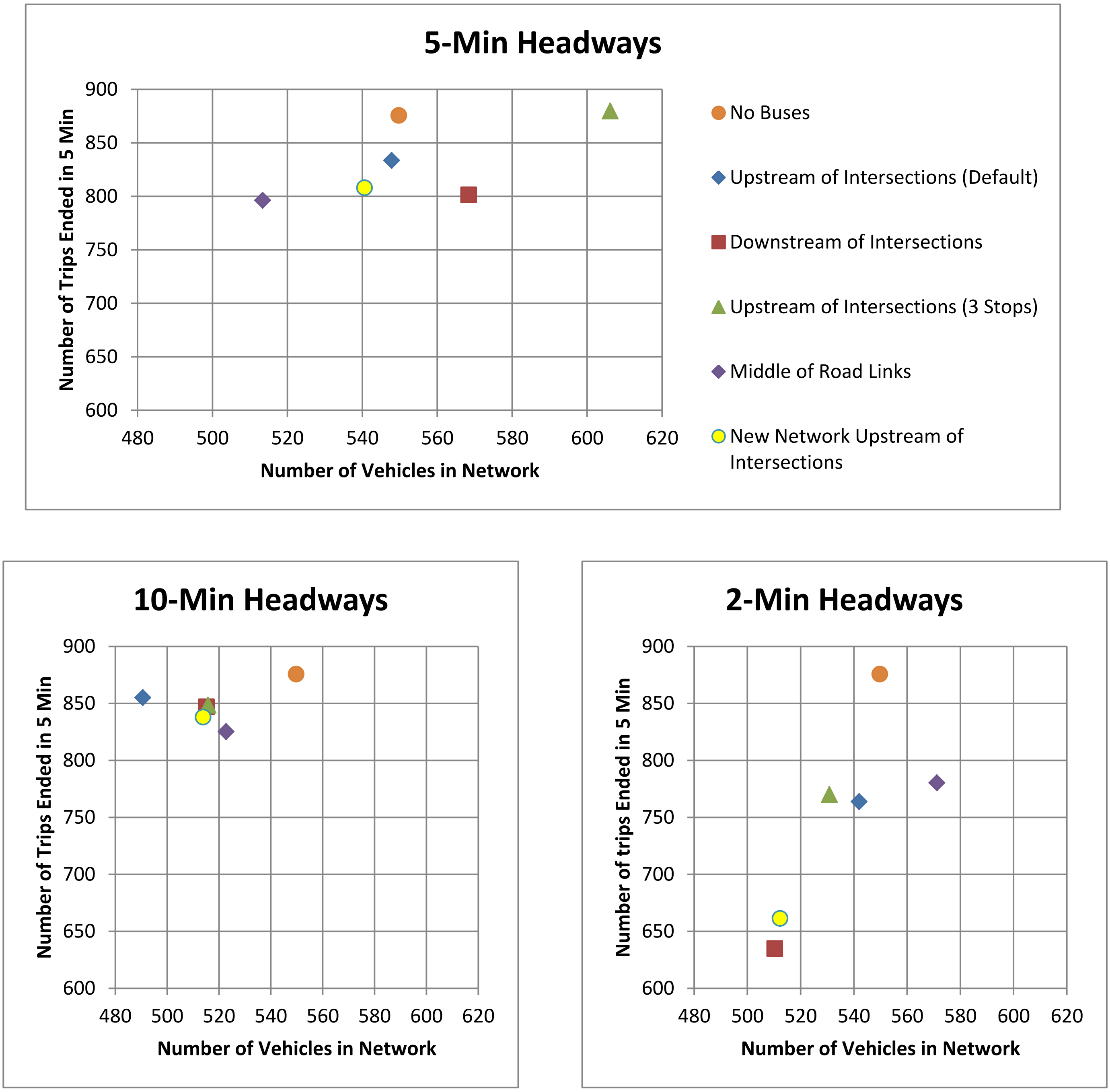


Source: Own Configuration

4.4.2 Network Configuration Comparisons

This sensitivity analysis focuses on the effects of the different network configurations for the most representative headways.

Figure 21 Capacity Levels for 10-Min, 5-Min & 2-Min Headways



Source: Own Configuration

Figure 21 presents the capacity results for the 10-Min, 5-Min and 2-Min headways. 5-Min headway is the most representative peak-hour headway and therefore it is centrally located. The available in the 5-Min headway legend is same also for the other plots. Important comments can be collected for the capacity decreases, the density behaviour and the average network speed reduction.

It is obvious that bus-frequency increase leads to substantial capacity decrease. 10-Min headways show comparable-to-the-reference-simulation results. Capacity is slightly lower than the no-buses simulation with simultaneous density decrease. Default network provides the highest results and “middle of road” the lowest ones. The remaining networks illustrate intermediate results. Generally it can be derived from the 10-Min diagram that speeds are equal or even higher than the no-buses one (see also section 4.6).

5-Min headway initiates showing the bus operational effects. First the majority of the capacities are reduced from the reference result. Only the “upstream” network with the three stops illustrates unexpected high capacity but effects also exist due to the density increase. The remaining configurations provide capacities close to 800 ended trips. It can be indicated that “downstream” and new network are the most sensitive configurations with the highest bus operational effects. Their capacities are low and this argument is verified in the 2-Min headway. The 5-Min headway provides lower speeds and only the “middle or road” one can be comparable to the no-buses speed. Speed decrease derives mainly from the combination of reduced capacities with increased densities.

Even more representative effects provide the 2-Min-headway results. Capacity effects are obvious with great differences from the no-buses. “Downstream” and new network are apparently the most influential configurations with the least capacities. Default network shows slightly lower capacity points than the upstream with 3 stops and the “middle of roads”. It is expected that bus-stop reduction and bus-stop transition away from the intersections would bring higher vehicle output. Another expected outcome is the average network speed reduction for the current headway. For instance, “downstream” network shows around 7% density decrease from the no-buses but it simultaneously provides 27% capacity decrease.

In total, “downstream” and new network are the highest influential configurations and this is more obvious for higher headways. Default network provides always higher results than the vulnerable ones. This output was expected considering the more advantageous bus-stop location and the more uniform bus-stop distribution. Result inconsistencies of the “upstream” with 3 stops and “middle of roads” networks necessitate more random-seed simulations to stabilize the sensitivity results.

4.5 Overall Network Capacity Results

Section 4.4 focuses on the result presentation and comparison. It is separates into comparison regarding the bus networks and the headways. Result sensitivity of the frequency, the bus-location and bus-line configuration changes is provided. One of the most representative MFD results for the network performance commendation is the capacity. Therefore, this section focuses on the summarization and the capacity comparison. Table 8 summarizes the capacity results from all the implemented headways and network configurations.

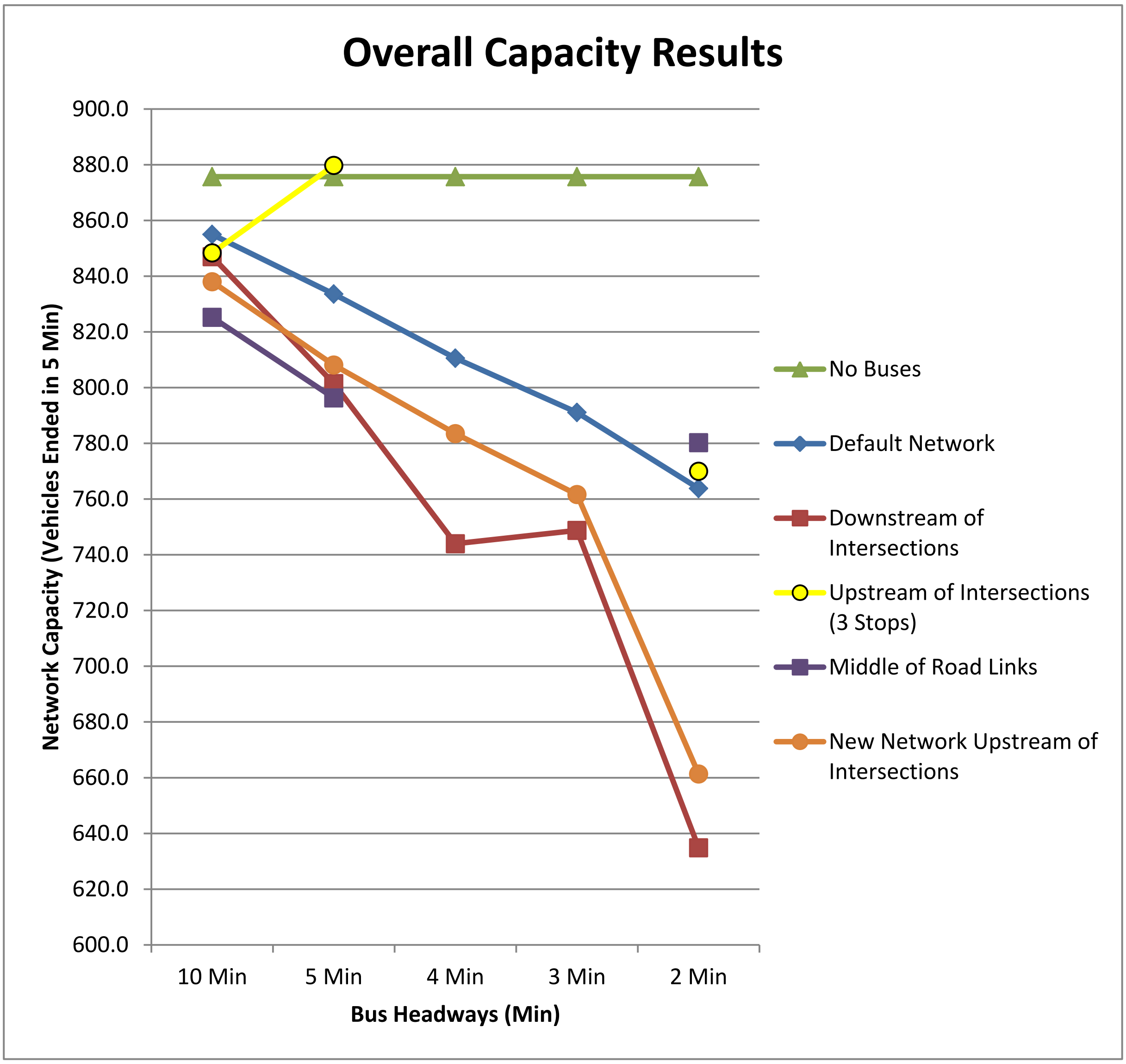
Table 8 Simulation Vehicle Output (Flow) Results for all Network Configurations & Headways

Network Description	10-Min Headway	5-Min Headway	4-Min Headway	3-Min Headway	2-Min Headway
No Buses			875.8		
Upstream of Intersections (Default)	855.0	833.2	806.3	807.4	766.8
Downstream of Intersections	847.0	801.5	745.8	748.8	640.9
Upstream of Intersections (3 Stops)	845.8	879.0	-	-	770.0
Middle of Road Links	832.0	796.3	-	-	777.4
New Network Upstream of Intersections	838.0	804.9	783.5	761.7	661.3

Source: Own Configuration

Effects of bus operations can be noticed based on the flow reduction both for the various networks and for all the simulated bus headways. Once again, it is clear that the 10-Min headway shows the lowest effects and it can be concluded that the capacity drops are not substantial compared to the no buses. All the configurations provide high flows that exceed 820 completed trips. As the bus frequency increases, the results become more influential. 5-Min headway is a typical peak-hour frequency. Its flow drops to 800 vehicles reaching up to 8% reduction from the no-buses simulation. Even higher frequencies, for instance 4-Min and 3-Min headway, follow the capacity drop and present similar results among them. The most influential headway, on which the most reasonable effects can be identified, is the 2-Min headway. Especially influential are the “downstream” and the new network with vehicle-output decrease rising to more than 25%. Figure 22 visualizes graphically the capacity reductions for the headway increases and for the various network configurations.

Figure 22 Capacity Levels for all networks & headways



Source: Own Configuration

Default network results show relatively expected flow results with a gradual decrease for the various headways. This illustrates that the bus-frequency increase burdens the unobstructed traffic performance. Similar results regarding the headway ranking are received from the new network, which shows steady decrease for lower headways (higher bus frequencies). The single difference among them is the substantial 2-Min-headway decrease of the new network both from the corresponding default network result and from the 3-Min-headway result. The "downstream" configuration does not differ much from the aforementioned networks. There is a gradual decrease until the 4-Min headway. This is accompanied by a huge drop when 2 minutes are implemented in the network. The only exception derives from the 3-Min-headway result which provides higher capacity than the 4-Min one. This is an implication that their effects differ only from each other at the density level despite the adverse capacity results. The higher operational effects of the 3-Min headways are noticed at network speed results (see also section 4.6).

On the contrary, the other two networks provide inconsistencies in their flow results. The scarce bus-stop configuration (3 stops) shows expected results for the 2-Min headways with the flow being higher than the default-network result. 10-Min-headway result, though, shows infeasibility because the vehicle output is lower than the default network and similar to the “downstream” network. It would be expected to receive higher results than the other networks. This, however, relies on the selected random seed (only one simulation) and the O-D route selection. More surprising is the result of the 5-Min headway which is the highest of all the simulations and more specifically higher than the no-buses simulation. Despite the fact that the existing number of stops is small enough, the bus dwell times and reduced travelling speeds should have affected the network performance. “Middle of road” is critical for the extremely low results of the 10-Min and 5-Min headways. It provides the lowest results among all configurations although the bus stops are located long away from the intersections. The single explanation that can be provided is the reduced vehicle accumulation space compared to the “upstream” networks and the relative easiness to create spill-back effects. Result verification, though, is necessary for these cases with the additional simulations.

In total, bus operations are in all the implemented simulations influential and therefore traffic performance should always be examined before the bus implementation, modification or addition in the network. For instance, the headway selection is a procedure that needs to adjust to the passengers’ demands. The simulations show for example that the 5-Min headway provides a higher output than the 4-Min despite their small headway difference. Moreover, the 4-Min and 3-Min headway results are similar to each other and transport planers can choose based on the public-transport demands and the urban policies. In addition, 2-Min headway is highly influential and provides much lower results than the 3-Min. Therefore, it should be examined if the necessities can be covered with 3-Min headway instead. As a result, the whole traffic would not suffer from long queues and traffic jams. Regarding the networks, it is obvious that the “downstream” network suffers from the directly created spill-back effects. Consequently, bus stops would ideally be located upstream of intersections at the transfer points and also in the middle of road links if needed[14]. The new network instability creates an argument about the urban policies for public transport use, the benefits for the public users, the higher provided accessibility (see chapter 6) and the compromises for the private transport. Conclusively, there is no direct suggestion and always the optimal solution needs to be identified for the most appropriate bus-line design.

4.6 Network-Speed Results

Maximum network performance is characterized basically from the capacity and the density level. Their correlation brings the average network speed and it is crucial to show the network speed effects after the bus implementation.

Figure 23 summarizes all the flow-density results from all the implemented headways and networks. This correlation provides the corresponding network speeds as a result output. Parallel to that, Table 9 presents the flow-density ratio which can be compared for the network speed. The table values are not the network speed but the ratio provides the relation of the ended trips and the active vehicles.

Table 9 NEF ratio for Network Speed Comparison of all Headways & Networks

Network Description	10-Min Headway	5-Min Headway	4-Min Headway	3-Min Headway	2-Min Headway
No Buses			1.593		
Upstream of Intersections (Default)	1.743	1.522	1.487	1.504	1.409
Downstream of Intersections	1.644	1.410	1.351	1.309	1.244
Upstream of Intersections (3 Stops)	1.645	1.451	-	-	1.451
Middle of Road Links	1.579	1.551	-	-	1.366
New Network Upstream of Intersections	1.631	1.495	1.337	1.382	1.291

Source: Own Configuration

The table and the figure show the relatively low ratio for the no-buses simulation. This is caused from the high density value despite the huge vehicle output. Consequently, the majority of the 10-Min-headway ratios are higher than the no-buses ones although their capacity is lower, as mentioned above. This is an indication that 10-Min bus operations cause negligible

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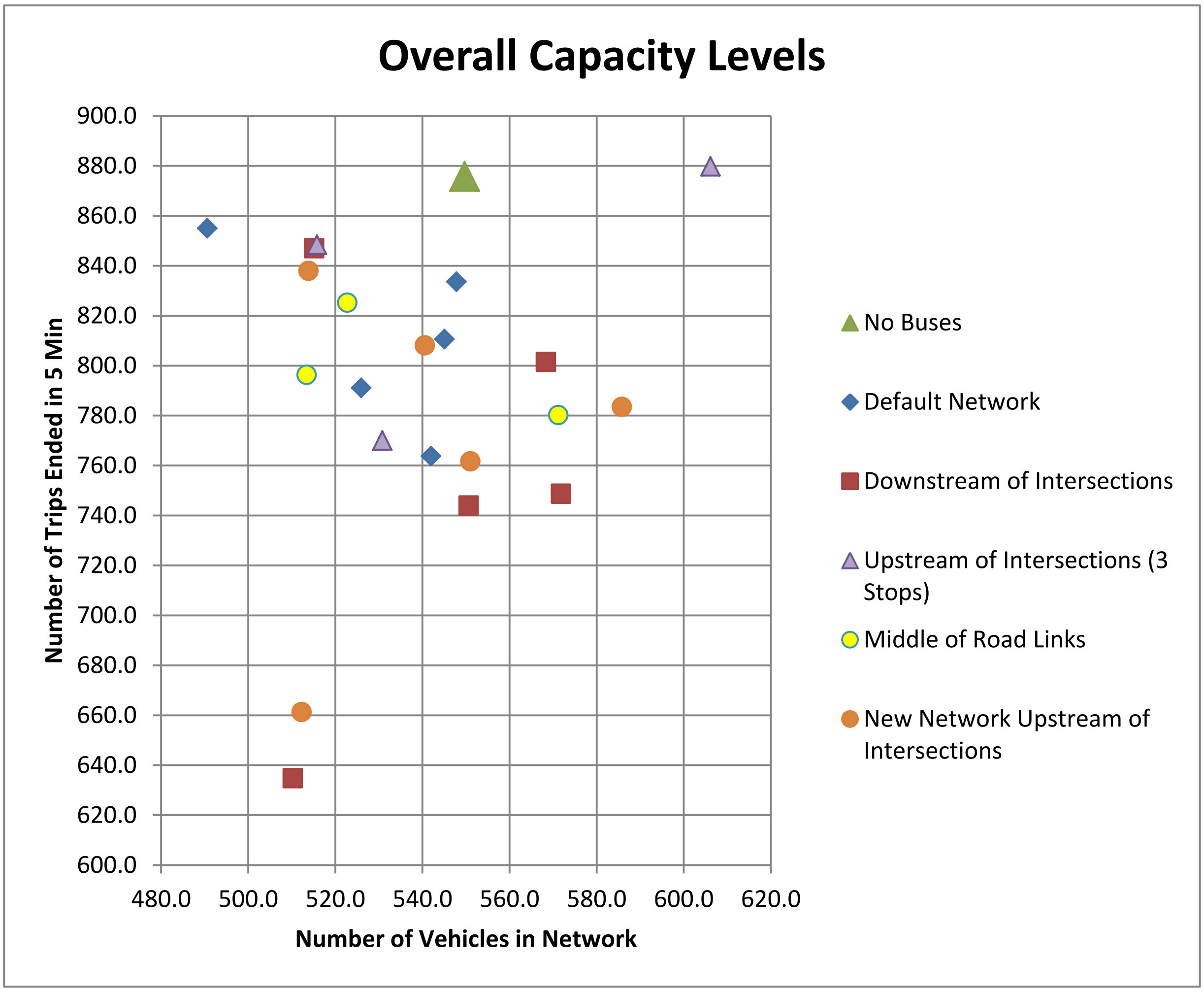
[14] There are bus stops located in the middle of road link to serve several surrounding buildings, for instance post and other public facilities.

effects on the traffic behaviour. Bus dwell times and reduced bus speeds are so rare that the overall network speed is not affected. The single configuration with lower-than-the-no-buses ratio for the 10-Min headway is the "middle of road". This network provides unexpectedly low capacity results for the 10-Min and 5-Min headway and this explains the low ratio.

Figure 23 Overall Capacity Levels for Network Speed Comparison



Source: Own Configuration

Speed decrease from the no-buses simulation can be identified for all the remaining headways. Ratio decreases with the headway increase. More analytically, 5-Min headway provides ratios on average 1.5 which drops to 1.4 for the 4-Min and 3-Min headway and to 1.3 for the lowest headway.

"Middle of road" network presents the highest ratio for the 5-Min headway among the other ones. This indicates that the network performance is not highly affected despite the low vehicle output. Expected are also the lower speeds of the "downstream" and the new network compared to the default one for all the implemented headways. As for these two networks, the "downstream" provides mainly lower results than the new network with the 4-Min headway being the single exception. The 3-stop network provides average ratios. Its 10-Min-headway ratio is lower than the default and the new network but higher than the "downstream" and the "middle of road". The ratio for the 5-Min headway is higher only from the "downstream" network. All these results are argumentative and additional random-seed simulation would verify these low speeds. More expected is the speed result for the 2-Min headway, in which the 3-stop network shows the highest value.

Generally, speed presentation verifies the no-buses high density level and it shows, once again, that the bus operations affect the traffic behaviour only for higher and equal to 5-minute frequencies.

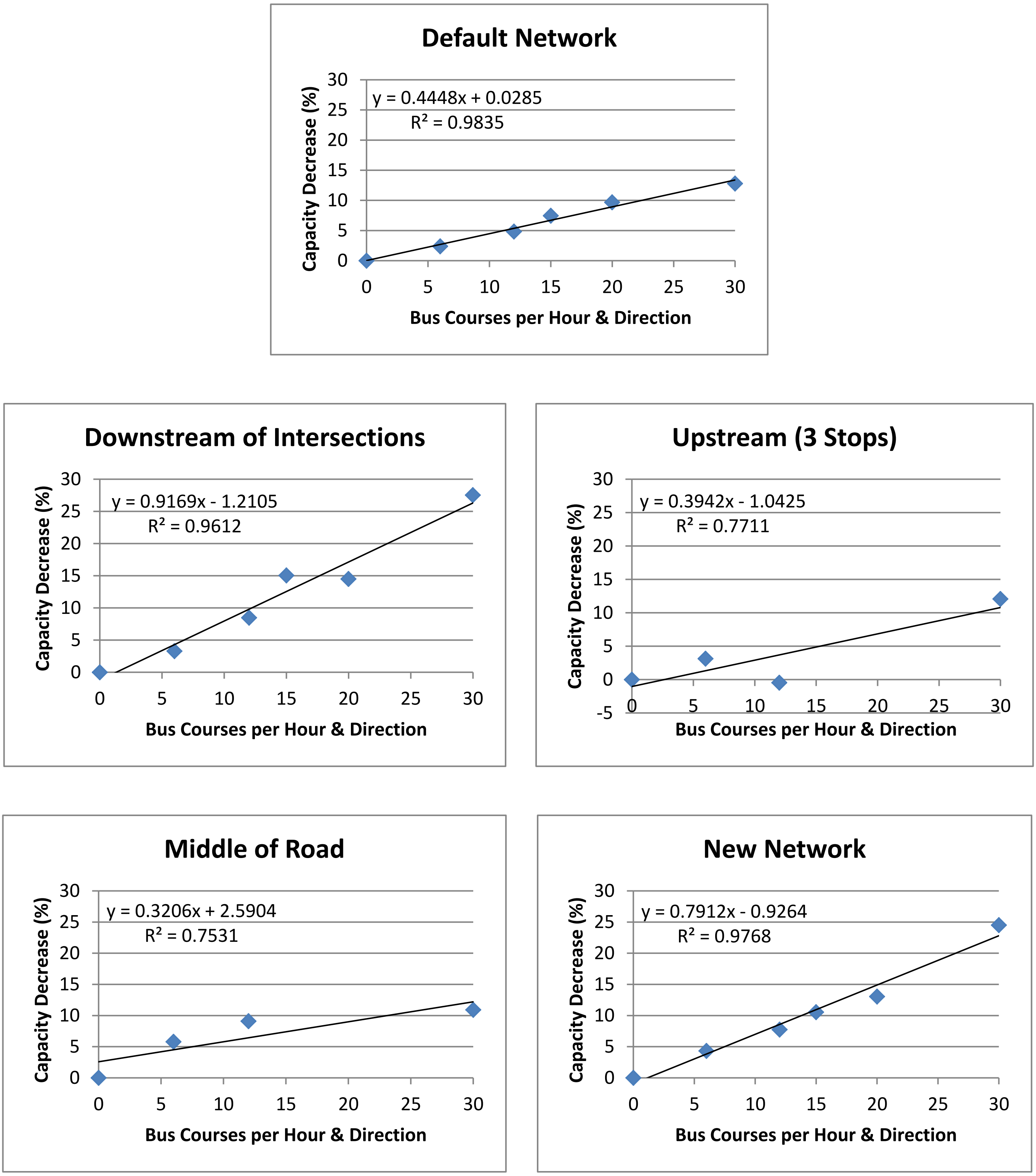
4.7 Capacity Decrease-Bus Frequency Correlation

Network capacity effects are significantly influential when buses are added in the network operations. Section 4.4.1 presents the capacity results with additional presentation of the percentage capacity difference from the no-buses simulation. The identified capacity decrease is, as expected, higher for lower headways (higher frequencies). An investigation issue that derives from the argument is the correlation between capacity decrease and bus courses.

10-Min-headway operation provides 6 bus courses per hour, line and direction. Double are the courses for the 5-Min headway. 4-Min and 3-Min headways show 15 and 20 bus-courses respectively. When buses follow the 2-minute frequency, there are 30 buses passing from each stop per hour and direction.

Figure 24 shows the correlation between the simulation capacity decrease and the aforementioned bus courses. Apparently, all the network configurations show extremely high linear correlation between these two parameters. It should be mentioned that the existing points cannot provide significant results. It is not statistically accepted to discuss about linear correlation with only five available capacity points. However, it is an indicator that bus operation increase leads to proportional network effects and as a result to proportional capacity decrease.

Figure 24 Capacity Decrease – Bus frequency Correlation



Source: Own Configuration

More specifically, the default network presents the highest correlation and R squared value almost reaches 1. This means that the higher the bus courses (lower headway), the more influential are the bus operations for the traffic performance. New and “downstream” network also illustrate an extremely high correlation. “Middle of road” network and upstream with 3 stops show significant correlations with reasonable R squared values higher than 0.75. However, there is a substantial correlation decrease compared to the previous ones. Point position from the line shows if the capacity is higher or lower than the expected. It is clear in the 3-stop upstream network that 5-Min-headway capacity decrease is considerably lower than the expected one and this reduces the correlation factor (R squared). “Middle of road” lower correlation is caused from the high capacity decreases that are noticed for the 10-min and 5-Min headways. Default network shows small deviations from the expected capacity decrease and only 4-Min and 3-Min provide slightly higher than the expected results. Downstream network provides higher capacity for the 4-Min and lower for the 3-Min headway. New network illustrates slightly lower and higher than-the-expected capacity decrease for the 4-Min and 2-Min headway respectively.

The equation slopes indicate the capacity-effect level at each network. More analytically, “downstream network” shows the highest effects among all the networks. It shows more than double capacity decreases than the default network. Next most influential is the new network that shows 50% higher capacity decrease than the default network. Additionally, it provides only 13% better traffic performance than the “downstream” network. The other two configurations are not as influential as the default network. 3-stop network illustrates an 11% higher network operation than the default one. Lowest bus operational effects are provided from the “middle of road” network with 27% higher-than-the default operation. Generally, this correlation provides clearly the bus operational effects of each network.

The intercept in the linear correlation equation indicates the comparison of the current and the virtual no-buses simulation result. Positive value means that bus operational effects are higher than the virtual linear correlation requirements and vice versa. Default network provides a small positive value. This explains that the no-buses result is slightly higher than the expected result. Positive is also only the “middle of road” network. It is clear in the diagram that the no-buses capacity result should have been 2.59% lower to follow the linear correlation. Negative are the values for the “downstream”, the 3-stop upstream and the new network. They require 1.21%, 1.04% and 0.93% higher no-buses capacity results respectively so that the no-buses result follows the absolute linear correlation. This is verification that the no-buses result is lower than the expected one.

5 Multimodal Transport-System Efficiency

All the previous analysis emphasizes on the effects of bus operations on urban networks. It is clear that the bus operations decrease the vehicular network capacity due to bus dwell times and reduced speeds. Even after adding the number of completed bus trips the capacity of the network is lower if buses are maintained as vehicles. This would have meant that the bus existence in the network should have been eliminated. However, it is important to extend this analysis to the passenger ended trips. This will bring higher passenger results for the bus operations due to the higher full factor of the buses. To be more specific, full vehicle factor (cars and trucks) is extremely low compared to bus passengers one. As a result, comparison of a network performance should not be limited only on the total vehicles ending their trips. It is more useful from the users' perspective to examine the overall amount of network users who are able to complete their trips. This would provide comparable results between the no-buses and the buses simulations.

Goal of the current chapter is to identify how the additional bus passengers can outweigh the vehicular bus-capacity decrease. More analytically, it is vital to estimate the minimum required bus passengers that need to be transported. This requirement satisfaction guarantees, then, that same passenger capacity is transported as in the no-buses operation. In addition, comparisons between the headways will be presented illustrating which headway application promises higher passenger trip completion.

Simulation processes provide the vehicular ended trips (flow until capacity level). Based on this data, it is important to identify the full vehicle factor so that we extract the passenger number travelling with private transportation. Basis for the full factor identification is data from the city of Zurich. The city of Zurich is also the reference for the length of the links determination (see section 3.1.2.).

Table 10 shows the occupancy degree of the vehicles for various transport purposes and the percentages of vehicles transporting either one or more persons. It can be noticed that more than 80% of the people moving for job, business activities and education prefer travelling alone. This is the explanation for the lower occupancy degrees.

Table 10 Average Occupancy Degree (Full Factor) of Private Vehicles & Number of People in Vehicle (2005)

Transport Purpose	Occupancy Degree (Persons / Vehicle)	Percentage of Vehicles (%) with Number of People per Vehicle			
		1	2	3	4+
Total	1.57	70.2	20.9	5.3	3.6
Job	1.11	91.4	6.6	1.2	0.7
Education	1.26	78.9	18.4	1.7	1.0
Retail	1.63	66.9	25.2	5.1	2.8
Business Activity	1.25	86.0	11.5	1.9	0.6
Ride Service	1.52	74.2	16.1	8.0	1.7
Leisure Time	1.92	55.5	29.6	8.2	6.7
Service & Escort	2.16	32.3	45.0	15.9	6.8

Source: ((BFS) & (ARE), 2007)

As mentioned above, the simulation period is the morning peak-hour. The majority of people being on the way during this period move mainly for work, for education or for other business activities ((BFS) & (ARE), 2007). Therefore the occupancy degree during the simulation period is assumed to be averaged. Good approximation is the occupancy degree assumption with the value of “1.20”. Passenger capacity calculation is based on the vehicular network capacity of Table 8 and the “1.20” value. Table 11 presents the passenger-capacity results both for the no-buses and for all the bus implementations.

Taking the passenger capacity decrease due to bus operations into consideration, it is useful to extract the required bus passengers. This value satisfaction offers the same passenger service between the buses and the no-buses network configuration. Completed bus trips at capacity level are averaged providing the average number of buses at the capacity level. Total passenger differences and average bus ended trips are used to calculate the number of passengers per bus. Outcome of this procedure is the required bus passenger number that equalizes the capacities before and after bus implementation.

Table 11 Simulation Car & Truck Passenger Capacity Results for all Network Configurations & Headways

Network Description	10-Min Headway	5-Min Headway	4-Min Headway	3-Min Headway	2-Min Headway
No Buses	1050.9				
Upstream of Intersections (Default)	1026.0	1000.3	972.7	949.3	916.6
Downstream of Intersections	1016.4	961.8	892.8	898.5	761.8
Upstream of Intersections (3 Stops)	1018.1	1055.8	-	-	924.0
Middle of Road Links	990.3	955.6	-	-	936.3
New Network Upstream of Intersections	1005.6	969.8	940.2	914.0	

Source: Own Configuration

Table 12 shows the bus passenger requirements for capacity satisfaction and Figure 25 illustrates these passenger necessities graphically.

Table 12 Required Bus Passengers from all Network Configurations & Headways

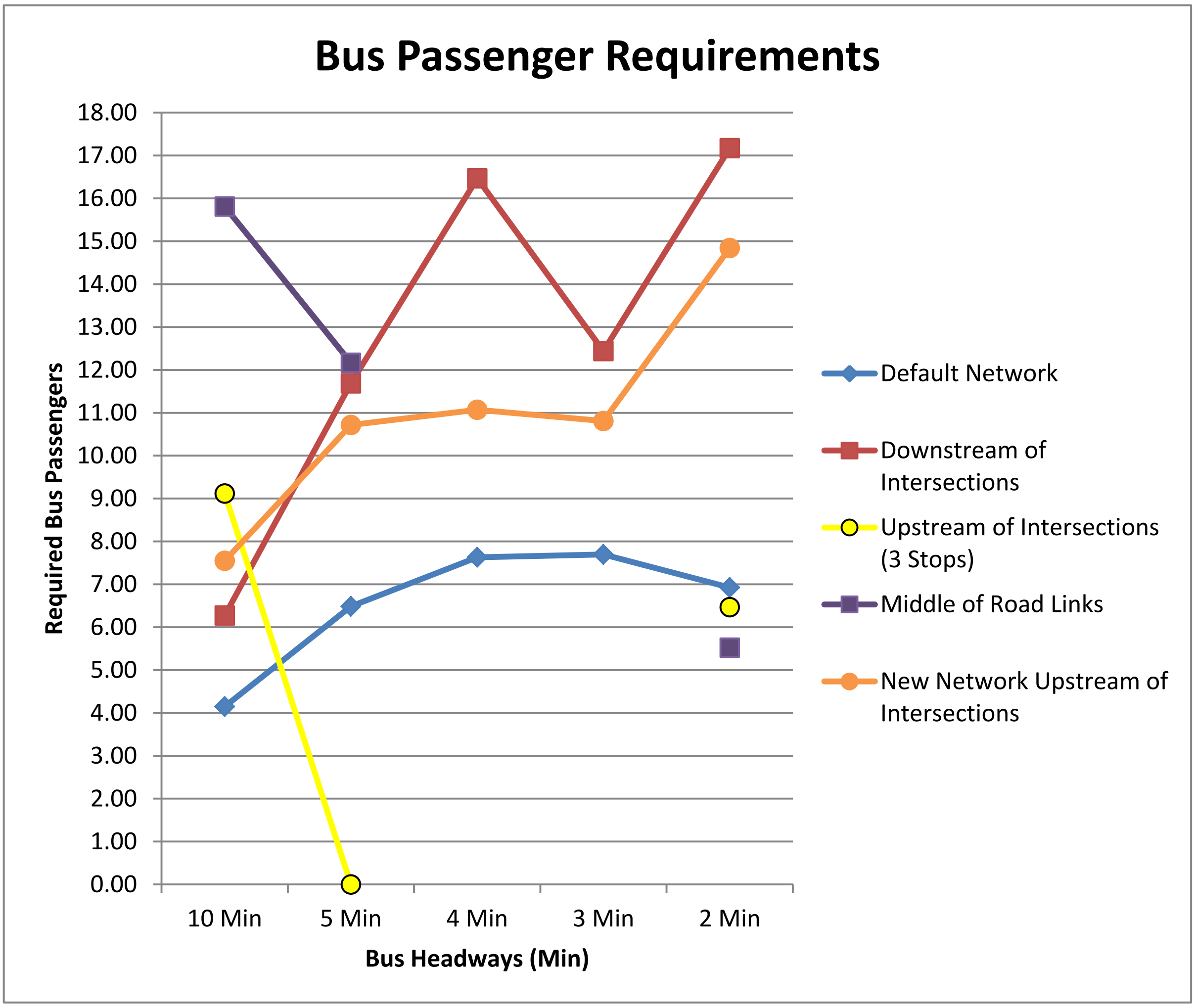
Network Description	10-Min Headway	5-Min Headway	4-Min Headway	3-Min Headway	2-Min Headway
Upstream of Intersections (Default)	4.15	6.48	7.63	7.70	6.92
Downstream of Intersections	6.27	11.69	16.47	12.44	17.17
Upstream of Intersections (3 Stops)	9.12	0.00	-	-	6.47
Middle of Road Links	15.81	12.17	-	-	5.52
New Network Upstream of Intersections	7.55	10.72	11.07	10.81	14.84

Source: Own Configuration

It should, first, be mentioned that the passenger requirements are only approximations based on the vehicle output and the bus output at the capacity level. Second, it is important to mention that the results are analogous to the capacity difference between bus simulation and the no-buses simulation.

More analytically the passenger-requirement range varies between 0 and 18 passengers. Default network shows a gradual increase in the passenger requirements initiating from 4 and reaching up to 8 passengers for the 3-Min headway. “Downstream” network shows the highest requirements, which is awaited due to the lower capacity results, with 18 passengers for the 2-Min headway. The scarce network shows, generally, low requirements and especially the 5-Min headway, in which there is no necessity for passengers. "Middle of road" network requires more passengers than all the other configurations for the 10-Min- and 5-Min headways. This is rather not-easily achievable considering the network unattractiveness with the lack of transfer points. New network follows the "downstream" requirements. It can be noticed that the required passengers for the 5-Min, 4-Min and 3-Min headways are similar and there is significantly higher demand for the 2-Min headway.

Figure 25 Bus Passenger Requirements for Equal-to-No-Buses Passenger Output



Source: Own Configuration

The most important issue of this demand discussion is the easiness of the passenger satisfaction among the network. To be more specific, default and "downstream" network offer exactly the same service with the same bus stops, the same bus lines and the same transfers. However, the outputs as well as the passenger demands are substantially different. Therefore it is more feasible that the default network satisfies more network users and reaches the no-buses passenger output. For instance, it is more feasible for a bus to transfer 4 passengers rather than 6 when the buses stop every 5 minutes. More intense is the difference for the 2-Min headway, which necessitates 7 and 17 passengers for the default and the "downstream" network respectively. New network provides also higher results but it is more attractive than the default network considering that it is a dense radial bus network. The requirements among them tend to be closer for the 4-Min and the 3-Min headway where the passenger demand rises from 7 to 11 passengers. Higher new network accessibility can provide more easily the high required passenger number. Passengers of this network would be more satisfied with the higher number of direct movements and the reduced travel times. The attractiveness of this network and the high accessibility (see chapter 6) can guarantee more passengers than the default network.

In addition to the network attractiveness, the headway can also involve in the passenger-requirement satisfaction. 2-Min headway offers an extremely frequent operation which is attractive for the users and offers higher transferability. However, the buses are almost following each other in short distances and time gaps. As a result, it is really difficult to "load" 15 passengers in each bus. On the contrary, the basic peak-hour frequency (5 minutes) shows more logical and feasible passenger demands despite the reduced transferability and the average waiting time (2.5 minutes on average) at the transfer points. On the other hand, 10-min requirements are high enough for the passenger satisfaction with such an unattractive for an urban region public-transport service. This is an explanation of the 5-Min headway selection for the morning and the evening peak hours. When demands exceed the bus capacities, transport agencies (public transport companies) offer additional courses to fulfil the specific requirements. These additional courses provide the company from empty buses for 2-Min headways. Consequently the high operational costs of the 2-Min headway are reduced and higher profits can be guaranteed.

In total, passenger capacity raises argumentative issues about the bus network design and the headway selection. Passenger demand is always dependent on the available bus lines and the headway selection. The previous analysis showed that passenger requirements are mainly proportional to the bus courses (see also section 4.7). However, this does not mean that 2-Min headways would definitely bring the highest passenger satisfaction and would cover the differences from the no-buses passenger output. It is vital to find out the optimal solutions without under- or overestimating the bus-networks necessities. Optimal solution derives from the analysis of the traffic performance reduction, the bus passenger output and the network accessibility.

6 Introduction to Network Accessibility

Another important topic that derives from the users' satisfaction is the accessibility level of each network configuration with use of public transportation. Private users select their route based on their experienced travel time. Due to users' equilibrium, they force to minimize their travel times on paths. On the contrary, public transportation passengers do not have this flexibility. It is necessary for them to walk to the closest pick-up bus stop and from the drop-off bus stop to the destination point. In addition, bus route do not cover all the O-D combinations and sometimes transfer is obligatory for the public-transport users.

In chapter 5 the required bus-passenger number to equalize the passenger capacities before and after bus implementation is calculated. The satisfaction of these numbers, though, depends on the attractiveness of the network and the provided opportunities to travel in-between the network without substantially longer time intervals. As a result, it is crucial to discuss about the accessibility of the various network configurations considering the overall travelling time. The latter consists of the following parameters:

- Walking distance (and time) from the origin point to the appropriate pick-up bus stop
- Waiting time for the bus arrival
- Bus travelling time
- Transfer time (if needed)
- Additional bus travelling time (if needed)
- Walking distance (and time) from the drop-off bus stop to the destination point

The consideration of the total public-transport travel time indicates the higher travel time of the public than the private transport. Important, though, is the percentage identification. This additional travel time is balanced by the reduced public-transport travel costs to the operational vehicle costs for gas and maintenance. In addition, optimization of the public transport network focuses on the travel time minimization which leads in some cases to comparable travel times among the private and public transport. The city of Zurich promotes public transport use by penalizing the private vehicle use through the Perimeter Control. In addition, full bus priorities at conflict points guarantees the bus-delay minimization (Menendez & Guler, 2014).

Basic criteria for the public network attractiveness are the line distribution, the existing transfer points and also the headway. The implemented simulations considered both various bus networks as well as various headways. It is shown that higher bus frequency reduces the vehicular performance but the passenger capacity is responsible for outweighing this reduction with the higher bus full factor. In chapter 5, it is mentioned that the bus fulfilment depends highly on the current-networks attractiveness. Therefore it is crucial to introduce basic information about the attractiveness of the two basic network configurations.

6.1 Methodology for Network Accessibility Calculation

Most reliable approach to fully cover the network accessibility is to compare the required travel times from all the origins to all the destinations. However, the current network consists of 60 parking zones (O-D points) and as a result there are 3600 combinations for the O-D matrix. The application of the shortest path selection for each of these pairs would minimize the travel times. This procedure, however, is not this survey goal, which mainly focuses on the bus operational effects and not on the successful bus network organization.

Taking all these into account, it is selected to cover part of the network accessibility as an example for the illustration of the network attractiveness. Accessibility outcome explains why, for instance, a radial network is preferred from the transport planers despite the lower traffic performance as seen in chapters 4.4.1, 4.4.2 and 4.5.

6.1.1 Network-Comparison Selection

Network accessibility comparison focuses on the following configurations:

- Bus stops upstream of intersections (default network)
- New network with bus stops upstream of intersections

“Downstream” network is excluded from this analysis due to the equalities with the default network. To be more specific, the bus stop location does not affect accessibility which in both cases is identical with the transfer points being next to the intersections. The network with the fewer stops is without doubt the most unattractive network which necessitates long walking distance. In addition, transfer points almost do not exist in this network. Therefore, it is not comparable to the other networks and consequently also excluded from the process. Analogous results would bring the “middle of links” network, which contains also walking distances for transferring. This would definitely become a drawback for the overall results. Apart from that, this network is not as realistic as the under-survey ones. Contemporary tendency for public-transport planning is the bus location close to intersections to enable potential transferability. This criteria and synchronous network design is fulfilled in the "upstream" and the "new network" configuration.

6.1.2 Accessibility Conditions

The existing network is a small urban area less than 1 km^2 and therefore there are four bus lines independent of the configurations. The majority of the daily network users cover much longer distances compared to the existing ones. Their general preference is trip selection without transfers. As a result, it is chosen that the maximum number of allowed transfers is one[15] . Otherwise the passengers would find the movements in-between this area unattractive.

Bus stop distance at the under-survey networks is 300 m which leads to rather dense bus network. As a consequence, the numerous existing bus stops and the network configurations guarantee that no one needs to walk more than 225 m in order to reach the closest bus stop. This is taken for granted regarding the origins and every public-transport user moves to the closest pick-up bus stop. Then the closest path from this stop is searched for the destination points sustaining the condition of one allowed transfer. Another condition is the walking distance from the drop-off bus stop to the destination points to be preferably less than 300 m. This is a condition which is not able to be fulfilled in all the movements. There are cases at each network, in which the walking distance increases to 375 m.

As for the waiting-for the bus time at the origin bus stops this is picked to be 120 seconds when there is only one available bus line. This is the waiting time for the public-transport users who normally know the bus schedule and go to the bus stops 2 minutes in advance. It is assumed that the bus lines follow a certain schedule and bus operations are not affected from traffic congestions for the accessibility calculations. In addition, there are transfer bus stops with more than one available line. For the transfer points with two bus lines the waiting time is selected to be 30 seconds. For those with three different lines there is no under-account waiting time. These differentiations are selected basically for the direct movements in which the pick-up bus stop offers two bus lines. The 30-second and zero waiting times promote the higher bus-line availability at the pick-up points.

Waiting transfer time is selected to be the average time dependent on the headways. If the headway is for instance 10 minutes, the waiting time is selected to be 300 seconds (5 minutes)

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[15] Each person uses at mot two bus lines.

because it can vary between 0 and 10 minutes. For the situation, in which two bus lines are available at the transfer point, waiting time is half the initial one (150 seconds).

6.1.3 Classification of Under-Survey Region

The selection of the under-survey region is basically based on the idea of the not-easily accessible area examination. It is selected that the accessibility of the southern part of the network will be investigated. Destination area of this analysis is mainly the northern part including parking zones in the northwest and northeast network regions. Therefore it is useful to identify the number of available bus stops in all these areas and to classify the various parking zones based on the corresponding bus-stop availability.

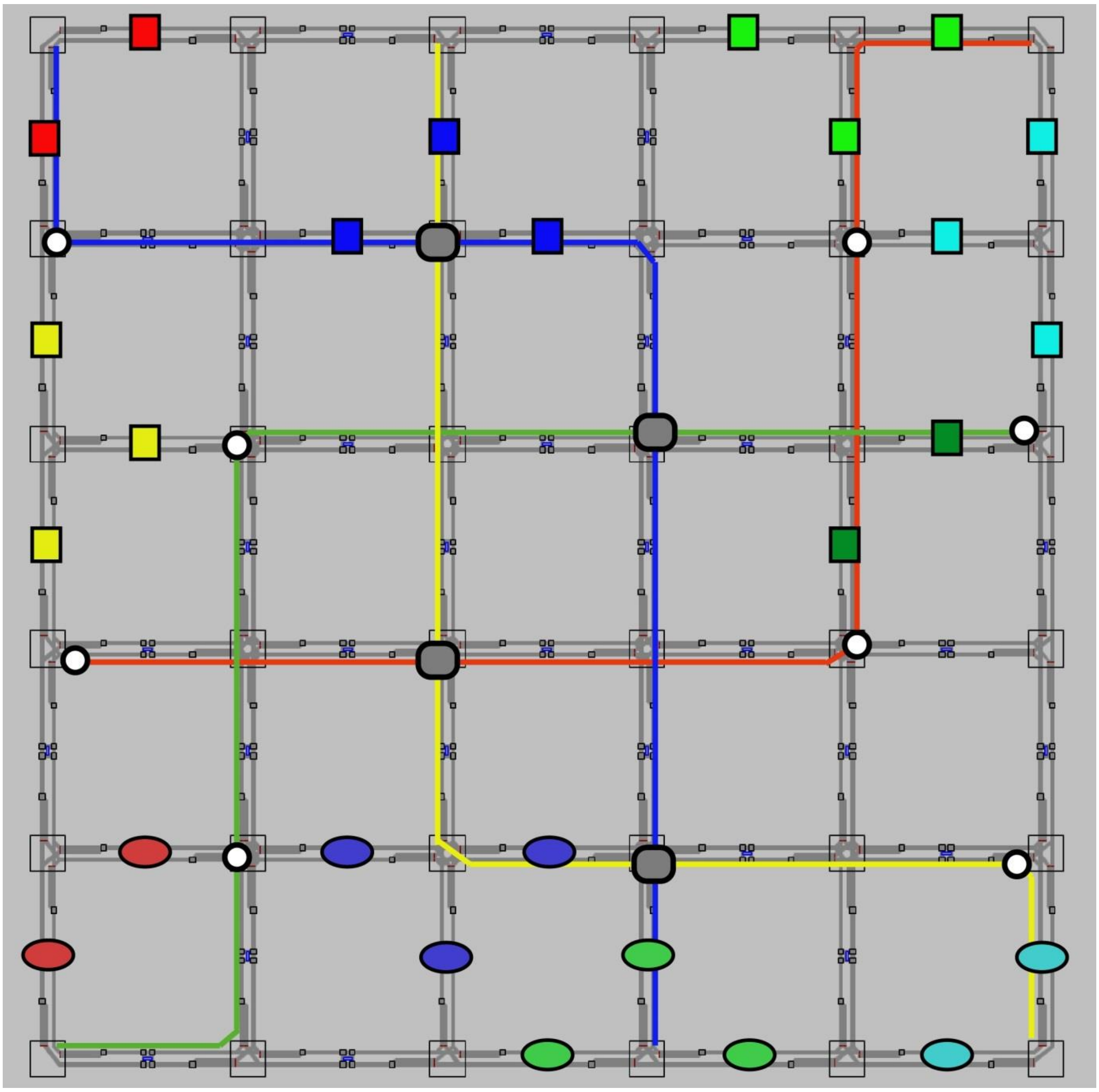
Figure 26 presents the classification for the default network and Figure 27 the corresponding results for the new network configuration. All the oval points represent the origins and all the rectangles the destinations. Basic concept behind the classification is the identification of the available bus stops close to the parking zones.

In the default network the red oval points offer similar accessibility to both stops at the red and the green line despite being at the network edge. Blue oval points are much more advantageous than the red ones because they offer accessibility to both transfer points (blue-yellow and red-yellow lines) as well as to the green line. The green oval points have only one bus stop nearby which is also a transfer point. The purple ones are close only to the southeast stop. Analogous is the idea for the destination points with the blue ones, for instance, being next to a transfer point and the light green being only close to the red line.

The new network classification follows an identical strategy with the red oval points being limited to the only stop at the red line. The green oval points have three stops, the one of which is a centrally-located transfer point. As for destinations, the red points are again limited to a transfer stop whereas the purple destination points have access only to the green line.

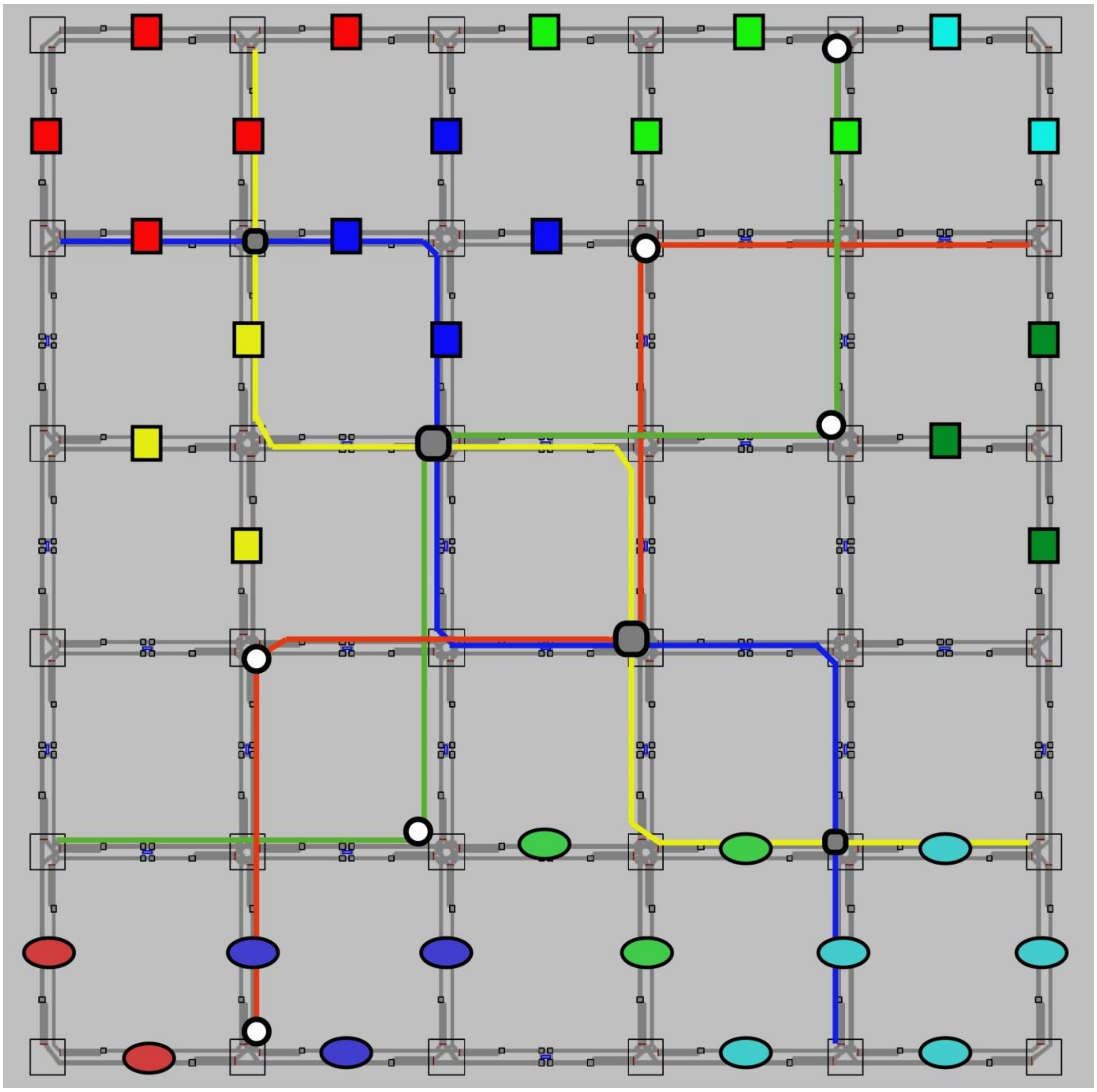
All the aforementioned characteristics illustrate that both classifications provide advantages and drawbacks. More specifically, blue and red oval points are more advantageous for the default network but green and purple ones are more attractive at the new network. As for the destinations, yellow, purple and dark green parking zones are highly connected in the “upstream” configuration. The remaining points are obviously more advantageous in the “new network” configuration.

Figure 26 Accessibility Classification of Default Bus Network



Source: Vissim 6 (2014), Own Configuration

Figure 27 Accessibility Classification of New Bus Network

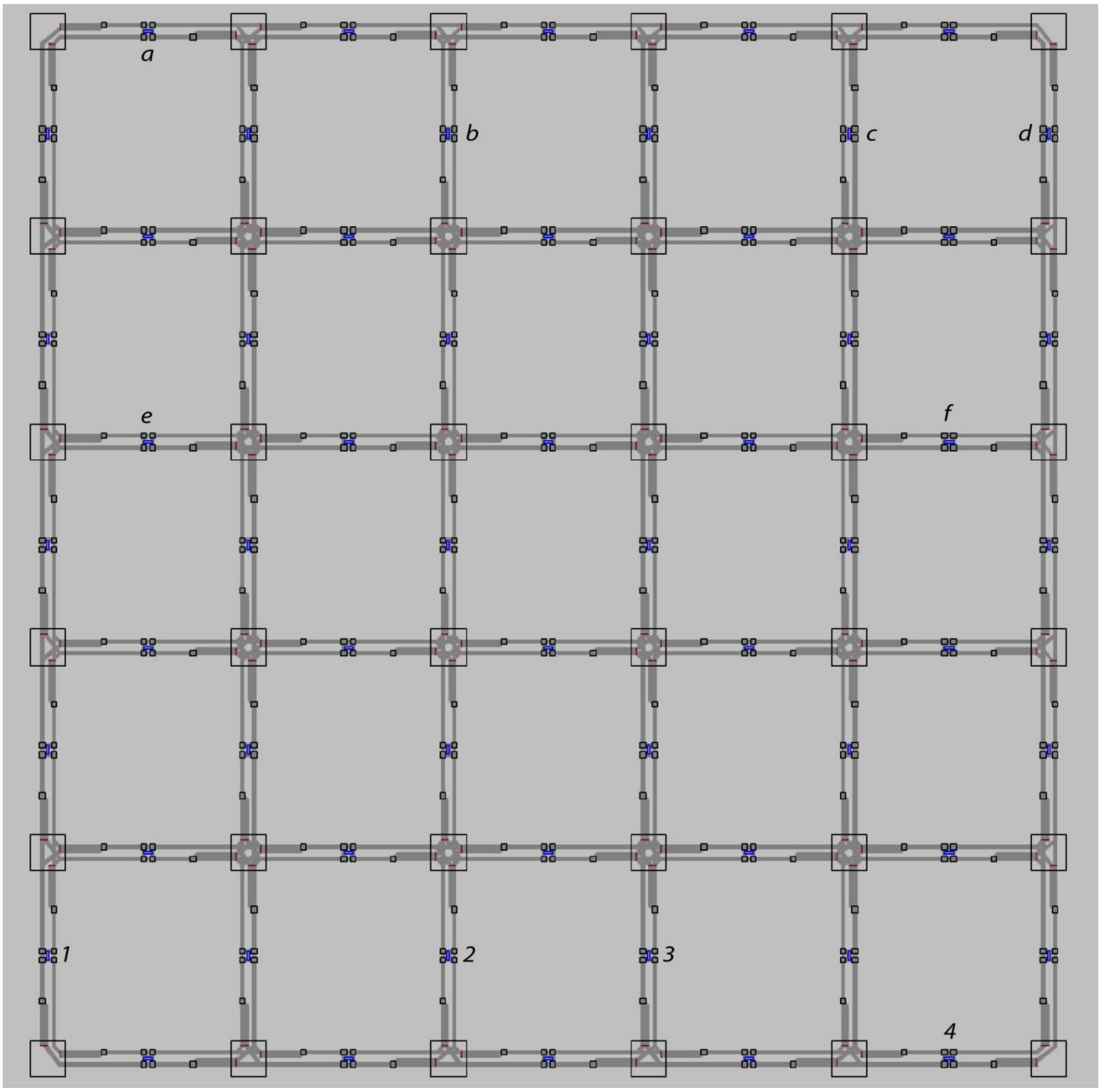


Source: Vissim 6 (2014), Own Configuration

6.1.4 Under-survey Accessibility Region Selection

Figure 28 provides all the under-survey points from the classification. Numbers represent the origins of the network users and alphabetical characters illustrate the destinations points[16].

Figure 28 Under-survey accessibility points



Source: Vissim 6 (2014), Own Configuration

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[16] Additional accessibility is provided for the combination 1-4 due to the difficulties with the tangential users' movements. They would prefer avoiding the crossing through the central area.

6.2 Network Accessibility Results for 10-Min Headways

Table 13 Accessibility Results for 10-Min Headways

O	D	Default Network				New Network				Comparison
		Bus Lines from Origin	Transfer Number	Bus Lines after Transfer	Travel Time (sec)	Bus Lines from Origin	Transfer Number	Bus Lines after Transfer	Travel Time (sec)	Travel Time Difference (%)
1	a	1	1	1	1129	1	1	2	979	13.29
1	b	1	1	1	828	1	1	2	883	-6.54
1	c	1	0	N/A	625	1	0	N/A	733	-17.29
1	d	2	0	N/A	643	1	0	N/A	841	-30.82
1	e	1	0	N/A	432	1	0	N/A	540	-24.99
1	f	1	0	N/A	625	1	0	N/A	744	-19.19
1	4	1	1	1	1033	1	1	2	883	14.53
2	a	1	0	N/A	733	1	1	2	678	7.40
2	b	1	0	N/A	432	1	0	N/A	432	0.00
2	c	1	0	N/A	528	1	0	N/A	517	2.24
2	d	1	0	N/A	636	1	0	N/A	625	1.86
2	e	1	0	N/A	432	1	0	N/A	432	0.00
2	f	1	0	N/A	540	1	0	N/A	420	22.18
3	a	1	0	N/A	625	2	0	N/A	546	12.52
3	b	2	0	N/A	330	2	0	N/A	450	-36.27
3	c	1	1	1	817	1	0	N/A	540	33.84
3	d	1	1	1	828	1	0	N/A	733	11.57
3	e	1	1	1	720	3	0	N/A	420	41.67
3	f	1	0	N/A	432	1	0	N/A	528	-22.25
4	a	1	1	1	1129	2	0	N/A	643	43.07
4	b	1	0	N/A	625	2	0	N/A	546	12.52
4	c	1	1	1	1021	2	1	1	846	17.08
4	d	1	1	1	1129	2	1	1	1039	7.97
4	e	1	0	N/A	744	2	0	N/A	546	26.60
4	f	1	1	1	936	2	1	1	835	10.88
4	1	1	1	1	1033	2	1	1	943	8.72

Source: Own Configuration

Table 13 summarizes all the accessibility results for both configurations and also provides a comparison between travel times among the two networks[17]. More analytically the table includes the origin and destinations, the bus-line number from the closest-to-the-origin bus stop, the necessity for transfer, the available number of bus lines after transfer and the travel time. All these are the crucial characteristics that identify the accessibility of each network. More in depth, it is advantageous for the users to be able to get in two lines at the origin point (mainly home). The majority of the network public users tries to avoid transferring and direct lines are always preferred. When this is inevitable, it is always desirable to have flexibility with various lines at the transfer points. Obviously the most important factor for the users is the travel time which optimally needs to be minimized.

More specifically, new network presents clearly a higher accessibility than the default network. Regarding the travel times, 68% of the combinations provide lower travel times in the new network and two of the combinations give equal travel times. Point 1 is advantageous at the default network with lower travel times due to the two available bus stops. The second under-survey point shows similarities in required time with a tendency for the new network to transfer the passengers quicker. The last two points are also more advantageous for radial the network than the default one. The only exceptions are the movements from 3 to b and f. Default network provides reduced travel times up to 36% for the former transfer but the new network has even higher time differences reaching up to 43% for the 4-a combination.

In addition, the new network offers higher flexibility with the central bus lines and with their co-existence at the main central arterials. Default network provides only in two cases variety regarding the boarding at the origins with two bus lines. On the contrary, the new network offers in nine combinations two bus lines and there is one combination with three available bus lines.

Transferring is a time-demanding procedure which is avoided by public-transport users and direct-movement is always preferred. As shown above, new network offers more direct movements without transfers. Only eight of the combinations demand transfers whereas the “upstream” network necessitates transfers at eleven of the pairs.

On the contrary, default network shows a more uniformly distributed bus-stop organization which results in lower walking distances. The origin points are selected in a way that they equidistant from the closest bus stop. As for the destinations, it is noticed that the radial network demands in more cases 225 m walking to the destination and 75 m is rarer. In addition,

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[17] Proportional difference between the travel times of the two configurations. Positive percentage means that travel time of default network is higher than the new network and vice versa.

there are two combinations which did not fulfil the parameter of not exceeding the 225m-walking distance. 375m is the required walking distance. Default network provides only one corresponding pair with more than 225 m walking distance.

However, despite the aforementioned drawbacks, it can be concluded that the new network is higher accessible than the default one. This outweighs the fact that the network performance regarding the capacities is higher for the default network. As a result, if transport planers invest on private traffic operations, public-transport users would be penalized and vice versa. Therefore there is no optimal decision regarding the public network planning and this relies upon the urban policies and the government prioritizations. The city of Zurich, for instance, selects the bus prioritization and penalizes the remaining vehicle performance with delays due to bus priorities and with space reduction (Menendez & Guler, 2014).

6.3 Sensitivity Analysis for Network Accessibility

Important is the accessibility comparison when the bus input is more frequent. The aforementioned comparison focuses on the 10-Min headways for the bus lines. It is vital to show the corresponding results for 5-Min- and 2-Min headways.

Table 14 provides the aforementioned sensitivity analysis for the network accessibility of 5-Min- and 2-Min headways. First the travel time of 10-Min headway is illustrated in the new travel times to be comparable to the initial one. The table contains only the combination pairs which include transferability. All the direct movements are excluded from the table. It is important to be mentioned that all the direct movements are always preferable and even the frequency increase does not alter the route preferences. This is the reason why the direct movements are excluded from Table 14. Transferability is probably acceptable for long trips, in which the transfer time is negligible compared to the total travel time. The area of this urban network is less than 1 km^2 and travel times vary among 500 to 1000 seconds. As a result, the average waiting time of 150 seconds from the 5-Min headway is substantially high compared to the travel times.

As for the transfer-pair results, it can be extracted that headway increase leads to substantial time decrease. When the headway increases to 5 minutes for the default network the travel time drops from 13 to more than 20%. Higher decrease is provided, as expected, from the 2-Min headways with the decrease varying among 20 and 33%. In contrast to the default network, the time decrease for the new network is not very high due to the already lower travel times for the 10-Min headways. More analytically, frequency of 5 minutes provides time decrease between 7.6 and almost 16% and the one of 2 minutes ranges between 12 and 25%.

Table 14 Sensitivity Analysis Results for Network Accessibility

O	D	Default Network					New Network				
		10 Min Headway	5-Min Headway		2-Min Headway		10-Min Headway	5-Min Headway		2-Min Headway	
		Travel Time (sec)	Travel Time (sec)	Time Decrease (%)	Travel Time (sec)	Time Decrease (%)	Travel Time (sec)	Travel Time (sec)	Time Decrease (%)	Travel Time (sec)	Time Decrease (%)
1	a	1129	979	13.29	889	21.26	979	904	7.66	859	12.26
1	b	828	678	18.11	588	28.97	883	808	8.50	763	13.60
1	4	1033	883	14.53	793	23.24	883	808	8.50	763	13.60
2	a	N/A	N/A	N/A	N/A	N/A	678	603	11.06	558	17.69
3	c	817	667	18.37	577	29.39	N/A	N/A	N/A	N/A	N/A
3	d	828	678	18.11	588	28.97	N/A	N/A	N/A	N/A	N/A
3	e	720	570	20.82	480	33.32	N/A	N/A	N/A	N/A	N/A
4	a	1129	979	13.29	889	21.26	N/A	N/A	N/A	N/A	N/A
4	c	1021	871	14.70	781	23.51	846	696	17.72	576	31.90
4	d	1129	979	13.29	889	21.26	1039	889	14.44	799	23.11
4	f	936	786	16.02	696	25.63	835	685	17.97	595	28.76
4	1	1033	883	14.53	793	23.24	943	793	15.91	703	25.46

Source: Own Configuration

In total, it can be noticed that the lower the travel times for scarce frequencies, the lower is the time decrease for higher frequencies. Another important outcome is that the new network is more efficient than the default one for the following reasons:

- New network provides more direct movements compared to the default network.
- Travel times are overall lower at the new network than at the default one. More specifically, travel times of default network for 5-min headways are comparable to the 10-min headways of the new network. In addition, there are result similarities in-between the default-network-2-min headways and the new-network-5-min headways. This means that the default network requires much higher frequencies to guarantee the same satisfaction with the new network.

Another crucial indication from the existing results is the fact that 5-Min headway is probably the optimal solution for the frequency selection. The travel time decrease for the 2-Min headway is not analogically high and consequently it may be overestimated. Direct movements remain constant for both headway and only transfers show a reduced travel time. To be more specific, this selection requires reasonable funds for the staff, the vehicles, the infrastructural and the operational costs without providing the expected result. Passengers would be either way satisfied with the 5-min travel times even though they are slightly higher than the 2-min. This high bus frequency might be an exaggeration considering that the supply might be much higher than the demand.

6.4 Accessibility, Passenger & Vehicular Capacity Discussion

Accessibility introduction covers the whole bus operational effects topic. Bus operational effect identification showed that network operations are negatively affected from buses. However, buses transport many passengers on a daily basis and this compensates for the capacity loss. They offer potentially higher passenger output than the no-buses operation. Passenger attraction and high passenger output depend, though, highly on the bus-line accessibility.

Capacity decreases linearly with the bus courses for the default and the new network. The decrease reaches 13% for the default and 25% for the new network. If this would be the single variable for the network selection, default network would have been preferred. However, as mentioned above, capacity loss can be compensated from the passenger number. Default network requires between 4 and 8 passengers whereas the new network needs 11 passengers for the 5-Min, 4-Min and 3-Min headway. 2-Min headway shows the highest passenger requirement and more specifically 15. A third parameter for the optimal network selection is the accessibility. Despite capacity loss and consequent higher passenger requirements, new network provides significantly higher accessibility. It offers more direct movements, less transfer requirements and higher flexibility for transferring than the default. Total travel time in the new network is mainly lower than the default. This means that it can be more probable to transport more bus passengers than the default network. To be more specific, the accessibility advantages at the new network can easier attract the 11 passengers for the peak-hour headways. Although the default network needs only 8 passengers at these headways, it is more demanding to achieve it due to the lower accessibility. Referring to the 2-Min headway, results are opposite. New network necessitates 15 passengers and default only 6. Accessibility benefits from the new network are not so high that they attract the required bus passengers. Moreover, 2-Min headway is a very frequent bus operation and it is very demanding to cover these passenger requirements every two minutes. In addition to this, network accessibility profits from this headway are almost negligible. Travel-times are only reduced at transfer points but the time decrease is high enough to cover the 2-Min passenger requirements. All this analysis shows that 5-Min headway for the new network configuration would be one of the optimal network solutions. It guarantees higher passenger output from the accessibility privileges and capacity loss can easier be compensated.

All this discussion provides qualitative comparisons and indicates that optimal bus operation depends on the appropriate headway and network configuration. It is useful to understand that bus frequency increase is not the one-way solution and optimal results can also be extracted from more rare headways. Important parameter is always the network design. Therefore priority should always be given to the most beneficial network configuration that covers spherically the passenger requirements.

7 Conclusions

Project goal is the effect analysis of bus operations on urban networks. Bus operational effects and network-performance decrease is the incentive of this survey extension to the passenger capacity considering the higher bus full factor. Additional incentive arises from the crucial-for-the-passengers network accessibility, which balances the vehicular decrease with the public-transport users' attraction.

Simulation process selection for the bus-effect identification resulted to be successive. Grid-network organization with bus-input and with DTA-application method illustrated clearly the bus operational effects despite the traffic-demand-determination requirements. First, the two-way street with protected left-turns and one lane per direction network is a usual urban category with potential direct movement ability to all the intersections. Direct movements offer average-trip shortage (Gayah & Daganzo, 2012). This realistic configuration with one lane per direction burdens the traffic operations more significantly than with two or more lanes per direction. Consequently the remaining traffic is more highly affected. Second, the network size selection with 6 X 6 intersections is a balance between the macroscopic analysis and the time-demanding DTA implementation. Infrastructural correct choices are also the long left-turn pockets that enable the vehicle accumulation and avoid blocking of the through moving vehicles. This is accompanied by the proportional-to-this-length green time phase. Lights should be shed on the conflict-area obstacle settlement. This obstructs the opposite-direction "over-passing" when vehicles block the intersections links due to spill-back effects. Initial simulation attempts without conflict-area obstacles failed to present the bus operational capacity decrease. For instance, the "downstream" configuration showed initially higher than the no-buses results.

Infrastructural selection success is followed by representative bus operational effects. Simulations showed reduced traffic performance with capacity decreases and density increases for all configurations and headways. Exception is only the network with the 3 bus-stops for 5-Min headway. Possible explanation for this output is the one-random-seed simulation execution. Additional simulation runs would possibly downgrade the unexpectedly high vehicle network performance. Other than this, traffic performance is affected by bus operations dependent on the network and on the selected headway. Referring to the headways, it is found out that 10-Min headway is non-frequent and the created due-to-buses perturbation dissipates in-between the headway period. As a result, capacity drops only at most 5% and the density increases slightly with expected small speed reductions. Results tend to show more significant effects for the 5-Min headways with capacity decreases in-between 5 and 9%. More substantial are the effects as the frequency increases to 4-Min- and 3-Min headways. Result similarity is provided among them with up to 7% capacity decrease from the 5-Min headway. 2-Min headway is a consequential bottleneck for the vehicle operations with tremendous capacity decreases reaching up to 27%. Important outcome is the performance decrease from the closest headway (3 minutes) which reaches 13 and 15% for the vulnerable "downstream" and new network respectively. Generally, 10-Min headways show comparable results to the no-buses simulation and 5-Min headway initiates illustrating traffic-performance effects. 4-Min and 3-Min-headways provide negligible differences among themselves but reasonable from the 5-Min and the 2-Min headway illustrates immense traffic operational effects.

Overall simulation process verified the bus operational effects due to headway increase. It also showed how bus-line alterations and bus stop locations can affect significantly the simulated vehicle output. Only the bus-stop transition from upstream to downstream-of-intersections location causes reasonable network-performance effects. Analogous are the traffic effects when the bus lines follow a denser, more central and radial distribution. On the contrary, bus operations provide more negligible capacity effects when bus stop reduction is implemented in the network. Similar negligible effects are illustrated when bus stops are transited from the intersections to the middle of the road links.

Capacity and density results provide the average network speeds. It is received that the 10-Min headway shows higher than-the-no buses speed results. This derives from the high density level of the no-buses result despite the high vehicle output. The remaining headways provide all speed reductions which increase as the headways decreases. 2-Min headway provides, expectedly, the lowest speeds with the "downstream" and the new network showing the lowest results. Additional survey outcome is the capacity decrease-bus courses correlation. It is illustrated that the capacity decreases proportionally to the bus courses addition in the network. The linear correlation is obvious and it is almost absolute for the default, the "downstream" and the new network. High correlation values are also shown for the remaining networks bus not as high as the previous ones. It is provided that "downstream" shows the highest performance effects and it is followed by the new network. Default network is the intermediate one and is more affected than the 3-stop network. "Middle of road" network shows comparably the highest traffic performance.

Vehicular capacity level can be compensated from the increased bus-passenger capacity due to the higher bus full factor. Therefore bus-passenger requirement identification equalizes the required passenger output of the bus simulations with the corresponding no-buses result. It is derived from the aforementioned calculations that the more frequent the bus operation, the higher is the passenger demand for this fulfilment. More analytically, there is a linear correlation between the capacity decrease and the bus passenger requirement. 10-Min headway provides the lowest passenger demands. Similarities are presented between the 5-Min, 4-Min and 3-Min headway with the passenger demand ranging between 7 and 11 passenger per course (exception is the 4-Min headway “downstream” network). Considerably higher are the results for the 2-Min headway especially for the “downstream” and the new network which necessitate more than 15 passengers.

High frequency attracts always more passengers and offers ideal transferability but the argumentative issue is the frequency overestimation. It is infeasible to collect 15 passengers in every bus course when they travel with 2 minutes difference. On the contrary, transferability is also acceptable for the 5-Min headway with average waiting times of 2.5 minutes at the transfer points. Although this operation is not as attractive as the previous one, it is more realistic to attract 7-11 passengers at every 5-Min course. Bus-passenger requirement observation illustrated requirement similarities for the 5-Min, 4-Min and 3-Min headways. The last headway is theoretically more attractive but practically the average transfer-time difference is only 1 min with the 5-Min. This is a negligible difference for a long total travel time of more than 30 minutes. In contrast, 3-Min operational costs are disproportionately-to-the-transfer-time-benefits higher than the 5-Min operation. Conclusively, it is necessary to search for the optimal headway that compromises the passenger demands with the operational costs.

Another factor that would lead to passenger-attractiveness increase is the network accessibility. Accessibility comparisons are partially provided between the default and the new network. The latter presents higher accessibility with more direct and quicker connections in-between the O-D network points. Headway increase from 10 to 5 minutes offers 7-20% reduced travel time. This increase is even higher for the 2-Min headway reaching 30% travel time decrease. However, it should be mentioned that there is no transition from direct movement to transfer combination despite the headway increase. Possible explanation for transfer avoidance is the network size and the small travel times in the current network. Transfer times tend to be negligible for longer travel times (longer than 30 minutes). Headway increase continues providing lower travel times for the new network than for the default one. This balances and outweighs the lower capacity results. Bus network selection between the two networks is a demanding procedure and should be based on passenger input-output data at the bus stops. Transport planers’ decision is complex and further infrastructural and potential development investigation is crucial for the bus network determination.

In conclusion, bus operations depend mainly on three factors, the vehicular output, the passenger output and the bus network accessibility. The current survey approaches quantitatively the vehicular decreases with the simulation processes. Initial results would elucidate that network with higher vehicular effects, for instance the “downstream” and the new network should be avoided. However, this contradicts to the passenger output in combination with the network accessibility especially for the new network. It is logical that capacity decrease requires higher passenger numbers. The passenger-requirement differences between the default and the new network are not substantially high. They can easily be compensated from the privileged new network accessibility. Headway selection is also important. 5-Min-headway application seems to be the optimal selection both for the default and the new network. Passenger requirements for 2-Min headway are high enough and they cannot be covered from the higher corresponding accessibility. All this qualitative discussion summarizes that the parameters for the bus network design. Bus-line network incorporation requires an appropriate bus-line design that guarantees low traffic operational effects and higher network accessibility. The latter satisfaction maximizes the passenger output. Last important parameter is the operational costs that need to be minimized. This happens only with the appropriate headway selection. Headway selection is responsible for the operational cost minimization and for the passenger attractiveness sustainability.

8 Further Analysis

Current survey identified successfully the bus operational effects on urban networks, correlated the decreased network vehicle performance with the passenger capacities and introduced the network accessibility for the users' satisfaction. However, the analysis conclusion raised new topics and various directions for further analysis.

Infrastructural extensions can be provided to the project. First, network size modifications and analyses with longer streets and more intersections can be implemented. Second, effects can also be investigated for the one-way and the two-way streets with prohibited left turns. Furthermore, all network infrastructures can be both simulated for one and for more lanes per direction with potential additional left-turn lanes. Moreover, there is a reasonable issue of space allocation and it is useful to extend the analysis to partial dedicated bus lanes. Additional contemporary tendency in real networks, for instance in the city of Zurich, is full bus priority at intersections. This is an important topic because bus prioritization causes traffic-signal-allocation fluctuations. It is also responsible for the diverse vehicle accumulation which creates non-uniformly distributed spill-back effects.

As for the simulations, computational load for the DTA application limited the simulation processes. Therefore it is vital to simulate additional random seeds for each case in order the O-D randomness to be eliminated.

Additional bus networks can be investigated with new radial, ring and raster designs. This can provide a clear and safe conclusion regarding the various operational-to-the-traffic-performance effects. This network variety especially for larger infrastructure would bring more realistic urban networks with more and longer bus lines.

The topic, though, that arises great possibilities for further analysis is the passenger capacity in combination with the network accessibility. All the existing information can be regarded as introduction to the balance of the network-performance reduction. Passenger capacity can be analysed in depth and there are potential examinations about the optimal headway that significantly satisfies the passenger requirements. This can be combined with the existing-for-each network accessibility in order to approach the topic more quantitatively. Network accessibility needs definitely to be investigated for all the O-D pairs and not selectively for some regions. Another factor that needs to be included in this analysis is the bus-line operational costs. For instance, it is ineffective to find out that the 2-Min headway is the optimal solution for a network if cost is excluded from the solution search. This headway may be economically inefficient and consequently it should be avoided. Generally, transport companies invest large amounts on annual operational costs and a new bus-line design is always accompanied by the additional operational investments. Therefore cost incorporation is an argumentative issue and cannot be excluded from further analyses.

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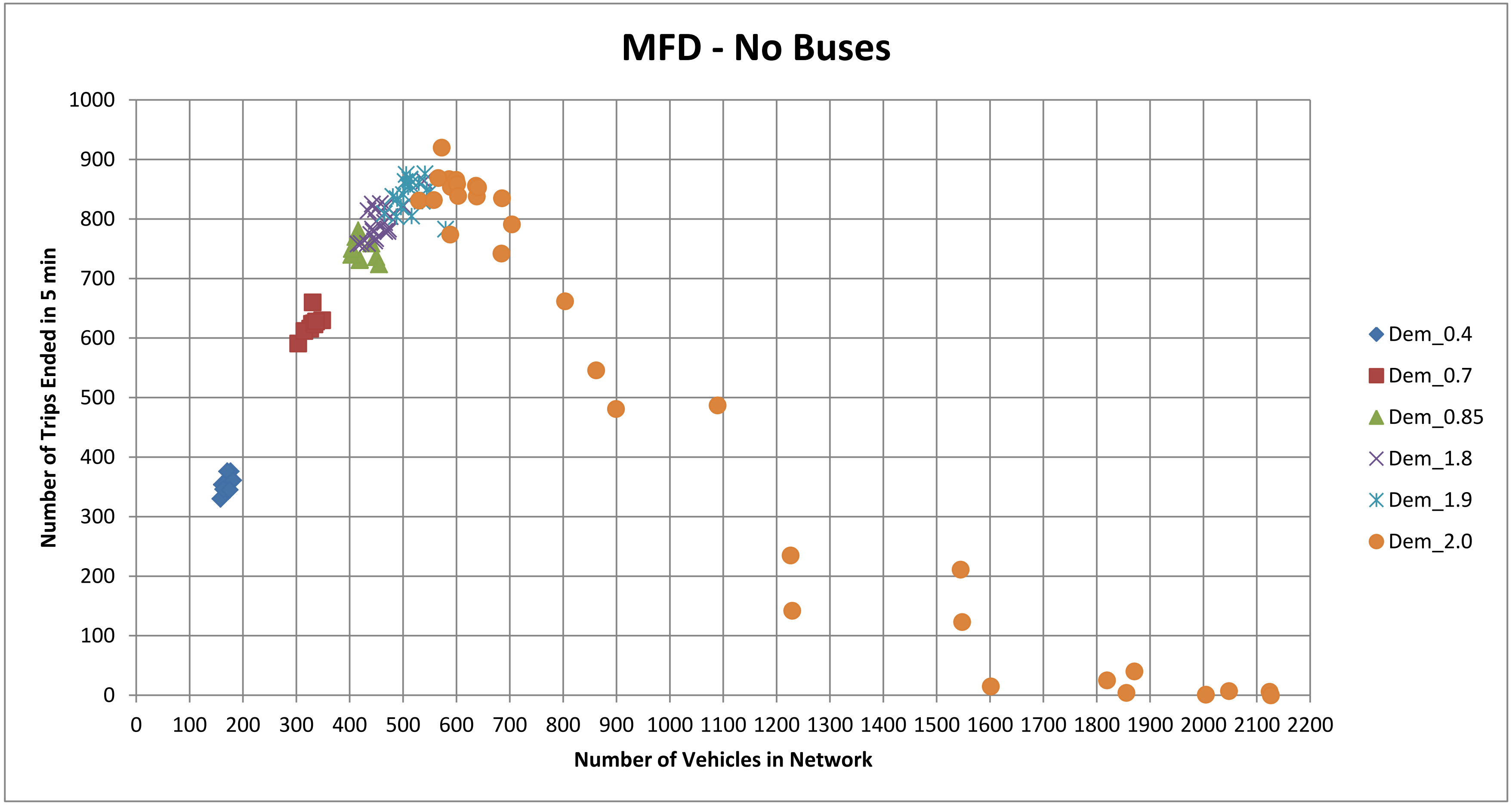
Appendix

Appendix Content

List of MFD Diagrams

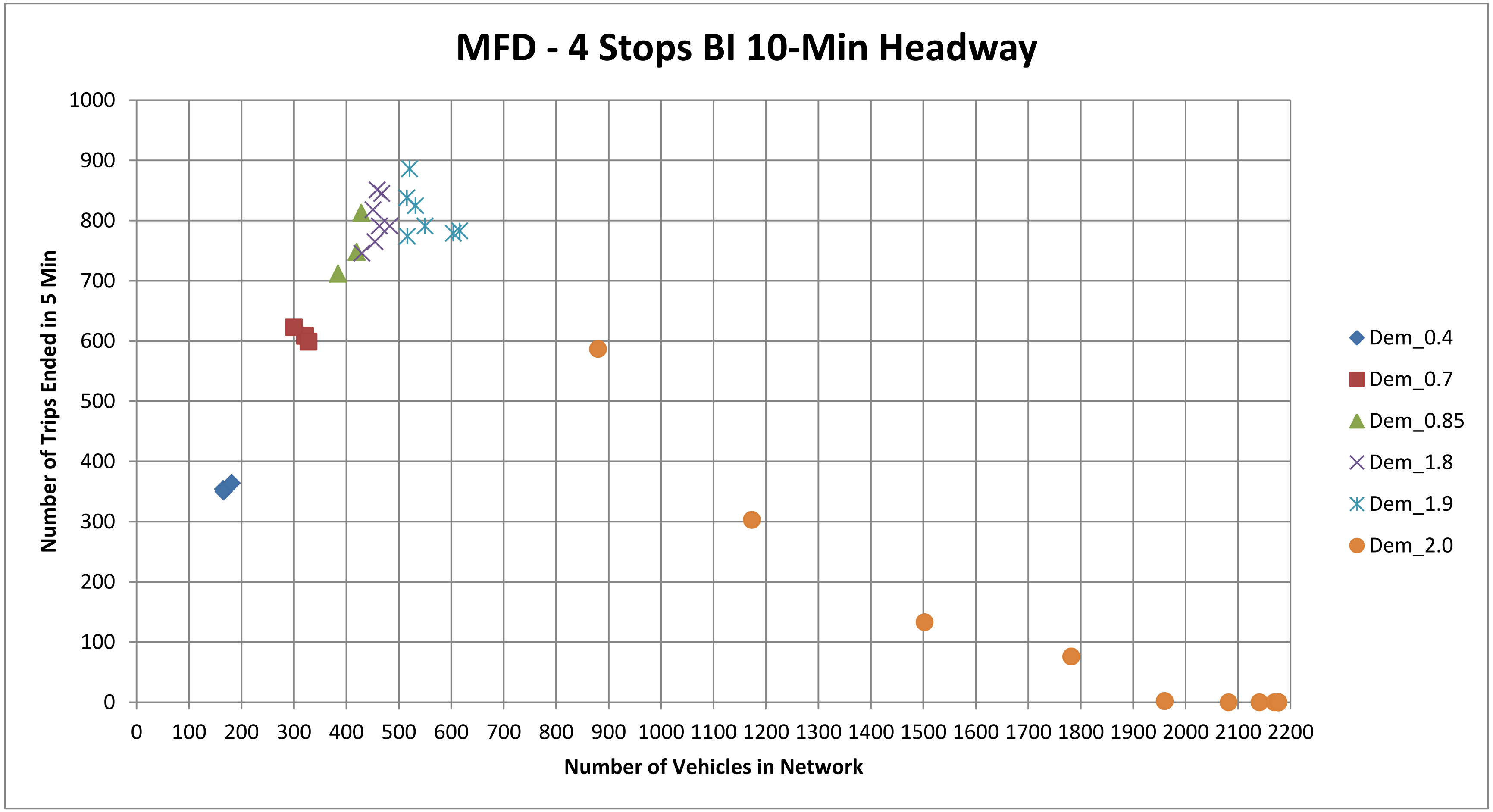
List of Accessibility Tables

A 1 MFD of No-Buses Implementation



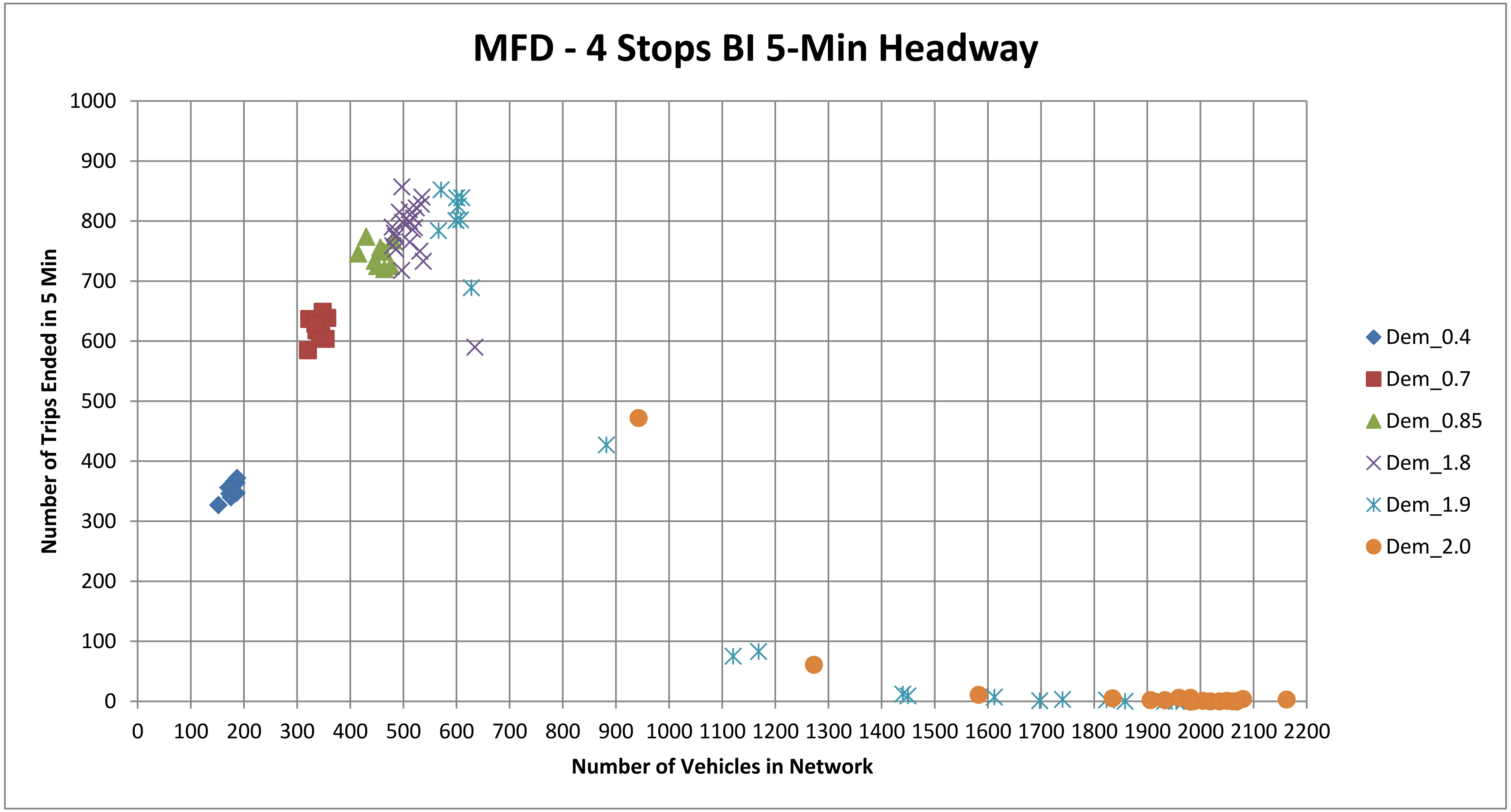
Source: Vissim 6 (2014), Own Configuration

A 2 MFD of Bus Stops Upstream of Intersections for 10-Min headway (Default Network)



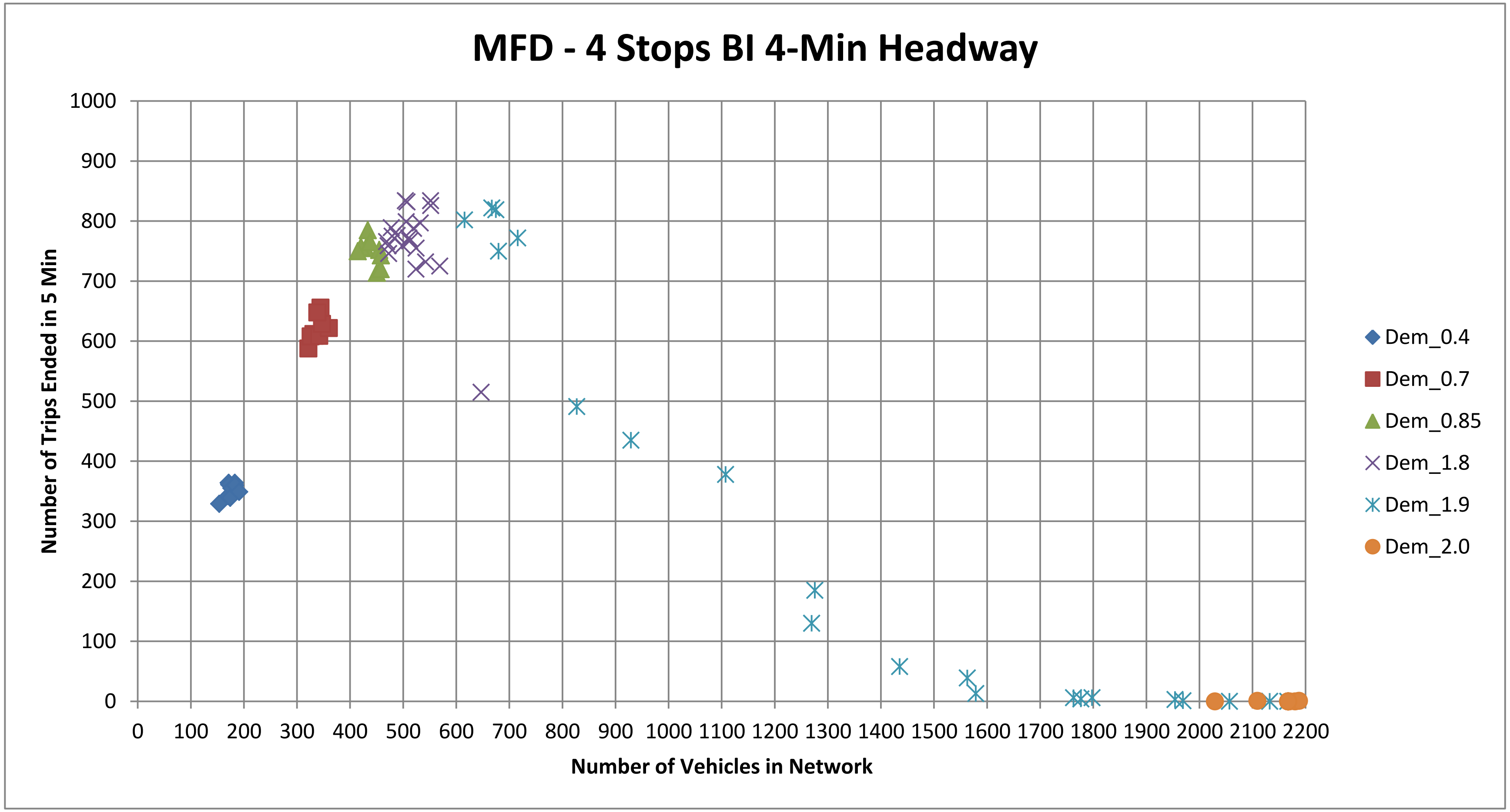
Source: Vissim 6 (2014), Own Configuration

A 3 MFD of Bus Stops Upstream of Intersections for 5-Min headway (Default Network)



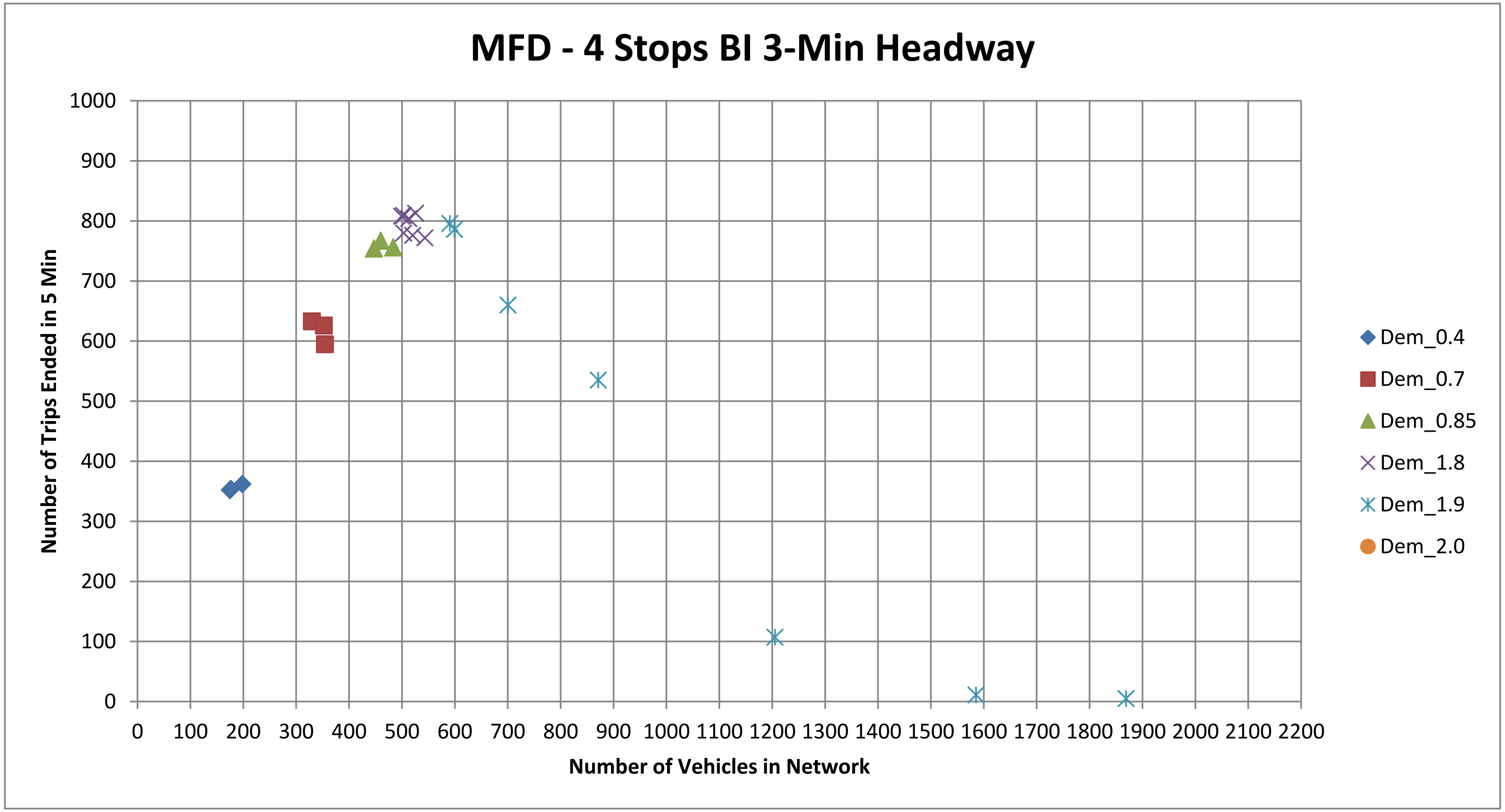
Source: Vissim 6 (2014), Own Configuration

A 4 MFD of Bus Stops Upstream of Intersections for 4-Min headway (Default Network)



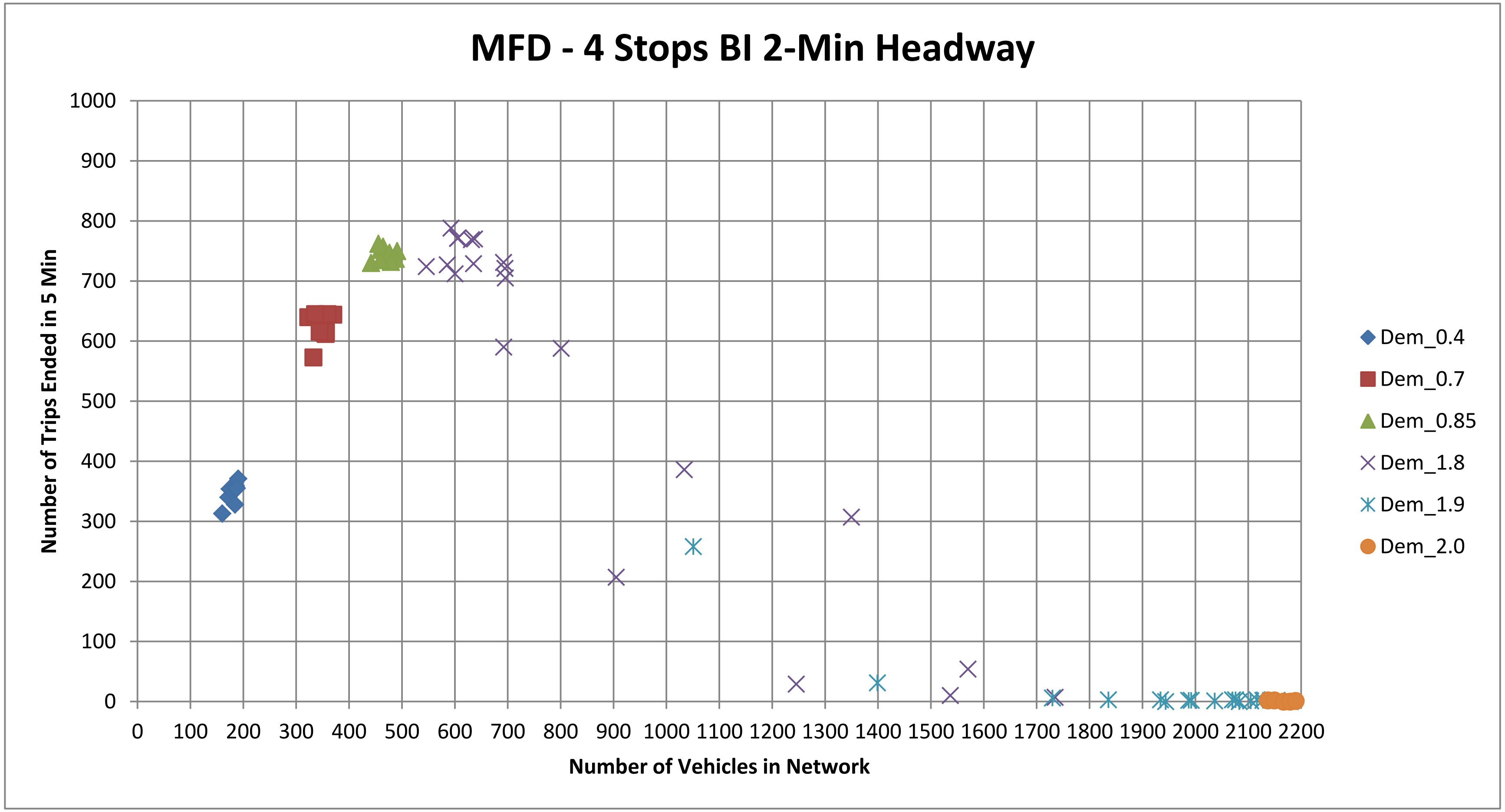
Source: Vissim 6 (2014), Own Configuration

A 5 MFD of Bus Stops Upstream of Intersections for 3-Min headway (Default Network)



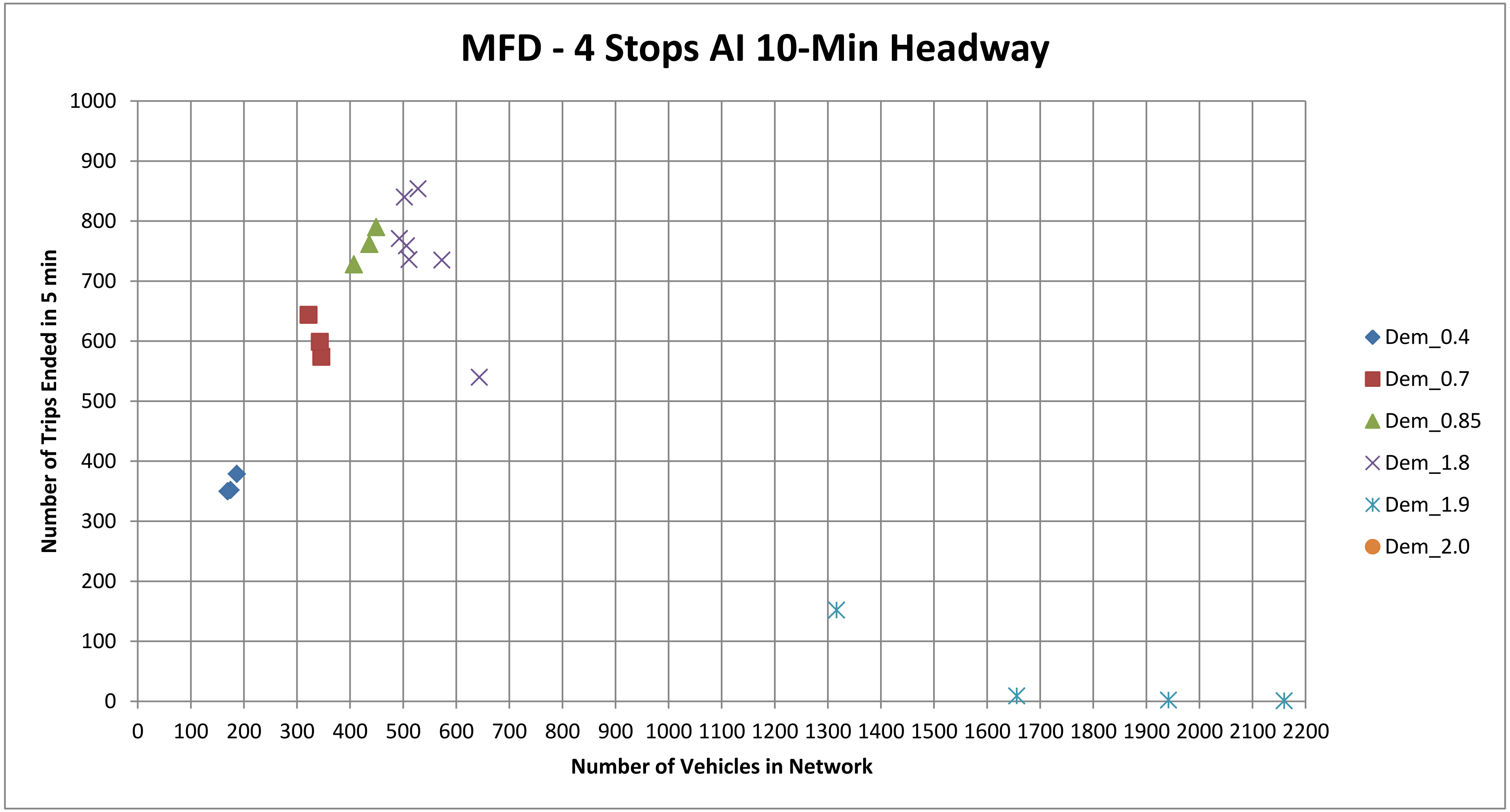
Source: Vissim 6 (2014), Own Configuration

A 6 MFD of Bus Stops Upstream of Intersections for 2-Min headway (Default Network)



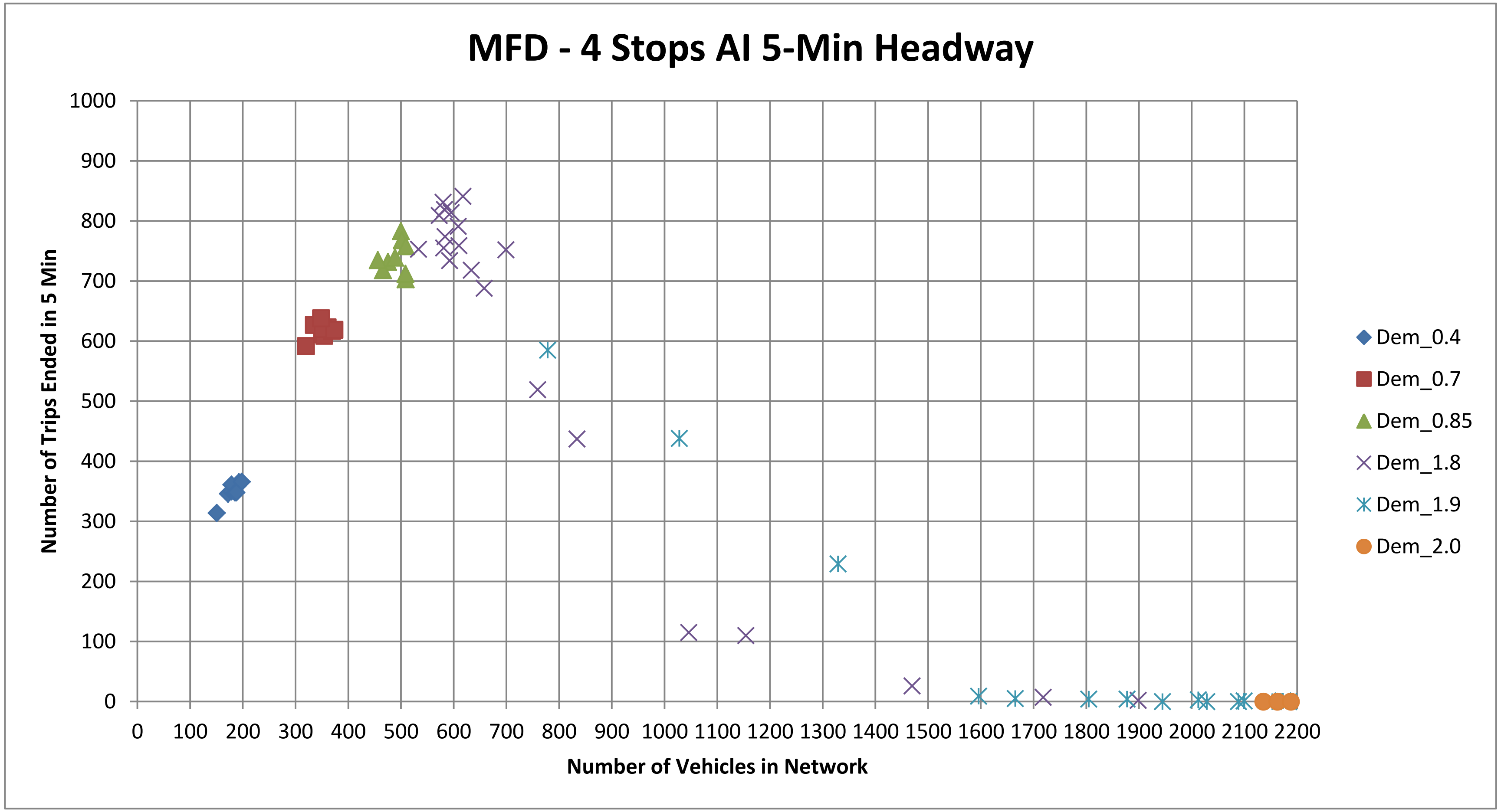
Source: Vissim 6 (2014), Own Configuration

A 7 MFD of Bus Stops Downstream of Intersections for 10-Min headway



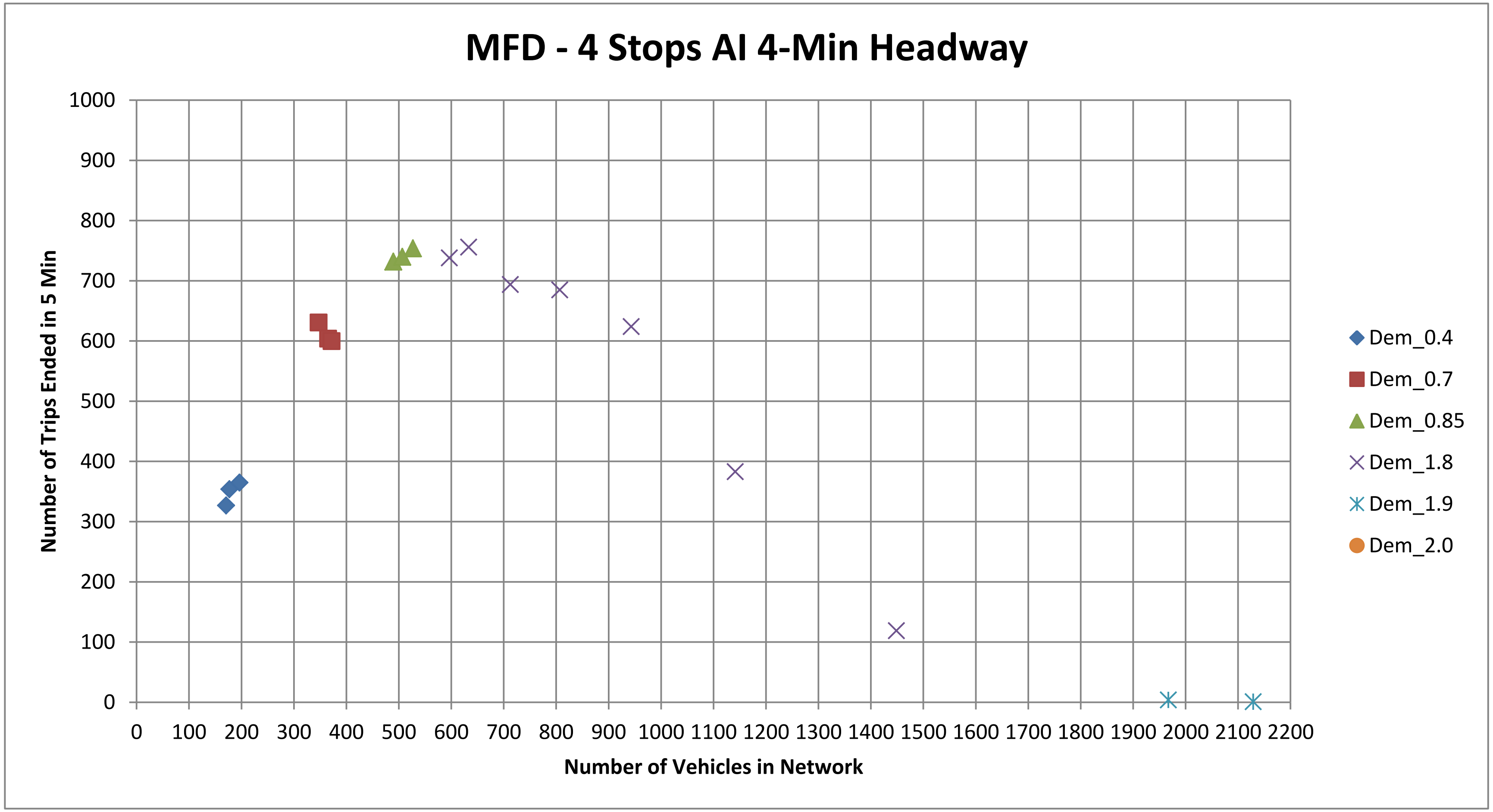
Source: Vissim 6 (2014), Own Configuration

A 8 MFD of Bus Stops Downstream of Intersections for 5-Min headway



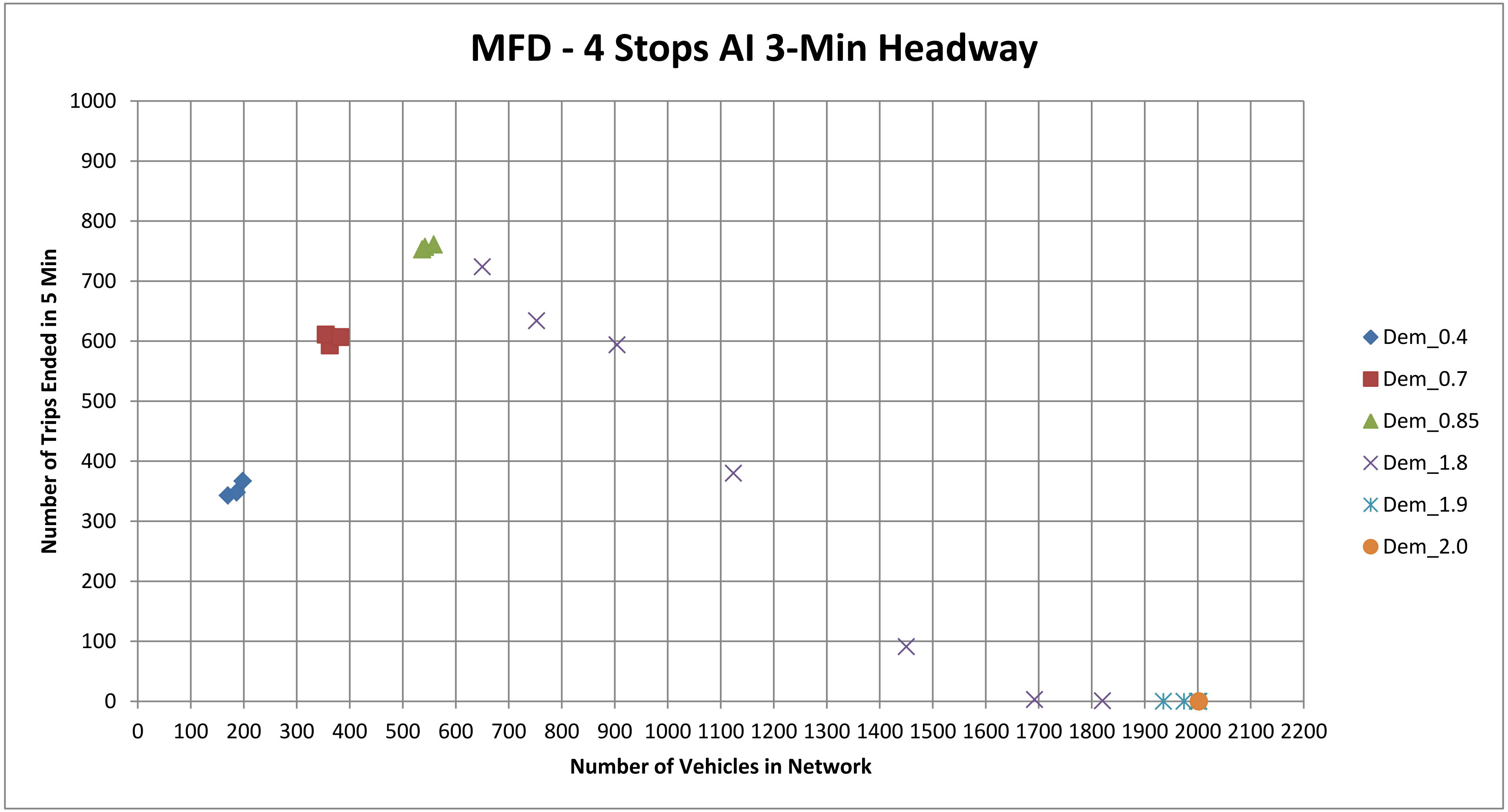
Source: Vissim 6 (2014), Own Configuration

A 9 MFD of Bus Stops Downstream of Intersections for 4-Min headway



Source: Vissim 6 (2014), Own Configuration

A 10 MFD of Bus Stops Downstream of Intersections for 3-Min headway



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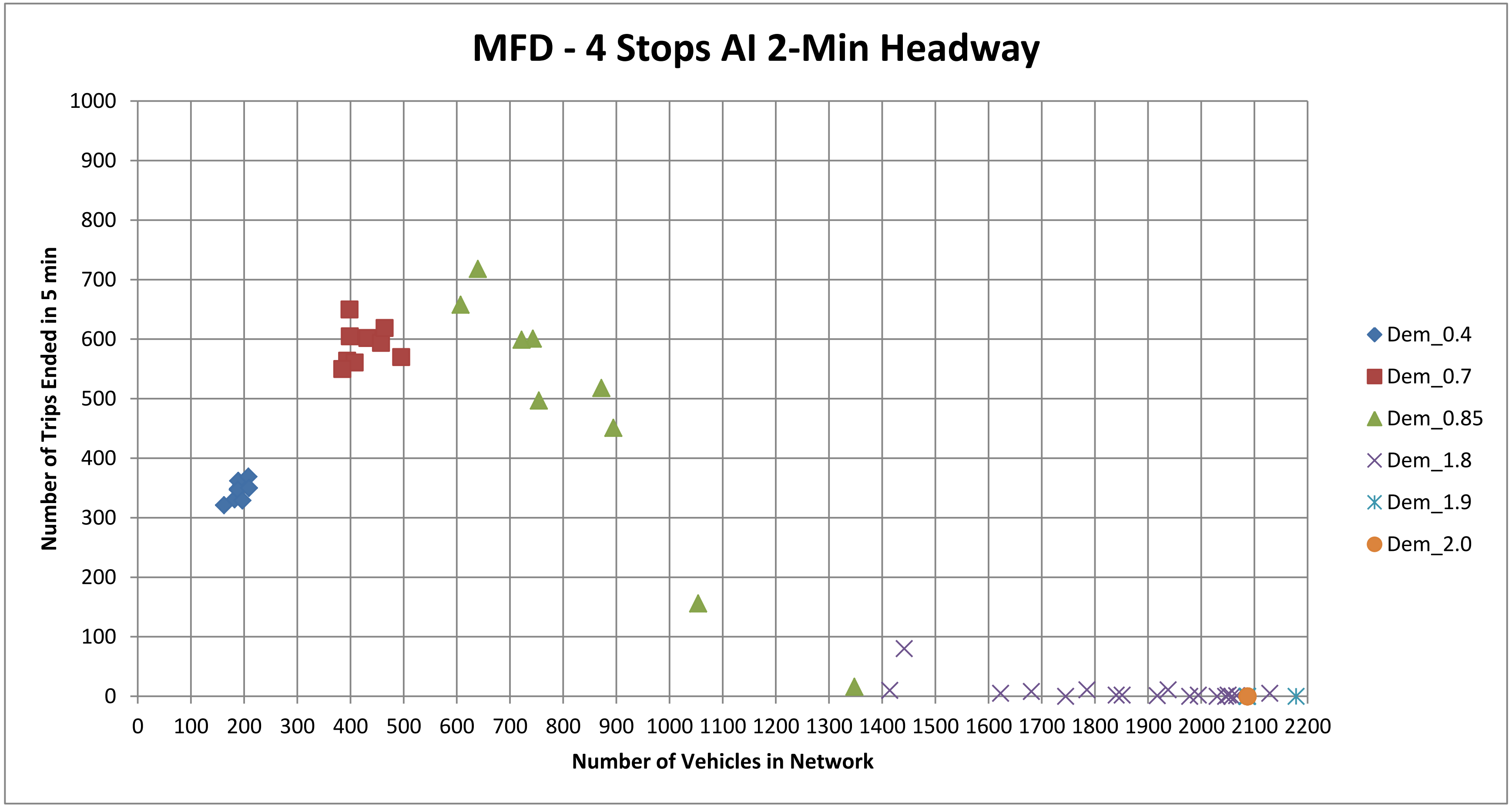
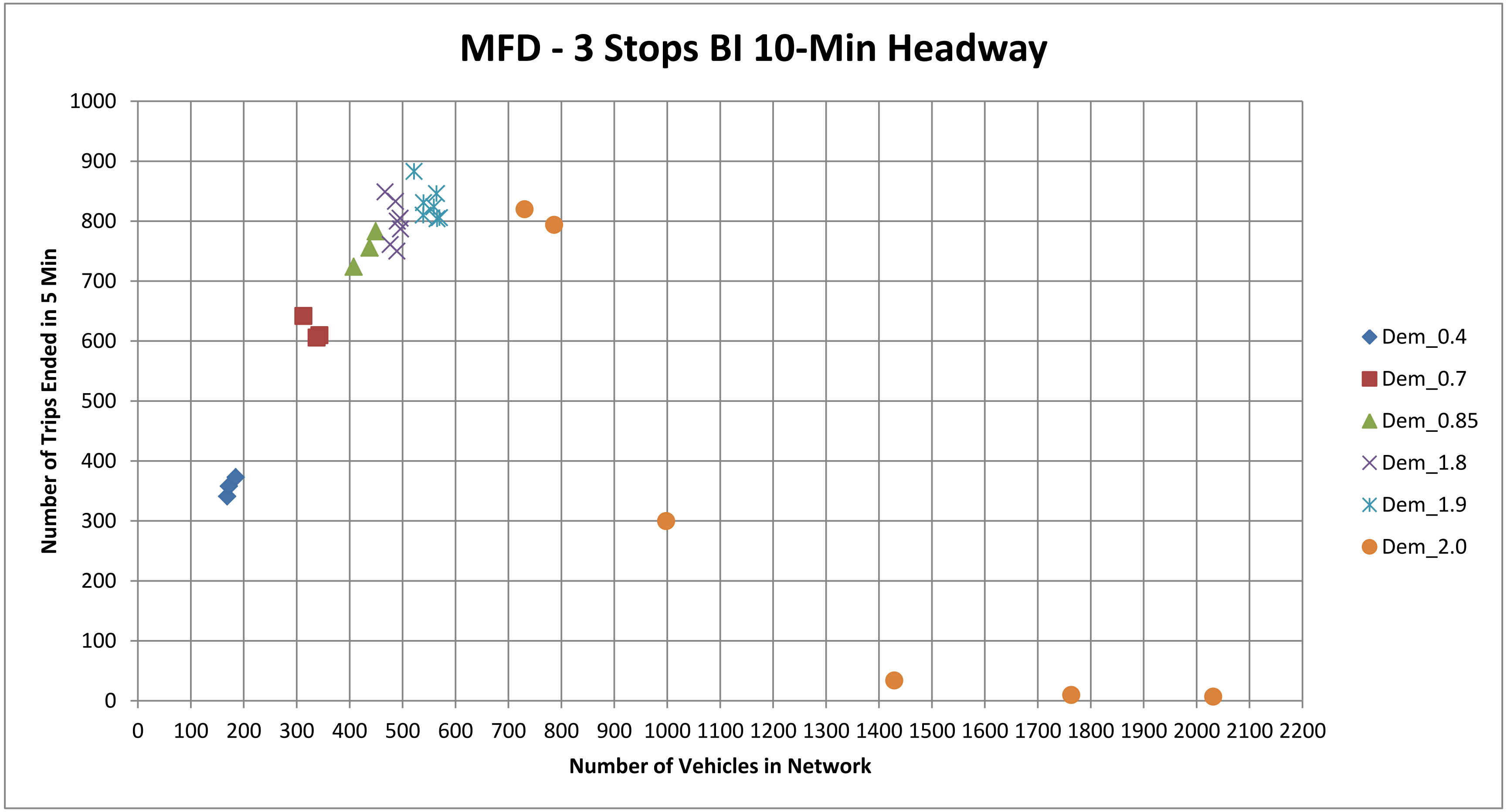
A 11 MFD of Bus Stops Downstream of Intersections for 2-Min headway



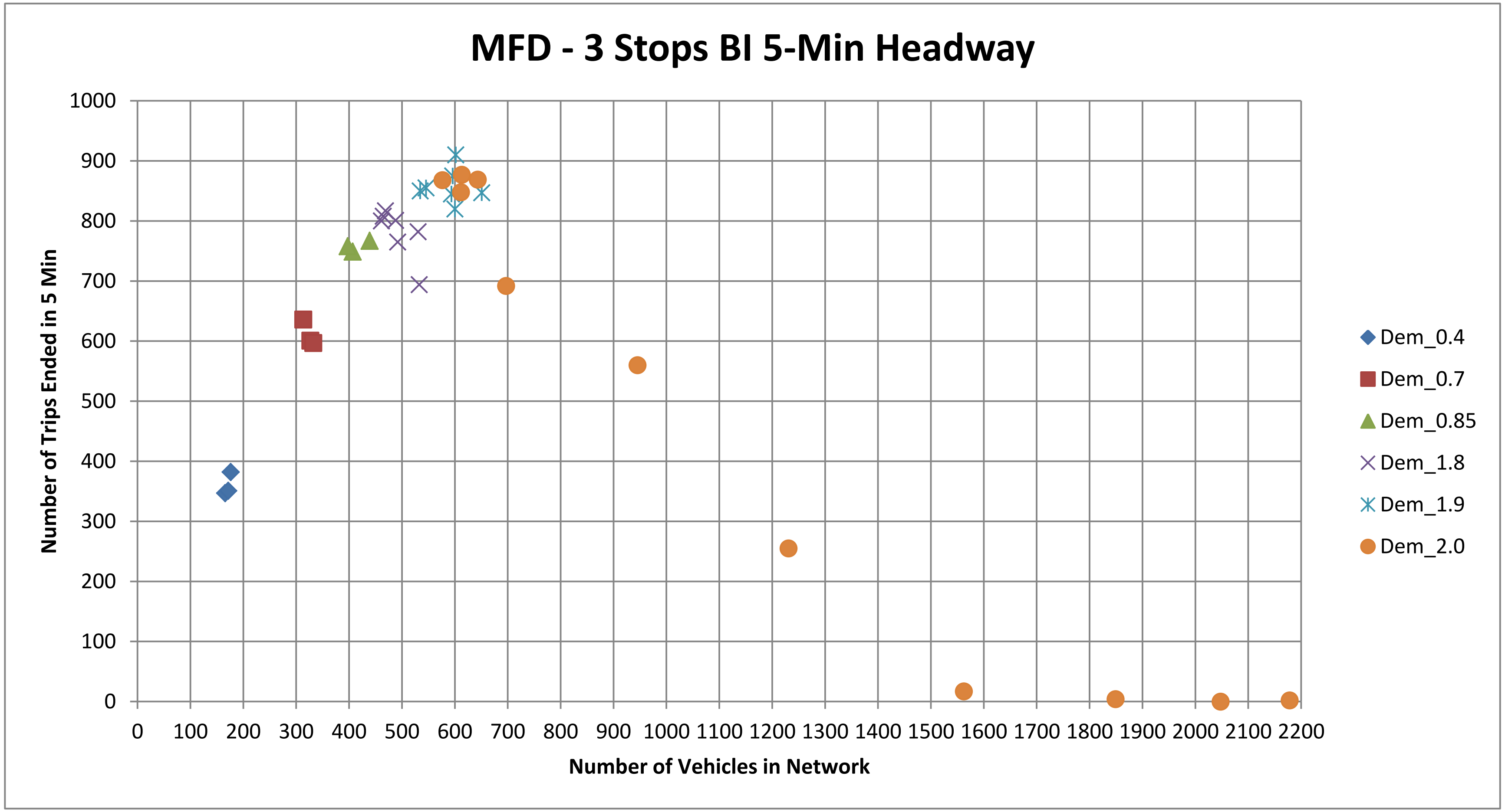
Source: Vissim 6 (2014), Own Configuration

A 12 MFD of Bus Stops Upstream of Intersections (3 Stops) for 10-Min headway



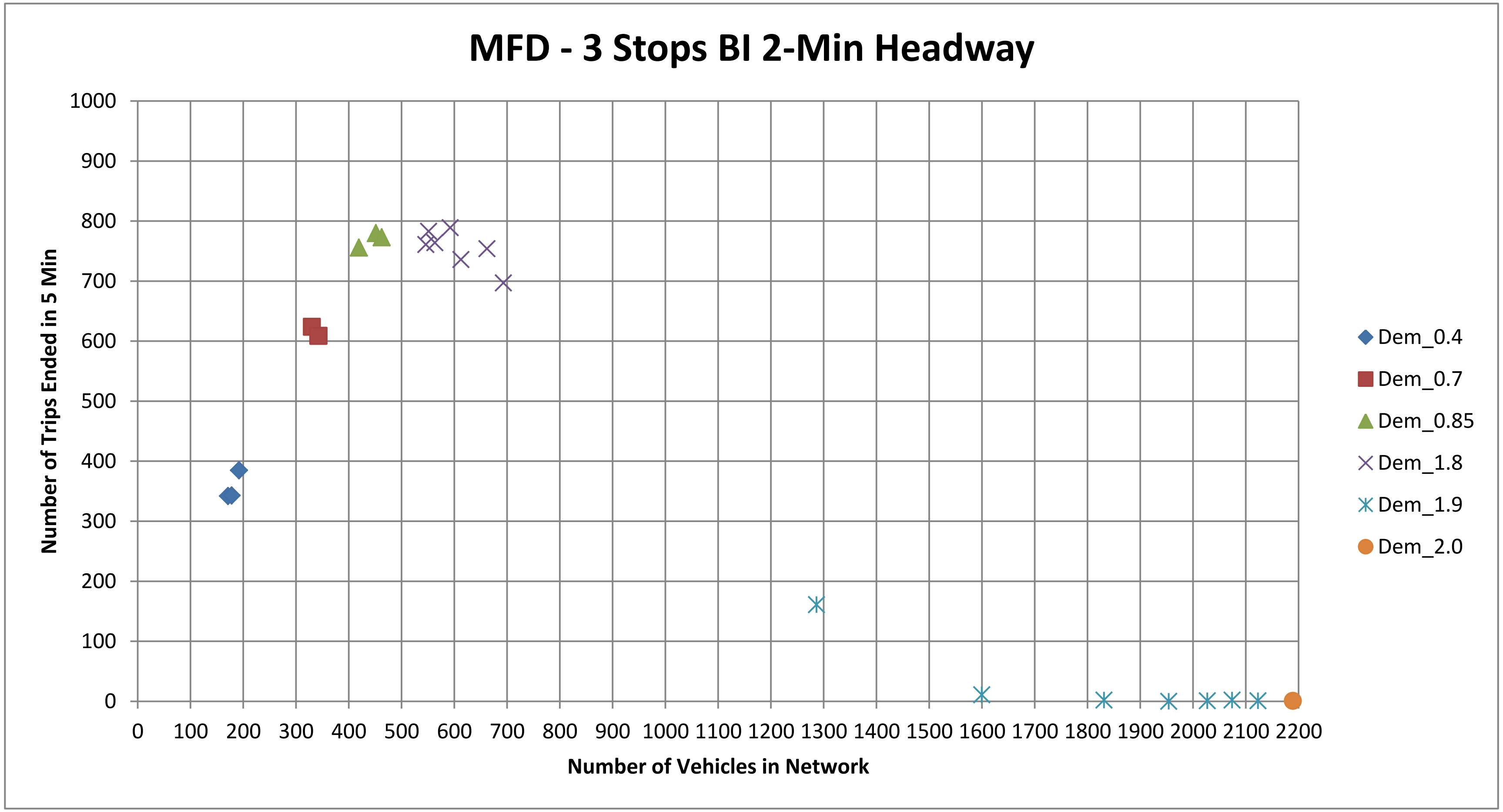
Source: Vissim 6 (2014), Own Configuration

A 13 MFD of Bus Stops Upstream of Intersections (3 Stops) for 5-Min headway



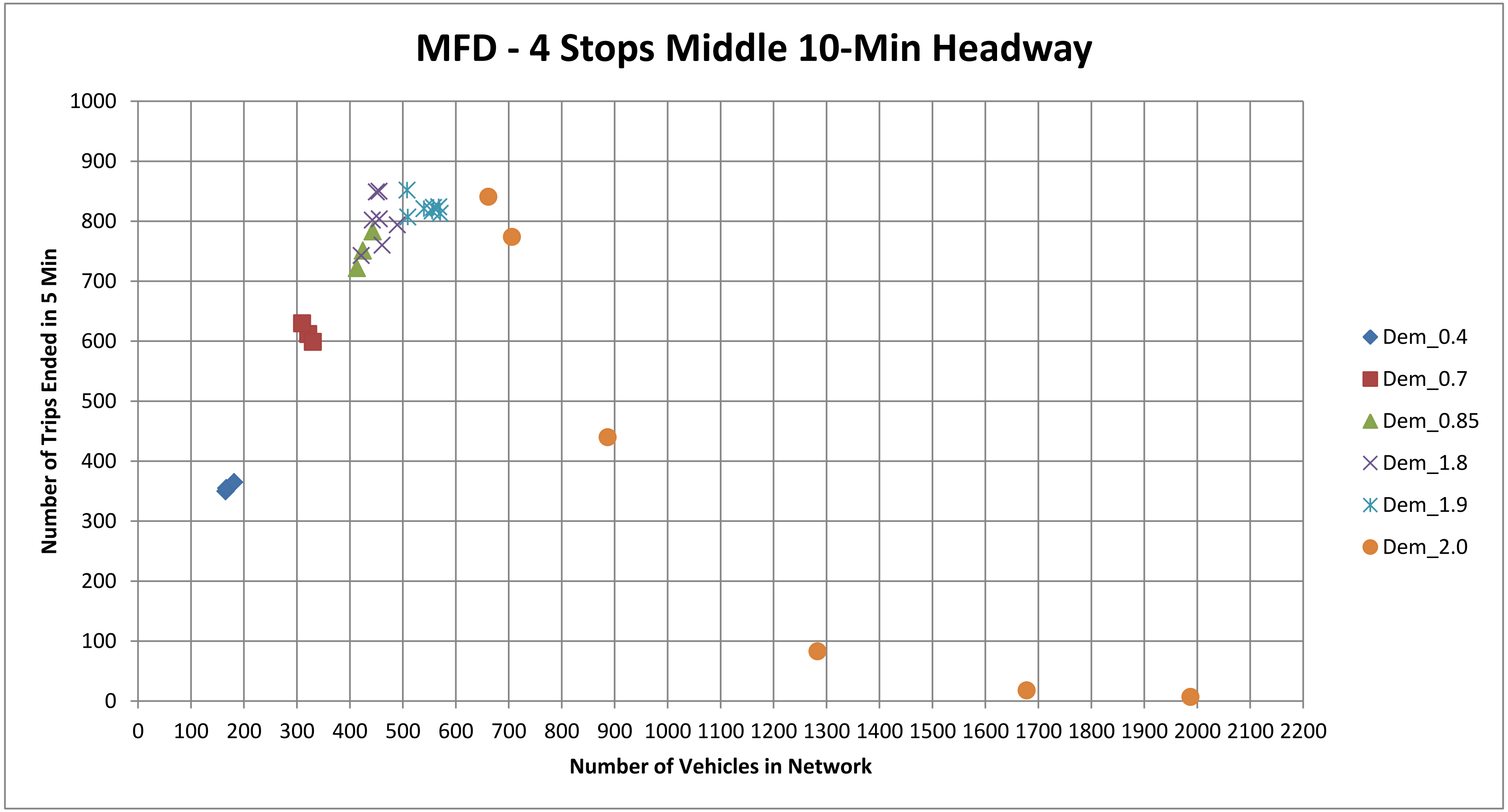
Source: Vissim 6 (2014), Own Configuration

A 14 MFD of Bus Stops Upstream of Intersections (3 Stops) for 2-Min headway



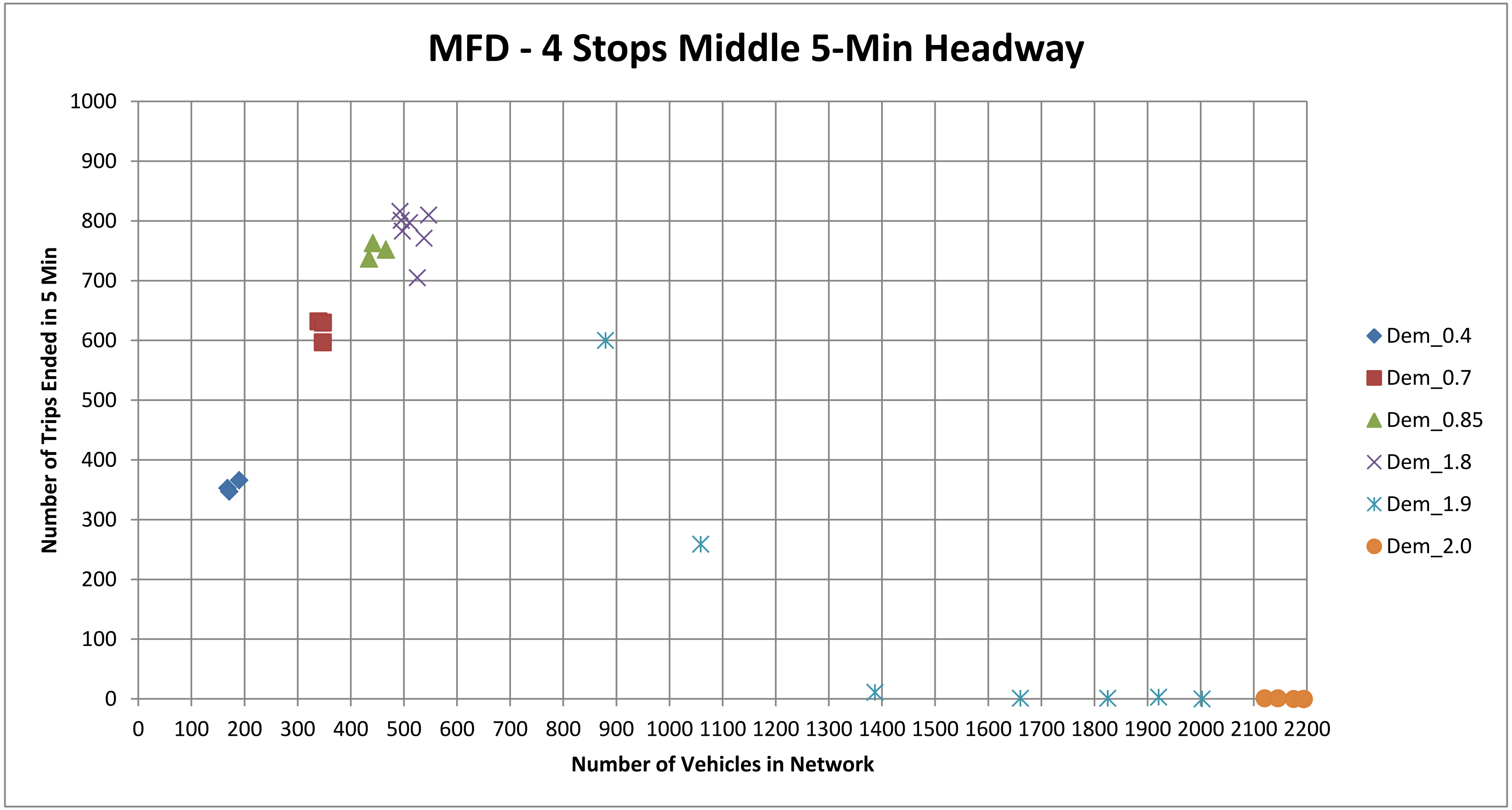
Source: Vissim 6 (2014), Own Configuration

A 15 MFD of Bus Stops Middle of Road Links for 10-Min headway



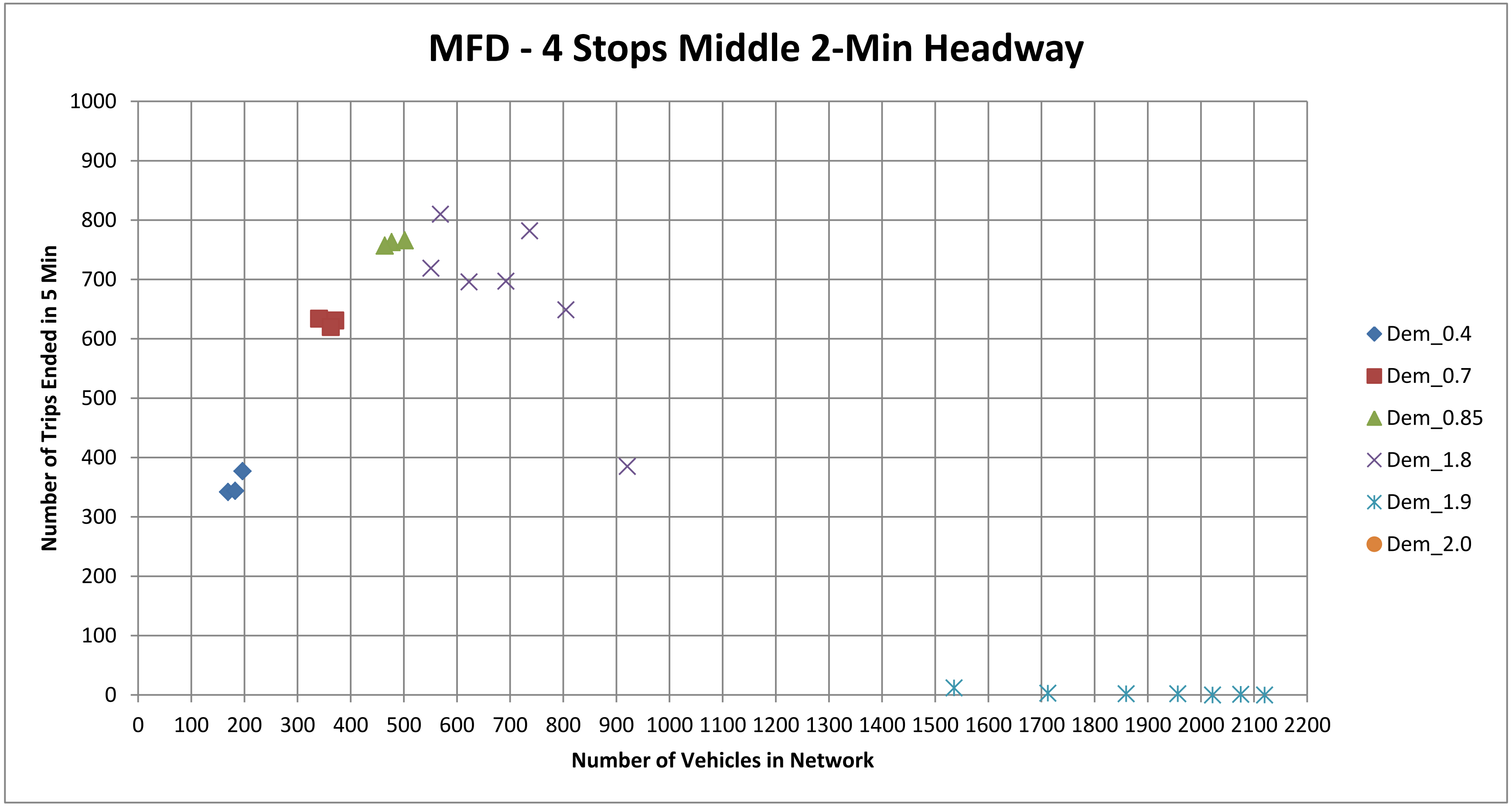
Source: Vissim 6 (2014), Own Configuration

A 16 MFD of Bus Stops Middle of Road Links for 5-Min headway



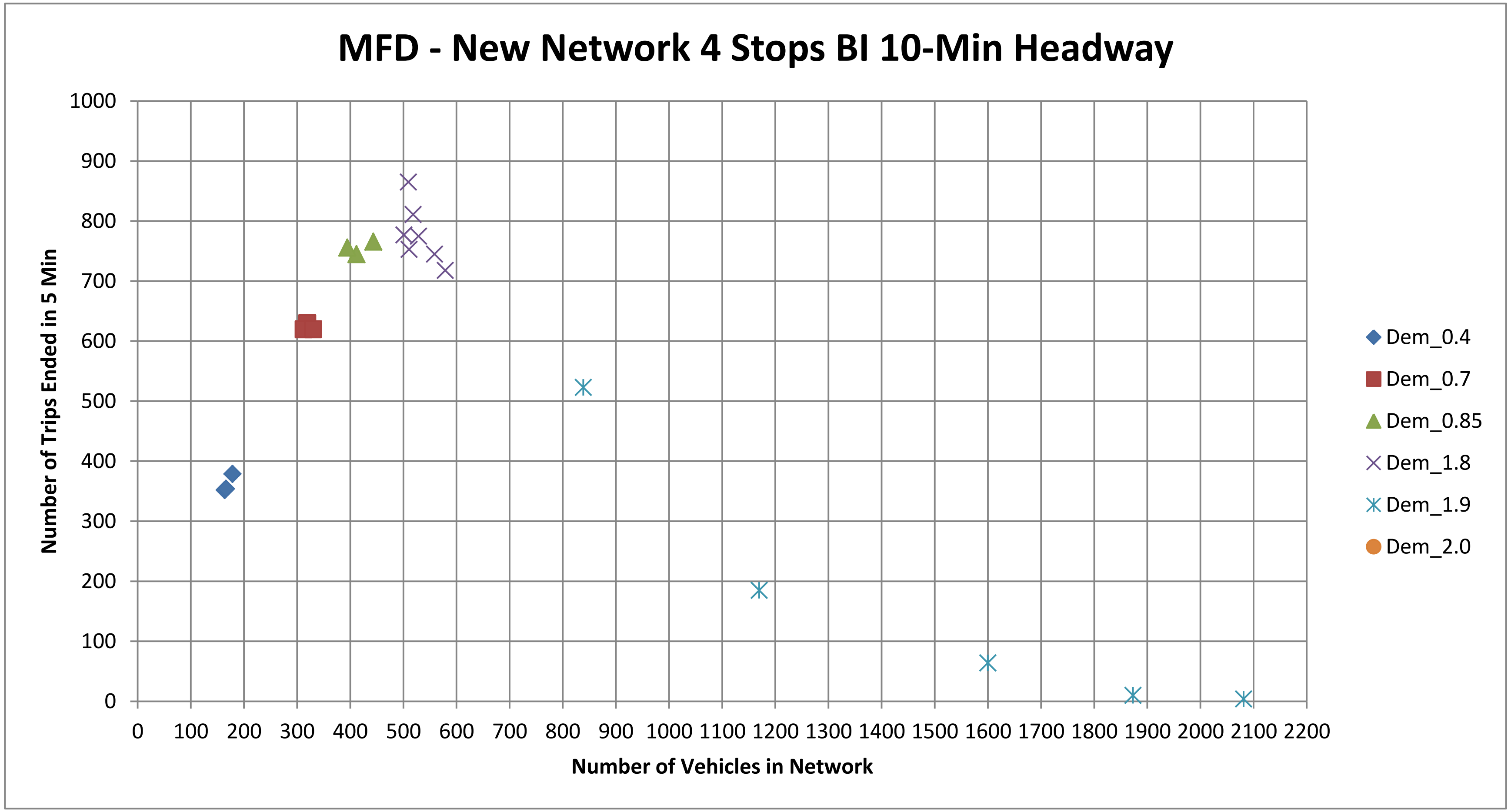
Source: Vissim 6 (2014), Own Configuration

A 17 MFD of Bus Stops Middle of Road Links for 2-Min headway



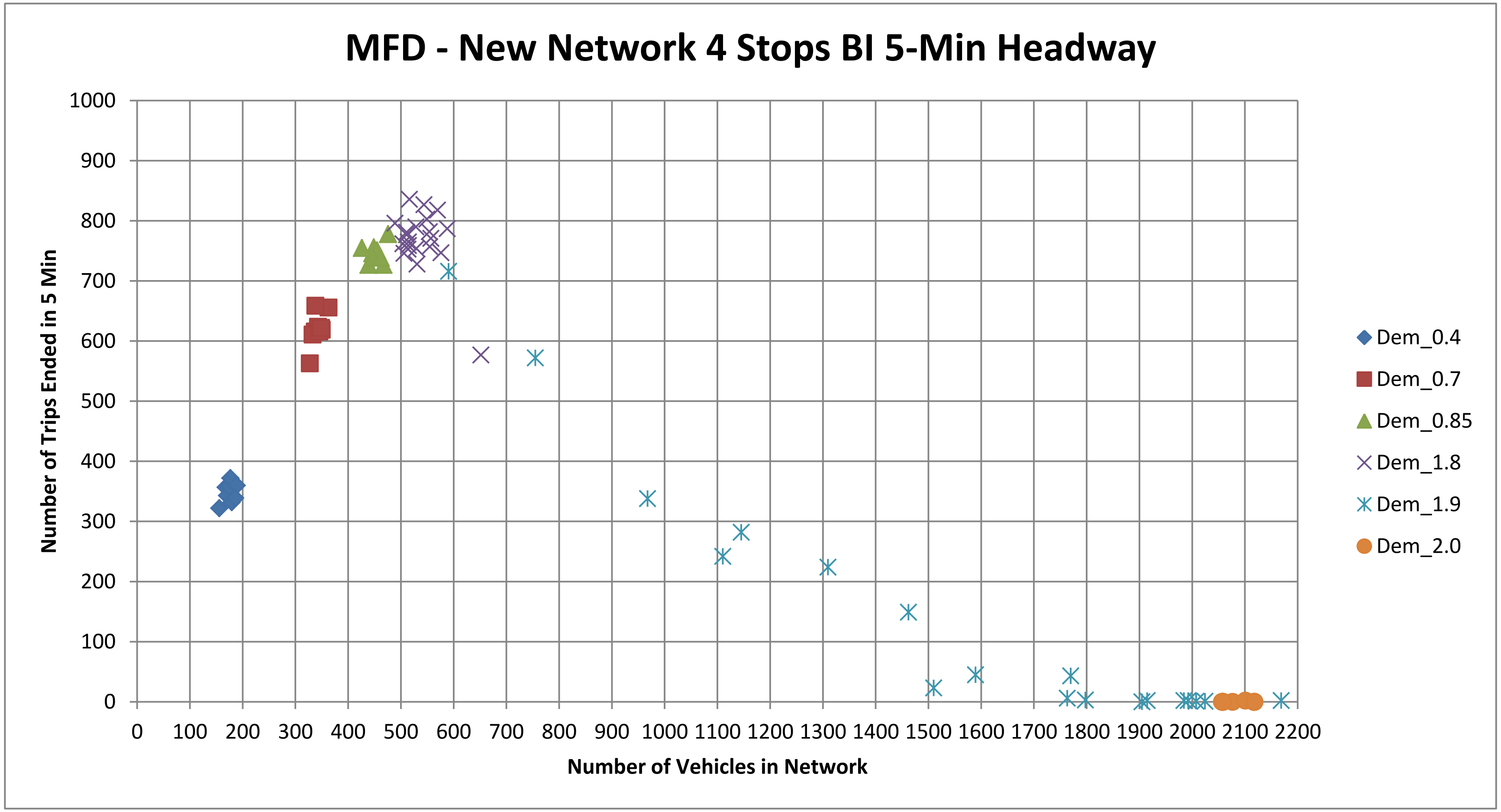
Source: Vissim 6 (2014), Own Configuration

A 18 MFD of New Network Bus Stops Upstream of Intersection for 10-Min headway



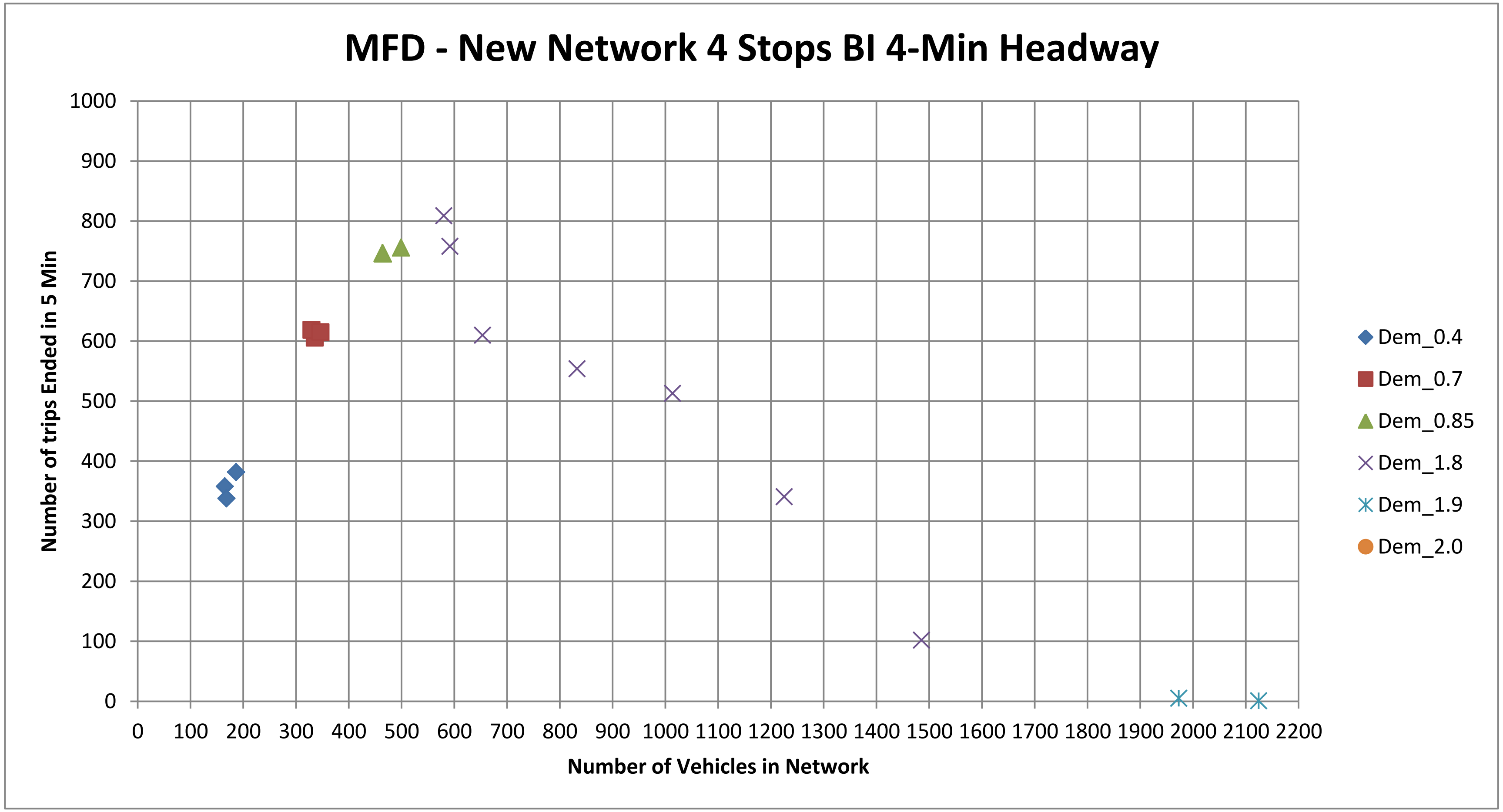
Source: Vissim 6 (2014), Own Configuration

A 19 MFD of New Network Bus Stops Upstream of Intersection for 5-Min headway



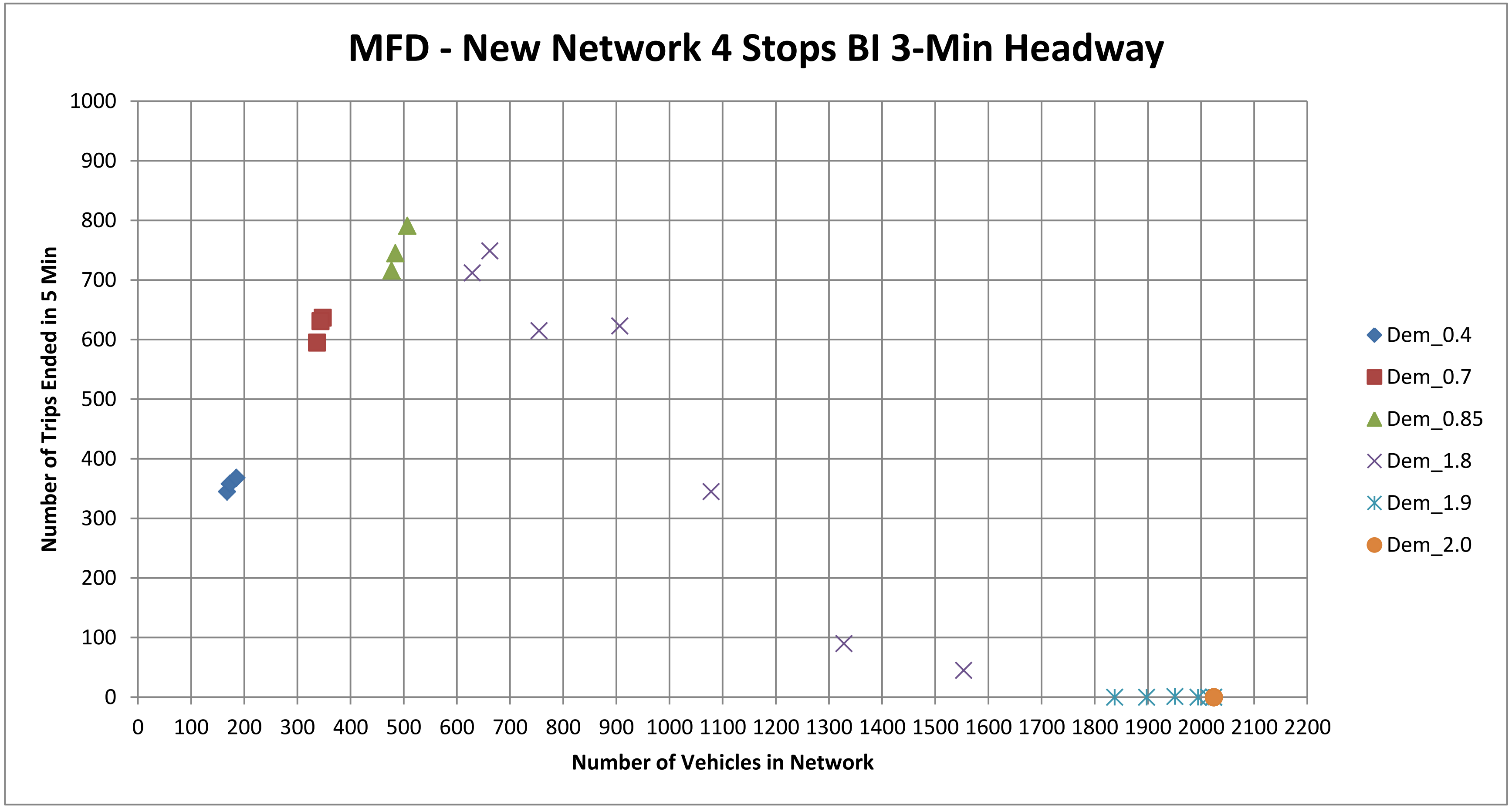
Source: Vissim 6 (2014), Own Configuration

A 20 MFD of New Network Bus Stops Upstream of Intersection for 4-Min headway



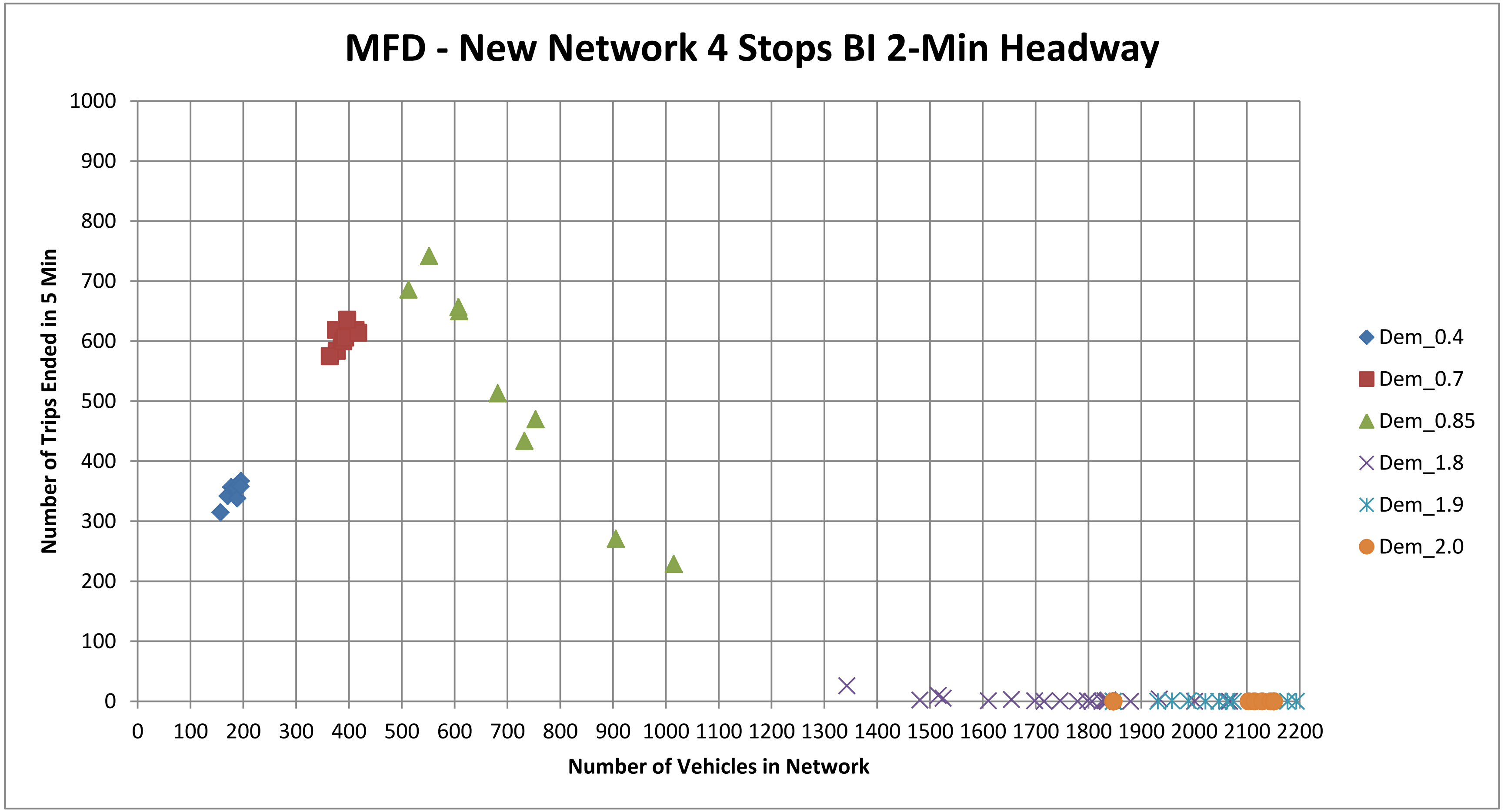
Source: Vissim 6 (2014), Own Configuration

A 21 MFD of New Network Bus Stops Upstream of Intersection for 3-Min headway



Source: Vissim 6 (2014), Own Configuration

A 22 MFD of New Network Bus Stops Upstream of Intersection for 2-Min headway



Source: Vissim 6 (2014), Own Configuration

A 23 Accessibility Table of Bus Network Upstream of Intersections for 10-Min Headway (Default Network)

Accessibility of Bus Network 4 Stops Upstream of Intersections for 10-Min Headway (Default Network)

O	D	Walking			Waiting Time (sec)	Bus Route 1			Transfer Time	Bus Route 2			Walking			Total Time	
		Distance (m)	Speed (km/h)	Time (sec)		Bus Distance (m)	Bus Speed (km/h)	Bus Travel Time (sec)	10 Min Headway	Bus Distance (m)	Bus Speed (km/h)	Bus Travel Time (sec)	Distance (m)	Speed (km/h)	Time (sec)	Sec	Min
1	**a**	225	5	162	120	600	11.23	192	300	600	11.23	192	225	5	162	**1129**	**18.81**
1	**b**	225	5	162	120	300	11.23	96	300	300	11.23	96	75	5	54	**828**	**13.81**
1	**c**	225	5	162	120	900	11.23	289	300	0	11.23	0	75	5	54	**625**	**10.41**
1	**d**	225	5	162	30	900	11.23	289	300	0	11.23	0	225	5	162	**643**	**10.71**
1	**e**	225	5	162	120	300	11.23	96	300	0	11.23	0	75	5	54	**432**	**7.20**
1	**f**	225	5	162	120	900	11.23	289	300	0	11.23	0	75	5	54	**625**	**10.41**
1	**4**	225	5	162	120	300	11.23	96	300	600	11.23	192	225	5	162	**1033**	**17.21**
2	**a**	225	5	162	120	900	11.23	289	300	0	11.23	0	225	5	162	**733**	**12.21**
2	**b**	225	5	162	120	300	11.23	96	300	0	11.23	0	75	5	54	**432**	**7.20**
2	**c**	225	5	162	120	600	11.23	192	300	0	11.23	0	75	5	54	**528**	**8.81**
2	**d**	225	5	162	120	600	11.23	192	300	0	11.23	0	225	5	162	**636**	**10.61**
2	**e**	225	5	162	120	300	11.23	96	300	0	11.23	0	75	5	54	**432**	**7.20**
2	**f**	225	5	162	120	300	11.23	96	300	0	11.23	0	225	5	162	**540**	**9.00**
3	**a**	75	5	54	120	900	11.23	289	300	0	11.23	0	225	5	162	**625**	**10.41**
3	**b**	75	5	54	30	600	11.23	192	300	0	11.23	0	75	5	54	**330**	**5.51**
3	**c**	75	5	54	120	300	11.23	96	300	600	11.23	192	75	5	54	**817**	**13.61**
3	**d**	75	5	54	120	300	11.23	96	300	300	11.23	96	225	5	162	**828**	**13.81**
3	**e**	75	5	54	120	300	11.23	96	300	300	11.23	96	75	5	54	**720**	**12.01**
3	**f**	75	5	54	120	300	11.23	96	300	0	11.23	0	225	5	162	**432**	**7.20**
4	**a**	225	5	162	120	900	11.23	289	300	300	11.23	96	225	5	162	**1129**	**18.81**
4	**b**	225	5	162	120	900	11.23	289	300	0	11.23	0	75	5	54	**625**	**10.41**
4	**c**	225	5	162	120	600	11.23	192	300	600	11.23	192	75	5	54	**1021**	**17.01**
4	**d**	225	5	162	120	600	11.23	192	300	600	11.23	192	225	5	162	**1129**	**18.81**
4	**e**	225	5	162	120	600	11.23	192	300	0	11.23	0	375	5	270	**744**	**12.41**
4	**f**	225	5	162	120	300	11.23	96	300	300	11.23	96	225	5	162	**936**	**15.61**
4	**1**	225	5	162	120	600	11.23	192	300	300	11.23	96	225	5	162	**1033**	**17.21**

A 24 Accessibility Table of Bus Network Upstream of Intersections for 5-Min Headway (Default Network)

Accessibility of Bus Network 4 Stops Upstream of Intersections for 5-Min Headway (Default Network)

O	D	Walking			Waiting Time (sec)	Bus Route 1			Transfer Time	Bus Route 2			Walking			Total Time	
		Distance (m)	Speed (km/h)	Time (sec)		Bus Distance (m)	Bus Speed (km/h)	Bus Travel Time (sec)	5-Min Headway	Bus Distance (m)	Bus Speed (km/h)	Bus Travel Time (sec)	Distance (m)	Speed (km/h)	Time (sec)	Sec	Min
1	**a**	225	5	162	120	600	11.23	192	150	600	11.23	192	225	5	162	**979**	**16.31**
1	**b**	225	5	162	120	300	11.23	96	150	300	11.23	96	75	5	54	**678**	**11.31**
1	**c**	225	5	162	120	900	11.23	289	150	0	11.23	0	75	5	54	**625**	**10.41**
1	**d**	225	5	162	30	900	11.23	289	150	0	11.23	0	225	5	162	**643**	**10.71**
1	**e**	225	5	162	120	300	11.23	96	150	0	11.23	0	75	5	54	**432**	**7.20**
1	**f**	225	5	162	120	900	11.23	289	150	0	11.23	0	75	5	54	**625**	**10.41**
1	**4**	225	5	162	120	300	11.23	96	150	600	11.23	192	225	5	162	**883**	**14.71**
2	**a**	225	5	162	120	900	11.23	289	150	0	11.23	0	225	5	162	**733**	**12.21**
2	**b**	225	5	162	120	300	11.23	96	150	0	11.23	0	75	5	54	**432**	**7.20**
2	**c**	225	5	162	120	600	11.23	192	150	0	11.23	0	75	5	54	**528**	**8.81**
2	**d**	225	5	162	120	600	11.23	192	150	0	11.23	0	225	5	162	**636**	**10.61**
2	**e**	225	5	162	120	300	11.23	96	150	0	11.23	0	75	5	54	**432**	**7.20**
2	**f**	225	5	162	120	300	11.23	96	150	0	11.23	0	225	5	162	**540**	**9.00**
3	**a**	75	5	54	120	900	11.23	289	150	0	11.23	0	225	5	162	**625**	**10.41**
3	**b**	75	5	54	30	600	11.23	192	150	0	11.23	0	75	5	54	**330**	**5.51**
3	**c**	75	5	54	120	300	11.23	96	150	600	11.23	192	75	5	54	**667**	**11.11**
3	**d**	75	5	54	120	300	11.23	96	150	300	11.23	96	225	5	162	**678**	**11.31**
3	**e**	75	5	54	120	300	11.23	96	150	300	11.23	96	75	5	54	**570**	**9.51**
3	**f**	75	5	54	120	300	11.23	96	150	0	11.23	0	225	5	162	**432**	**7.20**
4	**a**	225	5	162	120	900	11.23	289	150	300	11.23	96	225	5	162	**979**	**16.31**
4	**b**	225	5	162	120	900	11.23	289	150	0	11.23	0	75	5	54	**625**	**10.41**
4	**c**	225	5	162	120	600	11.23	192	150	600	11.23	192	75	5	54	**871**	**14.51**
4	**d**	225	5	162	120	600	11.23	192	150	600	11.23	192	225	5	162	**979**	**16.31**
4	**e**	225	5	162	120	600	11.23	192	150	0	11.23	0	375	5	270	**744**	**12.41**
4	**f**	225	5	162	120	300	11.23	96	150	300	11.23	96	225	5	162	**786**	**13.11**
4	**1**	225	5	162	120	600	11.23	192	150	300	11.23	96	225	5	162	**883**	**14.71**

A 25 Accessibility Table of Bus Network Upstream of Intersections for 2-Min Headway (Default Network)

Accessibility of Bus Network 4 Stops Upstream of Intersections for 2-Min Headway (Default Network)

O	D	Walking			Waiting Time (sec)	Bus Route 1			Transfer Time	Bus Route 2			Walking			Total Time	
		Distance (m)	**Speed (km/h)**	**Time (sec)**		**Bus Distance (m)**	**Bus Speed (km/h)**	**Bus Travel Time (sec)**	**2-Min Headway**	**Bus Distance (m)**	**Bus Speed (km/h)**	**Bus Travel Time (sec)**	**Distance (m)**	**Speed (km/h)**	**Time (sec)**	**Sec**	**Min**
1	**a**	225	5	162	120	600	11.23	192	60	600	11.23	192	225	5	162	**889**	**14.81**
1	**b**	225	5	162	120	300	11.23	96	60	300	11.23	96	75	5	54	**588**	**9.81**
1	**c**	225	5	162	120	900	11.23	289	60	0	11.23	0	75	5	54	**625**	**10.41**
1	**d**	225	5	162	30	900	11.23	289	60	0	11.23	0	225	5	162	**643**	**10.71**
1	**e**	225	5	162	120	300	11.23	96	60	0	11.23	0	75	5	54	**432**	**7.20**
1	**f**	225	5	162	120	900	11.23	289	60	0	11.23	0	75	5	54	**625**	**10.41**
1	**4**	225	5	162	120	300	11.23	96	60	600	11.23	192	225	5	162	**793**	**13.21**
2	**a**	225	5	162	120	900	11.23	289	60	0	11.23	0	225	5	162	**733**	**12.21**
2	**b**	225	5	162	120	300	11.23	96	60	0	11.23	0	75	5	54	**432**	**7.20**
2	**c**	225	5	162	120	600	11.23	192	60	0	11.23	0	75	5	54	**528**	**8.81**
2	**d**	225	5	162	120	600	11.23	192	60	0	11.23	0	225	5	162	**636**	**10.61**
2	**e**	225	5	162	120	300	11.23	96	60	0	11.23	0	75	5	54	**432**	**7.20**
2	**f**	225	5	162	120	300	11.23	96	60	0	11.23	0	225	5	162	**540**	**9.00**
3	**a**	75	5	54	120	900	11.23	289	60	0	11.23	0	225	5	162	**625**	**10.41**
3	**b**	75	5	54	30	600	11.23	192	60	0	11.23	0	75	5	54	**330**	**5.51**
3	**c**	75	5	54	120	300	11.23	96	60	600	11.23	192	75	5	54	**577**	**9.61**
3	**d**	75	5	54	120	300	11.23	96	60	300	11.23	96	225	5	162	**588**	**9.81**
3	**e**	75	5	54	120	300	11.23	96	60	300	11.23	96	75	5	54	**480**	**8.01**
3	**f**	75	5	54	120	300	11.23	96	60	0	11.23	0	225	5	162	**432**	**7.20**
4	**a**	225	5	162	120	900	11.23	289	60	300	11.23	96	225	5	162	**889**	**14.81**
4	**b**	225	5	162	120	900	11.23	289	60	0	11.23	0	75	5	54	**625**	**10.41**
4	**c**	225	5	162	120	600	11.23	192	60	600	11.23	192	75	5	54	**781**	**13.01**
4	**d**	225	5	162	120	600	11.23	192	60	600	11.23	192	225	5	162	**889**	**14.81**
4	**e**	225	5	162	120	600	11.23	192	60	0	11.23	0	375	5	270	**744**	**12.41**
4	**f**	225	5	162	120	300	11.23	96	60	300	11.23	96	225	5	162	**696**	**11.61**
4	**1**	225	5	162	120	600	11.23	192	60	300	11.23	96	225	5	162	**793**	**13.21**

A 26 Accessibility Table of New Network Upstream of Intersections for 10-Min Headway

Accessibility of New Network 4 Stops Upstream of Intersections for 10-Min Headway

O	D	Walking			Waiting Time (sec)	Bus Route 1			Transfer Time	Bus Route 2			Walking			Total Time	
		Distance (m)	Speed (km/h)	Time (sec)		Bus Distance (m)	Bus Speed (km/h)	Bus Travel Time (sec)	10-Min Headway	Bus Distance (m)	Bus Speed (km/h)	Bus Travel Time (sec)	Distance (m)	Speed (km/h)	Time (sec)	Sec	Min
1	**a**	225	5	162	120	600	11.23	192	150	600	11.23	192	225	5	162	**979**	**16.31**
1	**b**	225	5	162	120	600	11.23	192	150	300	11.23	96	225	5	162	**883**	**14.71**
1	**c**	225	5	162	120	900	11.23	289	300	0	11.23	0	225	5	162	**733**	**12.21**
1	**d**	225	5	162	120	900	11.23	289	300	0	11.23	0	375	5	270	**841**	**14.01**
1	**e**	225	5	162	120	300	11.23	96	150	0	11.23	0	225	5	162	**540**	**9.00**
1	**f**	225	5	162	120	600	11.23	192	300	0	11.23	0	375	5	270	**744**	**12.41**
1	**4**	225	5	162	120	600	11.23	192	150	300	11.23	96	225	5	162	**883**	**14.71**
2	**a**	75	5	54	120	300	11.23	96	150	300	11.23	96	225	5	162	**678**	**11.31**
2	**b**	75	5	54	120	300	11.23	96	300	0	11.23	0	225	5	162	**432**	**7.20**
2	**c**	75	5	54	120	900	11.23	289	300	0	11.23	0	75	5	54	**517**	**8.61**
2	**d**	75	5	54	120	900	11.23	289	300	0	11.23	0	225	5	162	**625**	**10.41**
2	**e**	75	5	54	120	300	11.23	96	300	0	11.23	0	225	5	162	**432**	**7.20**
2	**f**	75	5	54	120	600	11.23	192	300	0	11.23	0	75	5	54	**420**	**7.01**
3	**a**	225	5	162	30	600	11.23	192	300	0	11.23	0	225	5	162	**546**	**9.11**
3	**b**	225	5	162	30	300	11.23	96	300	0	11.23	0	225	5	162	**450**	**7.50**
3	**c**	225	5	162	120	300	11.23	96	300	0	11.23	0	225	5	162	**540**	**9.00**
3	**d**	225	5	162	120	900	11.23	289	300	0	11.23	0	225	5	162	**733**	**12.21**
3	**e**	225	5	162	0	300	11.23	96	300	0	11.23	0	225	5	162	**420**	**7.00**
3	**f**	225	5	162	120	600	11.23	192	300	0	11.23	0	75	5	54	**528**	**8.81**
4	**a**	225	5	162	30	900	11.23	289	300	0	11.23	0	225	5	162	**643**	**10.71**
4	**b**	225	5	162	30	600	11.23	192	300	0	11.23	0	225	5	162	**546**	**9.11**
4	**c**	225	5	162	30	300	11.23	96	300	300	11.23	96	225	5	162	**846**	**14.11**
4	**d**	225	5	162	30	600	11.23	192	300	600	11.23	192	225	5	162	**1039**	**17.31**
4	**e**	225	5	162	30	600	11.23	192	300	0	11.23	0	225	5	162	**546**	**9.11**
4	**f**	225	5	162	30	600	11.23	192	300	300	11.23	96	75	5	54	**835**	**13.91**

A 27 Accessibility Table of New Network Upstream of Intersections for 5-Min Headway

Accessibility of New Network 4 Stops Upstream of Intersections for 5-Min Headway

O	**D**	**Walking**			**Waiting Time (sec)**	**Bus Route 1**			**Transfer Time**	**Bus Route 2**			**Walking**			**Total Time**	
		Distance (m)	**Speed (km/h)**	**Time (sec)**		**Bus Distance (m)**	**Bus Speed (km/h)**	**Bus Travel Time (sec)**	**5-Min Headway**	**Bus Distance (m)**	**Bus Speed (km/h)**	**Bus Travel Time (sec)**	**Distance (m)**	**Speed (km/h)**	**Time (sec)**	**Sec**	**Min**
1	**a**	225	5	162	120	600	11.23	192	75	600	11.23	192	225	5	162	**904**	**15.06**
1	**b**	225	5	162	120	600	11.23	192	75	300	11.23	96	225	5	162	**808**	**13.46**
1	**c**	225	5	162	120	900	11.23	289	150	0	11.23	0	225	5	162	**733**	**12.21**
1	**d**	225	5	162	120	900	11.23	289	150	0	11.23	0	375	5	270	**841**	**14.01**
1	**e**	225	5	162	120	300	11.23	96	75	0	11.23	0	225	5	162	**540**	**9.00**
1	**f**	225	5	162	120	600	11.23	192	150	0	11.23	0	375	5	270	**744**	**12.41**
1	**4**	225	5	162	120	600	11.23	192	75	300	11.23	96	225	5	162	**808**	**13.46**
2	**a**	75	5	54	120	300	11.23	96	75	300	11.23	96	225	5	162	**603**	**10.06**
2	**b**	75	5	54	120	300	11.23	96	150	0	11.23	0	225	5	162	**432**	**7.20**
2	**c**	75	5	54	120	900	11.23	289	150	0	11.23	0	75	5	54	**517**	**8.61**
2	**d**	75	5	54	120	900	11.23	289	150	0	11.23	0	225	5	162	**625**	**10.41**
2	**e**	75	5	54	120	300	11.23	96	150	0	11.23	0	225	5	162	**432**	**7.20**
2	**f**	75	5	54	120	600	11.23	192	150	0	11.23	0	75	5	54	**420**	**7.01**
3	**a**	225	5	162	30	600	11.23	192	150	0	11.23	0	225	5	162	**546**	**9.11**
3	**b**	225	5	162	30	300	11.23	96	150	0	11.23	0	225	5	162	**450**	**7.50**
3	**c**	225	5	162	120	300	11.23	96	150	0	11.23	0	225	5	162	**540**	**9.00**
3	**d**	225	5	162	120	900	11.23	289	150	0	11.23	0	225	5	162	**733**	**12.21**
3	**e**	225	5	162	0	300	11.23	96	150	0	11.23	0	225	5	162	**420**	**7.00**
3	**f**	225	5	162	120	600	11.23	192	150	0	11.23	0	75	5	54	**528**	**8.81**
4	**a**	225	5	162	30	900	11.23	289	150	0	11.23	0	225	5	162	**643**	**10.71**
4	**b**	225	5	162	30	600	11.23	192	150	0	11.23	0	225	5	162	**546**	**9.11**
4	**c**	225	5	162	30	300	11.23	96	150	300	11.23	96	225	5	162	**696**	**11.61**
4	**d**	225	5	162	30	600	11.23	192	150	600	11.23	192	225	5	162	**889**	**14.81**
4	**e**	225	5	162	30	600	11.23	192	150	0	11.23	0	225	5	162	**546**	**9.11**
4	**f**	225	5	162	30	600	11.23	192	150	300	11.23	96	75	5	54	**685**	**11.41**
4	**1**	225	5	162	30	300	11.23	96	150	600	11.23	192	225	5	162	**793**	**13.21**

A 28 Accessibility Table of New Network Upstream of Intersections for 2-Min Headway

Accessibility of New Network 4 Stops Upstream of Intersections for 2-Min Headway																	
O	**D**	**Walking**			**Waiting Time (sec)**	**Bus Route 1**			**Transfer Time**	**Bus Route 2**			**Walking**			**Total Time**	
		Distance (m)	**Speed (km/h)**	**Time (sec)**		**Bus Distance (m)**	**Bus Speed (km/h)**	**Bus Travel Time (sec)**	**2-Min Headway**	**Bus Distance (m)**	**Bus Speed (km/h)**	**Bus Travel Time (sec)**	**Distance (m)**	**Speed (km/h)**	**Time (sec)**	**Sec**	**Min**
1	**a**	225	5	162	120	600	11.23	192	30	600	11.23	192	225	5	162	**859**	**14.31**
1	**b**	225	5	162	120	600	11.23	192	30	300	11.23	96	225	5	162	**763**	**12.71**
1	**c**	225	5	162	120	900	11.23	289	60	0	11.23	0	225	5	162	**733**	**12.21**
1	**d**	225	5	162	120	900	11.23	289	60	0	11.23	0	375	5	270	**841**	**14.01**
1	**e**	225	5	162	120	300	11.23	96	30	0	11.23	0	225	5	162	**540**	**9.00**
1	**f**	225	5	162	120	600	11.23	192	60	0	11.23	0	375	5	270	**744**	**12.41**
1	**4**	225	5	162	120	600	11.23	192	30	300	11.23	96	225	5	162	**763**	**12.71**
2	**a**	75	5	54	120	300	11.23	96	30	300	11.23	96	225	5	162	**558**	**9.31**
2	**b**	75	5	54	120	300	11.23	96	60	0	11.23	0	225	5	162	**432**	**7.20**
2	**c**	75	5	54	120	900	11.23	289	60	0	11.23	0	75	5	54	**517**	**8.61**
2	**d**	75	5	54	120	900	11.23	289	60	0	11.23	0	225	5	162	**625**	**10.41**
2	**e**	75	5	54	120	300	11.23	96	60	0	11.23	0	225	5	162	**432**	**7.20**
2	**f**	75	5	54	120	600	11.23	192	60	0	11.23	0	75	5	54	**420**	**7.01**
3	**a**	225	5	162	30	600	11.23	192	60	0	11.23	0	225	5	162	**546**	**9.11**
3	**b**	225	5	162	30	300	11.23	96	60	0	11.23	0	225	5	162	**450**	**7.50**
3	**c**	225	5	162	120	300	11.23	96	60	0	11.23	0	225	5	162	**540**	**9.00**
3	**d**	225	5	162	120	900	11.23	289	60	0	11.23	0	225	5	162	**733**	**12.21**
3	**e**	225	5	162	0	300	11.23	96	60	0	11.23	0	225	5	162	**420**	**7.00**
3	**f**	225	5	162	120	600	11.23	192	60	0	11.23	0	75	5	54	**528**	**8.81**
4	**a**	225	5	162	30	900	11.23	289	60	0	11.23	0	225	5	162	**643**	**10.71**
4	**b**	225	5	162	30	600	11.23	192	60	0	11.23	0	225	5	162	**546**	**9.11**
4	**c**	225	5	162	30	300	11.23	96	30	300	11.23	96	225	5	162	**576**	**9.61**
4	**d**	225	5	162	30	600	11.23	192	60	600	11.23	192	225	5	162	**799**	**13.31**
4	**e**	225	5	162	30	600	11.23	192	60	0	11.23	0	225	5	162	**546**	**9.11**
4	**f**	225	5	162	30	600	11.23	192	60	300	11.23	96	75	5	54	**595**	**9.91**
4	**1**	225	5	162	30	300	11.23	96	60	600	11.23	192	225	5	162	**703**	**11.71**