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 UC Berkeley Center for Future Urban Transport
A **VOLVO** Center of Excellence



August 2009

**Multimodal Transport Modeling for Nairobi, Kenya:
Insights and Recommendations with an Evidence-Based Model**

FINAL REPORT FOR VREF AND PARTNERS

VOLVO WORKING PAPER

Eric J. Gonzales, Celeste Chavis, Yuwei Li, and Carlos F. Daganzo

UC Berkeley Center for Future Urban Transport,
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Executive Summary

Traffic congestion is a growing problem in Nairobi, Kenya, resulting from rapidly increasing population and the crowding of motorized traffic onto a limited street network. This report includes analysis of the traffic conditions in Nairobi, the expected effects of further growth in demand, and a set of recommendations for how to improve the performance of the street network. Data describing motorized vehicle traffic was used to build a simulation model of Nairobi's street network considering cars and matatus. This model was used to analyze traffic conditions at the city-scale under existing conditions and future growth scenarios. The results provide insights for improving the network performance and support recommendations for Nairobi.

City-scale analysis of the street network was conducted with the use of the macroscopic fundamental diagram (MFD) which relates the number of vehicles circulating on the street network to the rate at which trips reach their destinations. The results of simulations with different demand patterns show that there is a consistent MFD relating vehicle accumulation to network flow in Nairobi's central business district (CBD). Therefore, detailed knowledge of demand is not necessary to understand how the network performs, because the MFD depends on the properties of the street network itself. Monitoring and controlling the number of vehicles in the network is sufficient to maintain traffic flow on the city's streets. As traffic demand grows in the future, the streets will quickly become more congested, so measures should be taken to improve the system.

The first recommendations seek to control the accumulation of vehicles in the network so that traffic flow is maximized according to the MFD. One method is to meter the rate at which vehicles can enter the CBD in order to control accumulation so that everyone can reach their destinations sooner. Metering can be effective in the morning when more vehicles are entering the CBD from outside, but during the evening there are many internally generated trips which will tend to jam the network anyway. Policies that reduce the peak travel demand by shifting trips to public transport or spreading the demand across more time can reduce traffic congestion in the evening.

A second set of recommendations expand the shape of the MFD itself by increasing the capacity of the streets in the network which is largely dependent on how intersections operate. Traffic circles (roundabouts) are common in Nairobi, but signalized intersections can have greater capacity. Converting intersections will also reduce the congestion effects when queues spill back into upstream intersections. Capacity can be further increased by adding redundancy to the network.

An analysis of dedicating lanes to buses and matatus on radial arterials shows that queues in the remaining lanes will grow longer. In the morning, these queues grow away from the center, so matatus experience reduced travel times, but in the evening, the queues back up into CBD increasing delays for everyone.

The simulation study provides an illustration representing Nairobi approximately, so results are relevant and qualitatively useful. Further data could be collected to estimate the real MFD for Nairobi and provide more accurate quantitative values. Although Nairobi's streets are congested and bound to get worse, the network performance can be improved by making strategic investments in the transport network.

1 Introduction and Background

The urban transport system in Nairobi, Kenya, is characterized by a poorly connected street network crowded with competing modes of transport. As the mode share of motorized transport increases, there is a need to rationalize the way the network is shared by private and public vehicles. This report describes an analysis of the street network of Nairobi and its ability to serve motorized vehicle trips including private cars and informal paratransit vehicles called *matatus*. By looking at traffic patterns at the neighborhood level, rather than focusing on the details of demand and traffic operation on individual streets, this report broadly describes the current traffic conditions in Nairobi. Insights are also provided for how the network can be reliably improved as well as the shortfalls of some traffic control policies.

The report is structured in six sections. This first section describes the characteristics of the existing transportation system in Nairobi. The second section describes the macroscopic city-scale approach which we use to analyze the current traffic conditions in the city, and the reasons why this approach is preferred to detailed microscopic studies of traffic on individual streets. This is followed by a description of the simulation model of Nairobi that we have built to study the macroscopic traffic conditions in Nairobi. We then analyze the existing conditions and possible future growth scenarios in Nairobi based on the data available and simulations of a network which approximately represents Nairobi. Finally, we diagnose some sources of traffic congestion in Nairobi and discuss possible policies to manage street traffic.

1.1 Current Traffic Conditions in Nairobi

Traffic conditions in Nairobi are characterized by congested and unsafe roadways with unreliable performance. For a city of roughly 4 million inhabitants, Nairobi has few streets to serve traffic demand relative to cities of similar size in countries with more motorized traffic. The city's physical street infrastructure consists primarily of paved roads emanating radially from the center of the city to surrounding neighborhoods and the communities beyond. There are only a handful of roads linking the radial arterials outside of the central business district (CBD) as shown in Figure 1. Major intersections are typically managed with traffic circles (roundabouts) and there are no signalized intersections outside of the CBD.

Within the city center, at least 18 intersections are reportedly equipped with traffic signals (Katahira & Engineers International, 2006), although phase timing data was only available for 11 signals. The intersections where major arterials from the surrounding neighborhoods enter the CBD are typically controlled with large traffic circles such as those along the Uhuru Highway, Ring Road, and the Globe Roundabout (see Figure 2). All other intersections are managed by nothing more than posted signs. The compact city center is composed of a grid-like network of streets.

The small number of streets for carrying automobile, truck, bus, and matatu traffic in Nairobi results in the following conditions:

- *Concentration of Vehicles on Limited Infrastructure* – Since there are few streets, and most arterials are radial, vehicular trips between different neighborhoods must share limited paved street space, concentrating traffic onto the sparse network of major roads. This is particularly problematic in and around the CBD.
- *Lack of Redundancy* – The connections between the major arterials are few and far

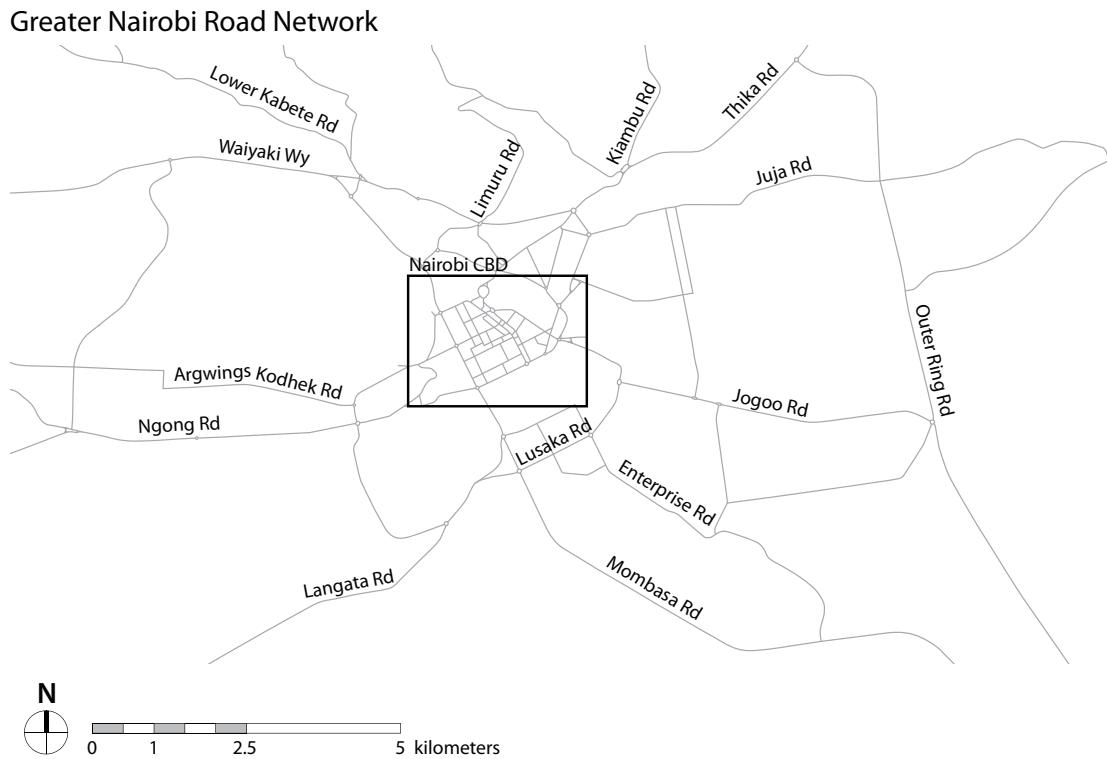


Figure 1. The road network in Nairobi is primarily composed of radial routes connecting surrounding regions to the CBD. The lack of circumferential roads forces many peripheral trips through the center.

Nairobi Central Business District
Vehicles Enter/Exit CBD Through Few Intersections

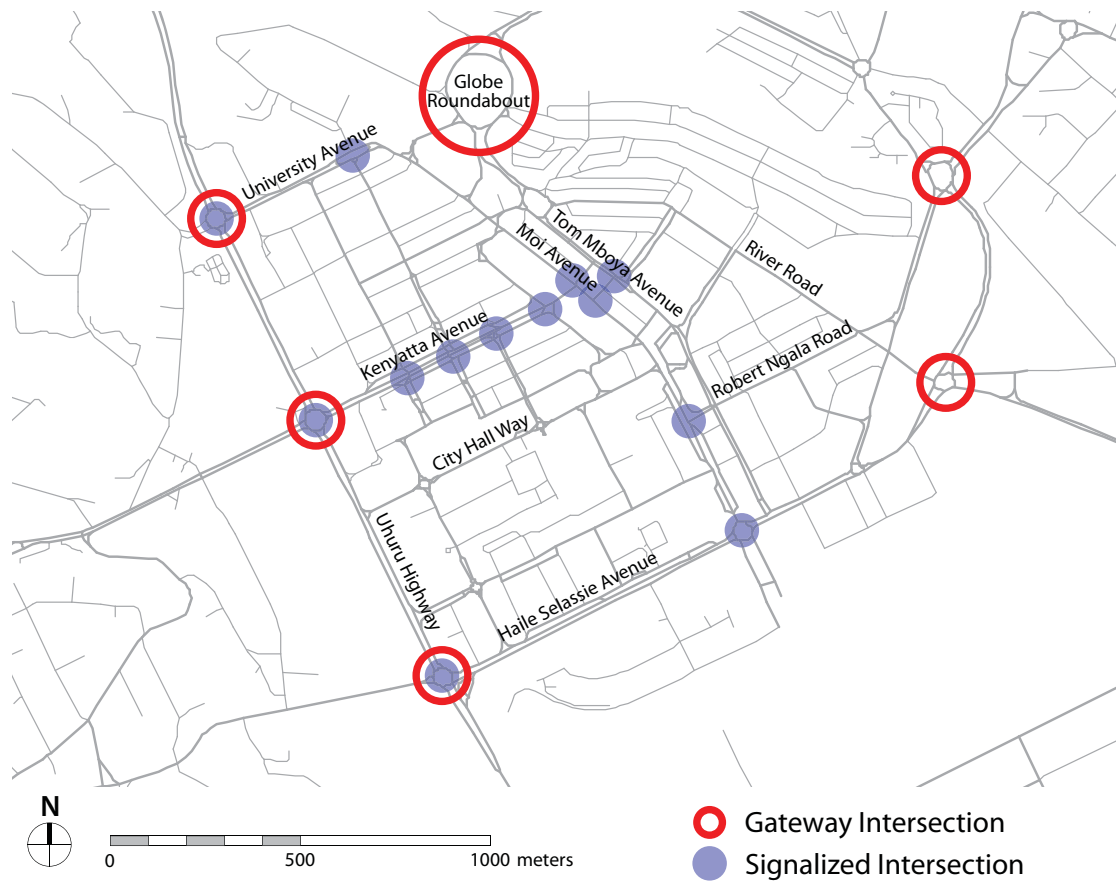


Figure 2. The street network of central Nairobi is restricted by 6 intersections through which all traffic entering and exiting the CBD must pass. Only 13 of the intersections in the city center are controlled with traffic signals.

between, so there are usually no more than one or two reasonable routes for any origin-destination pair. This means that traffic cannot be redistributed to use street infrastructure more efficiently. Due to the lack of ring roads many peripheral trips must pass through the CBD which compounds traffic congestion in the center.

These conditions contribute to the following problems:

- *Traffic Congestion and Delays* – The concentration of vehicles onto few streets and through few intersections, along with the limited available routes, makes traffic congestion on Nairobi’s streets inevitable. In order to drive into or out of the city center, vehicles must pass through one of six gateway traffic circles on the CBD’s edge (see Figure 2). This means that the capacity of the street network to serve trips entering and exiting the CBD from surrounding neighborhoods cannot exceed the capacity of these six intersections.
- *Unreliable Road Network Performance* – Travel on Nairobi’s street network is notoriously unreliable because congestion can arise unexpectedly and last for hours. This is a symptom of the lack of redundancy in the network; when critical parts of the network such as intersections near the CBD are unable to serve the traffic demand, vehicles cannot choose alternative routes to by-pass congestion. Small, localized incidents can have widespread effects.

Safety is also a concern for both pedestrians and vehicle passengers on Nairobi’s streets (Aligula et al., 2005). The relatively high rate of pedestrian fatalities due to road traffic collisions is in part due to the lack of alternative infrastructure for people to walk. The absence of sidewalks forces pedestrians to walk along the shoulders of busy roads. The crowded state of infrastructure is further exacerbated by the encroachment of markets and commercial activities onto transport right of way. This puts very diverse modes (from pedestrians to private automobiles) on an even narrower road space. Pedestrians are not considered as a focus of this study, but the interactions that cause inefficiencies for vehicular traffic operations also represent a severe safety hazard for people walking in the streets.

1.2 Role of Public Transport/Matatus

Of the nearly 4.8 million trips made each day in Nairobi in 2004, only 16% were made in private vehicles; 36% used public transport and 48% were made on foot. The vast majority (about 80%) of public transport trips in Nairobi are carried by matatus. The remaining public transport trips are served by traditional fixed route buses, a commuter rail line, and other shuttle services such as those run by schools. On the major corridors, matatus make up anywhere from 15% to 50% of the vehicles on the road making them a significant component of the vehicular traffic on Nairobi’s road network as shown in Table 1.

As Nairobi’s population grew following Kenya’s independence, and the need to travel to the city center for work became more important, so did the need for public transport service. Matatus were not always a prominent mode in Nairobi, but they emerged to meet the demand not served as the British-established formal bus company, Kenya Bus Service (KBS), deteriorated (Aligula et al., 2005). The vehicles are typically Japanese-made minibuses with about 14 seats. Although the operation of matatus was illegal at first, they were allowed to legally compete with formal bus operations in 1973, and KBS has been steadily losing market share ever since. The network of scheduled bus routes has been gradually reduced as routes are abandoned and taken over by matatus (Post Buckley

Table 1. Daily traffic counts by vehicle type on main roads (Source: Aligula et al., 2005)

Road	Cars	Matatus	Other	% Matatus
Langata Rd	14,835	3,688	1,064	19
Mombasa Rd	28,286	8,097	1,389	21
Jogoo Rd	17,741	13,303	2,354	40
Juja Rd	5,854	6,298	1,812	45
Thika Rd	16,580	13,326	3,176	40
Kiambu Rd	4,663	2,833	404	36
Limuru Rd	12,407	4,834	408	27
Waiyaki Way	25,243	8,451	2,494	23
Ngong Rd	8,348	4,291	1015	31

International, Inc., 1998). The mode share of formal public bus services in Nairobi has slipped from 36% of all trips in 1994 to 3.5% in 2004 (Aligula et al., 2005). It is out of this history of decaying formal public transport that the informal sector, namely matatus, has emerged to carry the bulk of public transport demand.

Matatus play a critical role in Nairobi’s transport system because they serve a need that is not met by other modes. The wealthiest residents of Nairobi tend to travel by private vehicle or taxi, and they are motivated in large part by concerns about the safety and security of traveling by matatu or walking. On the other end of the socio-economic spectrum is the vast population who cannot afford to travel by any means other than walking. The largest slums lie within a few miles of the city center, so residents travel on foot. Where matatu service becomes critically important is in connecting the city center to outlying townships and communities. Where distances are too far to walk, matatus provide the only affordable means of transport for many people. With such a major role in the regional transport mix, disruptions to matatu operations result in significant and hard felt effects on the population at large. The significance of this is that policies affecting matatu performance will have a large effect on matatu riders, and thus strategies to improve traffic congestion must consider the effects on these users of the road network in addition to people who travel in private vehicles.

2 Modeling Urban Traffic

The purpose of an urban street network is to provide accessibility for people in a city. The traffic on this street network can be viewed as a collection of vehicles which carry people and move towards their destinations. To maximize accessibility for a given distribution of the traveling population, the street network should serve as many trips as possible. In this study, we use models to identify how changes to the network (e.g. building new streets, adding lanes and bus lines, or changing intersection controls) affect the ability of the street network to serve trips.

Models of urban traffic fall into two categories: microscopic models look at the movements of individual vehicles on each street, while macroscopic models produce aggregated outputs by looking at the vehicles in the network collectively. Microsimulations are data-intensive, requiring enormous data-collection and calibration efforts in return for detailed, yet unreliable, outputs. Microsimulations fare poorly because urban traffic is a chaotic system in which small disturbances can result in very different traffic conditions on individual

streets. Macroscopic modeling approaches, on the other hand, require only observable data inputs and provide reproducible aggregate results. Although traffic conditions can vary greatly from street to street, the collective performance of all the streets in a neighborhood such as a city center is more consistent. The differences between microscopic and macroscopic models are described in greater detail in a previous report on modeling methods for Nairobi (Daganzo et al., 2007).

For modeling traffic in Nairobi, we use an aggregated, macroscopic approach which does not provide detailed results for specific streets or intersections, but instead describes the mobility provided by the network of streets in a consistent way. In this way, we can gain insights about how the street network in Nairobi is currently operating, how it will operate if the demand grows, and what effect changes to the network or traffic control will have on traffic congestion.

2.1 Macroscopic Fundamental Diagram (MFD)

The amount of traffic that a city’s street network can serve is limited by the physical space available on the streets for moving vehicles and the capacity of intersections to serve conflicting vehicle movements. To consider aggregated urban traffic in a neighborhood of interest (e.g. CBD), we can visualize the street network in a neighborhood as a large and complex traffic circle where a vehicle enters, circulates, and then exits the system in order to complete a trip. The goal of such a network is to serve as many trips with as little infrastructure as possible. Increasing the rate at which trips can be completed means that more people can reach their destinations in the same amount of time, hence the street network is providing greater accessibility to travelers.

The relationship between the accumulation of vehicles on a neighborhood’s street network and the productivity of the network to serve trips appears to be described consistently by a macroscopic fundamental diagram (MFD) (Daganzo, 2007; Geroliminis and Daganzo, 2008). An MFD is illustrated in Figure 3, where the network outflow (in vehicles per time) on the vertical axis is plotted against the network accumulation of vehicles on the horizontal axis. Network outflow is a measure of the productivity of the network, which describes the rate at which trips in the neighborhood are completed either by reaching an internal destination or reaching the edge of the neighborhood. The greater this rate, the more quickly people are reaching their destinations. If the average length of trips made in the neighborhood of interest is not changing, then the outflow is proportional to the average flow on streets in the network (the average network flow). In this way, we can talk about the MFD in terms of outflow or network flow because these quantities are proportional.

The concave shape of the MFD can be understood if one looks at Figure 3 from left to right. On the left, the streets are near-empty because the accumulation is low; few vehicle-kilometers are traveled and flow on the network is low. As more and more vehicles fill the streets, more trips are served, but eventually a maximum network flow is reached, indicated by the peak on the diagram. This is the critical range of accumulation that produces maximum flow. Adding more vehicles would then reduce flow; in this regime (on the right) delays are incurred as queues block other vehicles from moving along the crowded streets. Continuing to add vehicles to the streets would eventually bring the system to a state of complete gridlock.

The maximum network flow on the MFD is where the road network is serving the most vehicle trips and it is associated with a “sweet-spot”. Accumulation above the sweet-spot causes traffic congestion to grow more rapidly, and the higher the accumulation the faster the

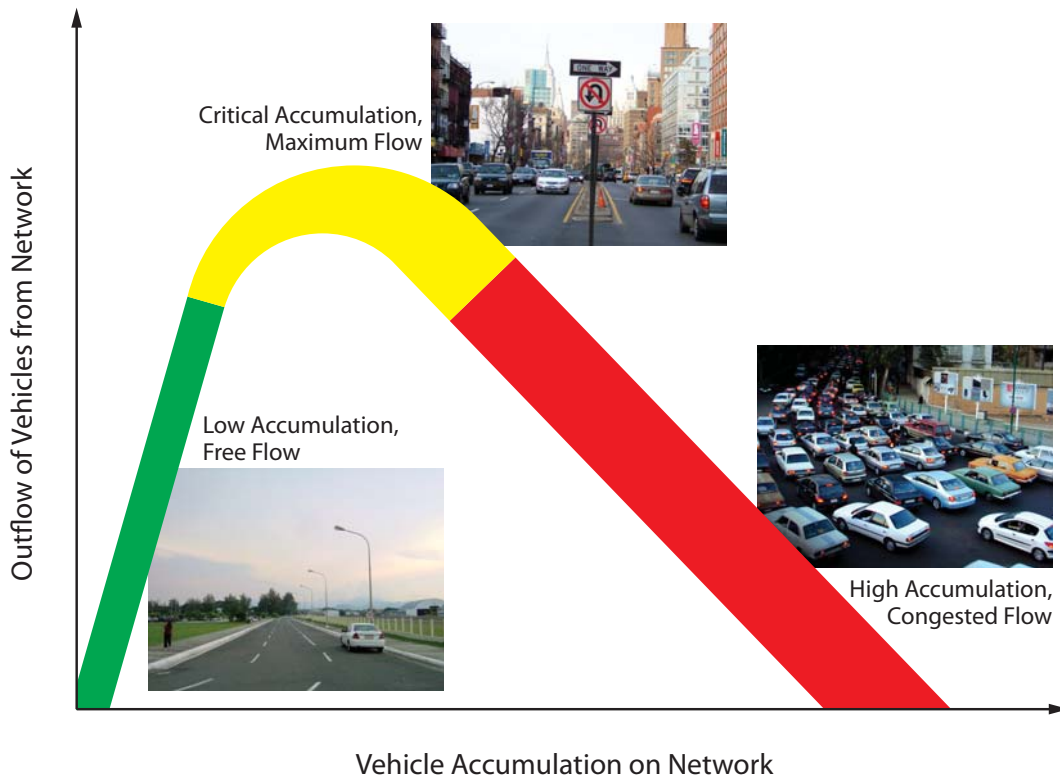


Figure 3. The structure of a macroscopic fundamental diagram (MFD); the outflow of vehicles from a network is consistently determined by the number of vehicles in the network.

flow drops (Daganzo, 2005, 2007). Therefore, it is very important to prevent accumulations from exceeding the sweet spot. Theory shows that any time traffic conditions are severely congested, significant time and resources are being wasted because more trips could have been served without congestion if the number of vehicles on the streets had been controlled.

2.2 Applying the MFD

An important feature of the MFD is that it depends on the geometry of the street network and how the intersections are controlled but is consistent across different demand patterns. An upper bound of the physically achievable network flow can be predicted theoretically based on the block length, signal timings and offsets, maximum discharge flow of vehicles per lane, free-flow speed of vehicles, and the jam density of vehicles per lane (Daganzo and Geroliminis, 2008). From these values, a theoretical MFD can be constructed which describes the maximum network flow for all accumulations independent of the demand pattern. This theoretical bound will be tight if four conditions are satisfied: redundant street network, homogeneous street network, uniformly distributed demand, and negligible effect of turning vehicles. No real city satisfies these assumptions perfectly, but the existence of a consistent MFD has been verified through applications in two cases: using simulated data in San Francisco (California), and measured data in Yokohama (Japan), both shown in Figure 4.

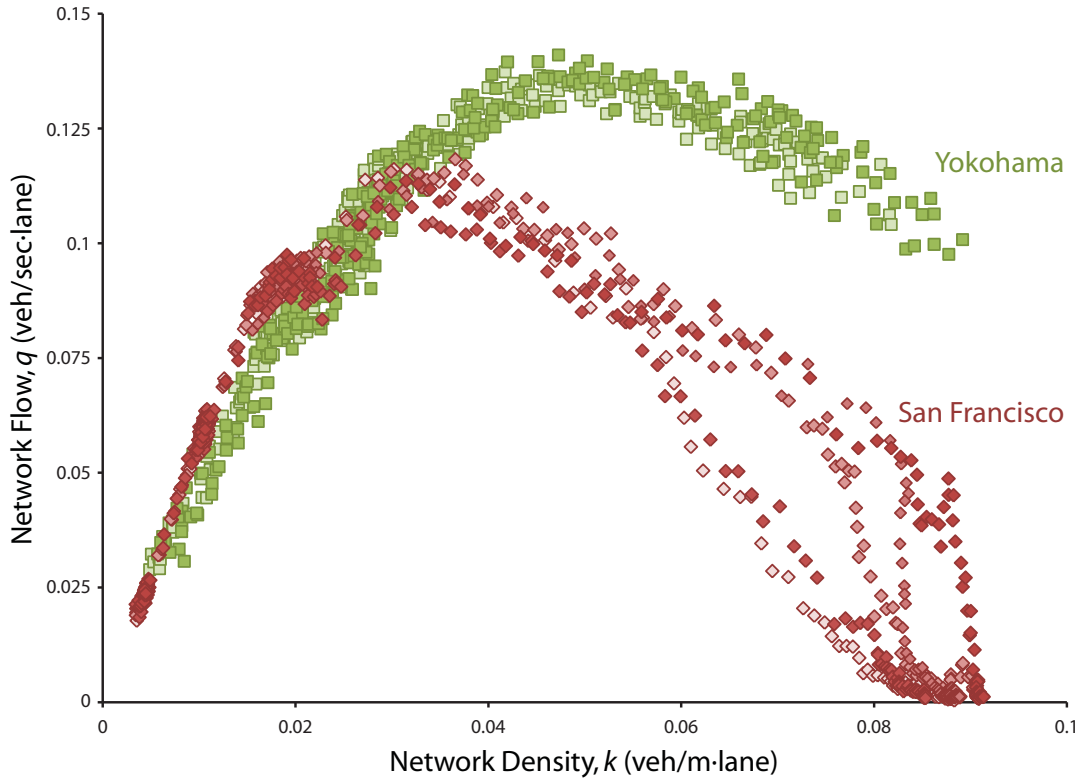


Figure 4. Simulated macroscopic fundamental diagram (MFD) for San Francisco shown with four shades of diamonds representing four different origin-destination tables (Geroliminis and Daganzo, 2007). Measured MFD for Yokohama for days indicated by the two shades of circles (Geroliminis and Daganzo, 2008). The data is expressed in units per network length to compare the performance of the networks per lane meter.

In San Francisco, a microsimulation of the CBD was constructed by incorporating detailed data about the street network, intersection configurations, and signal timings. Using a 4-hour simulation with estimated demands scaled to cover a full range from empty streets to complete gridlock, Geroliminis and Daganzo (2007) show that the flow carried by the network is related to the accumulation in the predicted way as shown in Figure 4. The points closely follow a curve, and this represents a simulated MFD of the street network in San Francisco’s CBD.

The simulation of San Francisco was then repeated for three very different demand scenarios, and each of these scenarios corresponds to a different shading of data points in Figure 4. In one case the demands are predominantly inbound, with 80% of the trips beginning outside the CBD and terminating within, while another case is dominated by outbound trips with 70% of trips generated internally and leaving the CBD. Despite the very different demand patterns, the points follow the same curve, so the MFD for San Francisco is robust for many different demands.

Using data collected from loop detectors and GPS-equipped taxis in central Yokohama, Geroliminis and Daganzo (2008) measured data relating network density to network flow. Although the data collected from individual detectors across the network varied greatly, the aggregation of the values from all the detectors revealed a smooth concave curve as shown in Figure 4.¹ This relation was plotted for data collected on two different days, and the results are consistent. Furthermore, the study showed that the rate of trips ending is proportional to the average network flow, so two claims about the MFD are supported from measured data: 1) that the MFD for a city network is consistent and reproducible, and 2) that increased network flow corresponds directly to an increased rate of trips reaching their destinations. Therefore, the MFD can be used as a tool for managing traffic in cities in order to improve mobility for network users.

2.3 What might be Expected from Nairobi

The street networks of San Francisco and Yokohama are not perfectly homogeneous, and the demand in these cities is not uniformly distributed, yet the traffic conditions in these cities appear to be described by MFDs as theory would predict. Nairobi’s street network and traffic patterns violate all of the assumptions for the theoretical MFD, so in the following sections we will explore if a reproducible relationship between network accumulation and average flow exists despite the violation of the following conditions:

1. *Redundant Network* – Nairobi’s street network lacks redundancy which is one of the causes of the city’s inconsistent congestion. The network does not provide sufficient route choice and often there are no roads available to divert traffic around incidents or locations of congestion.
2. *Homogeneous Network* – Nairobi’s streets are hierarchical. Major arterials are paved and serve the purpose of connecting neighborhoods while local streets are often inadequately maintained and offer poor connectivity. In turn, traffic is concentrated onto the main streets and the side streets cannot feasibly serve through traffic.

¹We conjecture that the sweet-spot for San Francisco is lower (i.e. less favorable) because the San Francisco network is less symmetric and therefore, less uniformly loaded than Yokohoma’s. The scaling of the MFD on a per lane meter basis also depends on how many streets are included in the network of study.

3. *Uniformly Distributed Demand* – Traffic in Nairobi is concentrated on the larger roads connecting the various neighborhoods in the city. Due to land use patterns that favor suburban housing, there is strong peaked flow drawing people into the city center each morning and out to the surrounding neighborhoods each evening.
4. *Negligible Effect of Turning Vehicles* – Turning vehicles have a disfavorable effect on the MFD because turning maneuvers interrupt regular traffic flows. This is particularly problematic in Nairobi because there are many unsignalized intersections, where left turning vehicles can cause substantial traffic delays.

The subsequent sections will 1) explore the existence of a macroscopic relationship for Nairobi despite violating all of the theoretical assumptions and 2) analyze the effect matatus have on the movement of vehicles and, more importantly, drivers and passengers.

3 Nairobi Traffic Model: Building the Simulation

A simulation of traffic in Nairobi was constructed in order to study the traffic conditions in the city. By modeling the street network and intersections as accurately as possible, the evolution of congestion on a city-wide scale can be compared for various demand scenarios. In this way, we can identify if a macroscopic relation between vehicle accumulation and network flow exists. This model is the basis for the analysis of the existing conditions and the effects as travel demand increases. Microsimulation software is used to model detailed vehicle interactions and random variations in the behavior of different drivers. The software is used to simulate traffic data which is aggregated to view the network traffic conditions macroscopically as well as produce a visualization of vehicle mobility and traffic congestion on the network.

3.1 Available Data

The simulation model is based on data provided by Columbia University’s Center for Sustainable Urban Development (CSUD), the University of Nairobi, and the Kenya Institute for Public Policy Research and Analysis (KIPPRA). The data is supplemented with information in the Japan International Cooperation Agency’s (JICA) 2006 report entitled “The Study on Master Plan for Urban Transport in the Nairobi Metropolitan Area in the Republic of Kenya” (Katahira & Engineers International, 2006). Aerial photographs from Google Earth and Microsoft Live were also used to estimate network properties where other data was not available.

The network geometry was determined using GIS data provided by CSUD. The map includes information on the width and classification of each street. In addition, lane configurations were verified using aerial photography. Network characteristics such as free flow speed, lane capacity, and jam spacing were estimated using information in the JICA report and verified with a 2007 video of the traffic circle at Uhuru Highway and Kenyatta Avenue. Signal control was placed on all intersections as stated in the JICA report and data from KIPPRA (see Figure 2 for specific locations). Detailed signal phases and cycle times for 11 of the intersections were provided by KIPPRA; the rest were estimated to match adjacent signal designs.

An origin-destination table was estimated based on the cordon counts in the suburbs and the locations of traffic generators in the center of the city (e.g. parking lots and matatu

terminals). The cordon counts were reported at 30-minute resolution and located at major intersections outside of the CBD. The matatu route structure and frequencies were based on the JICA report and waybill occupancy data provided by KIPPRA. Appendix A summarizes the sources of all the input data used to develop the simulation model.

3.2 Loading the Model with Multiple Vehicle Classes

The model was developed and run using the microscopic simulation software CORSIM. Because this software was designed primarily for use by the United States Federal Highway Administration, modifications were needed to properly simulate the traffic in Nairobi. Nairobi traffic drives on the opposite side of the street than the United States, so the network was flipped, as if viewed in a mirror, to account for right-handed driving in the simulation. We are interested in the flow of vehicles inside the CBD; therefore, only the main roads that connect outlying communities are included outside of the CBD. This allows for the inclusion of all major entrance and exit locations to the city. The simulation includes the main and secondary roadways within the CBD, as shown in Appendix B.

The model takes into account two classes of vehicles: automobiles and matatus. The automobile flows are based on origin-destination (OD) flows between generation and attraction nodes. These values were estimated using the cordon counts provided by KIPPRA. The automobile routes are then based on the navigation model used in CORSIM. The subsequent section outlines the calibration process.

Matatus were modeled as short buses operating on fixed routes. The routes outside of the CBD are defined based on the descriptions in the JICA report. All routes are assumed to begin in the suburbs and end in the CBD or vice versa. The matatu headways were calibrated in order to approximate the daily passenger flows given in the JICA report. In addition, peak flows were calibrated to roughly match the proportional vehicle flows given in the cordon counts. Our understanding is that matatus operate primarily on radial routes to and from the city center and are organized into route associations so that routes are more or less fixed. Stops to pick up passengers vary in that there are matatu terminal where vehicles have established collection locations, but matatus may also stop anywhere along the route to pick up additional passengers.

The vehicle operation of matatus is very different than that of typical fixed route buses, so the vehicles were modeled using two approaches: 1) with random stopping behavior at fixed stops and 2) as moving bottlenecks. The fixed-stop approach reduces matatu speeds and flows more drastically than the moving bottleneck approach, perhaps even unrealistically because CORSIM requires that all buses pass stops in the shoulder lane to see if a passenger is waiting. This creates additional congestion that may not exist in reality since full matatus are more likely to choose the fastest lane for travel. For this reason, the fixed-stop approach was not used for the final analysis.

The moving bottleneck approach avoids this problem. It maintains the fixed routes but no longer utilizes bus stops. Instead, the matatus are modeled to travel at a slower average speed than other traffic by endowing them with a decreased acceleration rate. We have calibrated this rate to ensure that the commercial speed of the matatus is realistic. Under this approach, the matatus will have a larger effect on congestion inside the CBD due to a higher density of streets which results in more stops.

3.3 Fitting Parameters to Available Data

Simulating traffic on a network that matches the actual geometry, signage, and lane configuration in Nairobi produces unrealistic traffic behavior, because CORSIM assumes a North American operating environment and driving style. In order to make the model representative of conditions in Nairobi, adjustments to fit available data focused on two aspects of the model: traffic operations at intersections, and the distribution of traffic demand across the city.

3.3.1 Intersection Calibration

As described in Section 3.1, Nairobi’s street network was modeled as accurately as possible using the GIS map for geometry and aerial photographs for lane configurations. Information about the signage was unavailable for most intersections, so in these cases they were initially modeled as unsigned. Traffic circles were modeled to match the real diameters and numbers of lanes in each case because the capacity of these intersections is sensitive to the size and configuration of the circle. Preliminary simulations with the accurate geometry revealed unrealistic traffic behavior and very low capacities. Many circles had a simulated capacity well below traffic counts reported in the data (see Table 2), and circles would tend to jam unrealistically with vehicles waiting to make unnecessary lane changes. In order to match traffic flows in the simulation to those observed in the data, yield signs were used to prevent unsignalized circles from jamming unrealistically, and legal turn movements were adjusted to utilize the full street capacity. These markings do not match the actual markings in Nairobi, but the result is that they make the simulated traffic behave more like the traffic in Nairobi. The data sources for calibrating intersections are illustrated in Figure 5, and example calibration data is displayed in Table 2.

The signal-controlled traffic circles on Uhuru Highway were also compared with the operations observed in a video of a couple signal cycles of the intersection of Uhuru Highway and Kenyatta Avenue. This video showed how the signal phases were timed and off-set, and more importantly, how traffic streams from each approach used the intersection. From this video, the signal timings in the simulation were designed to make traffic flows match those observed in the video. Furthermore, where each approach in the video was queued, the capacity of a lane could be estimated from the discharge flows (approximately 500 vph per lane with the existing timing plan). In some cases, the data tables we received and the JICA counts appeared to be flawed (e.g. many more vehicles were counted entering an interchange than leaving it). In these cases, intersections were calibrated to achieve realistic flows consistent with those observed in the video.

Other unrealistic traffic behavior at unsignalized intersections required adjustments to signage in order to prevent the traffic from locking up the simulation in an unrealistic way.² Yield signs were added to many smaller intersections to achieve a more balanced flow of vehicles from different approaches. In their absence, a timid driver in the simulation may wait forever to make a left turn when in reality impatience would eventually lead to a more aggressive maneuver or change of route. In some cases left turns were banned in the simulation where the markings of wear in aerial photographs suggested these maneuvers are rare. This prevents unrealistic gridlock from stubborn left-turning vehicles which block traffic but never complete the turn due to queues in the opposing direction.

²This is a problem with microsimulation in general, not just CORSIM, when taken out of their domain of application.

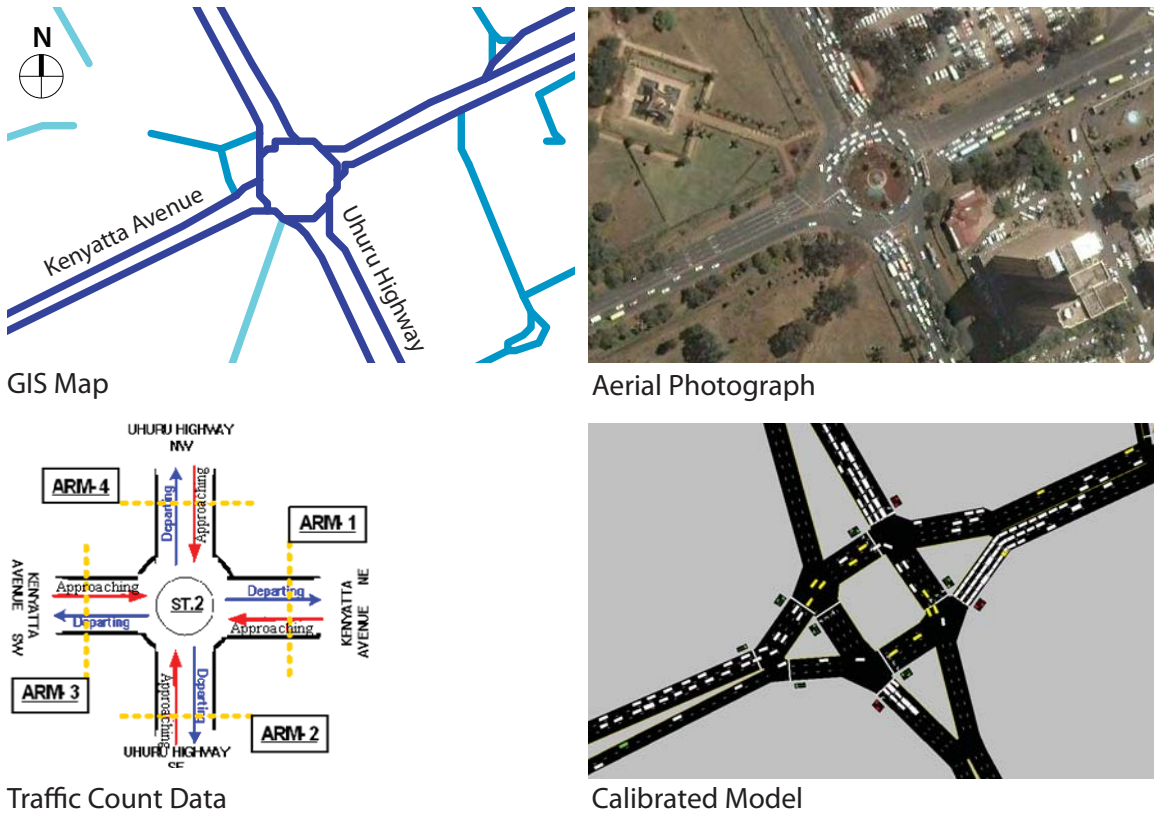


Figure 5. Data from 3 sources were used to calibrate intersections in the model, such as Uhuru Highway and Kenyatta Avenue shown here. The GIS map shows general network structure, the aerial photograph shows detailed lane configuration, and signal phase timings (not shown) provide enough information to model the intersection geometry and control. Traffic counts of approaching and departing vehicles provide performance data for calibration.

Table 2. Calibration of Uhuru–Kenyatta Intersection for AM Peak Hour (7:00-8:00)

Approach	Inbound (vph)	Outbound (vph)		
		Data	Uncalibrated	Calibrated
Kenyatta Ave, NE	1163	2154	1236	2094
Uhuru Hwy, SE	1866	1684	996	1652
Kenyatta Ave, SW	1886	1570	1182	1562
Uhuru Hwy, NW	2286	804	524	818

3.3.2 Demand Calibration

The OD table for Nairobi was estimated from cordon counts at intersections outside the city center. Despite unknown OD information, we are confident, based on prior experience (Geroliminis and Daganzo, 2007), that any reasonable OD table consistent with the data should provide realistic traffic patterns and levels of congestion for status quo analysis. Given the traffic counts available, possible OD tables for the morning and evening commute were estimated (see Figure 6). With traffic patterns within the CBD unknown, internal traffic was generated to match congestion levels suggested by the traffic speeds reported in the JICA report. Two additional OD tables (one with predominantly eastbound traffic, the other with predominantly westbound flows) were generated to compare the macroscopic relationships across different demand scenarios. The simulation shows that in Nairobi the relationship between network accumulation and flow is insensitive to the demand pattern, as described later in Section 4. Therefore, this calibration does not affect the shape of the MFD, but it is important for determining where current traffic conditions lie on this curve.

3.4 Traffic Assignment

An important aspect of the traffic model is how each vehicle’s route choice is determined. In CORSIM, the traffic demand can be entered in two ways: 1) as fixed traffic counts and turn movements at intersections or 2) as a time independent OD table. If the demand data is entered as trip generation and turn percents, then vehicles chose their routes implicitly by making turns in the prescribed proportions at each intersection. When traffic demand is entered via an OD table, CORSIM estimates a static equilibrium distribution of traffic on the network consistent with the demand and generates equivalent traffic generation and turn movements to recreate this distribution. The first approach requires detailed turn movement information. As this data was unavailable, the traffic demand was defined by an OD table. Another benefit of using OD demand is that this describes trips rather than traffic patterns, so if conditions on the network change, the same trips can be served by routing vehicles differently on the network.

A major drawback of CORSIM traffic assignment is the unrealistic manner in which drivers navigate the network. CORSIM performs static traffic assignment, based on a static equilibrium distribution of traffic demands which assigns turn percentages at each intersection based on the OD table, and does not adjust route choice if demand or traffic conditions on the network change over time. For this project, we modified CORSIM with scripts to incorporate a dynamic, stochastic traffic assignment navigation algorithm that allowed drivers to adapt to existing traffic conditions. A detailed description of the algorithm is provided in the Appendix C.

4 Nairobi Traffic Model: Status Quo Analysis

We find that central Nairobi (as shown in Figure 2) has a reproducible MFD. We also identify some factors affecting its character and finally forecast what may happen in the future if nothing is done while travel demand grows. The analysis uses the model described in Section 3 fitted to the most recent data available. This includes some knowledge of which streets are congested and the traffic flows at specific intersections. The analysis differs from previous applications of the MFD in that the street traffic is composed of two vehicle classes with different operating characteristics: private vehicles, and matatus. Furthermore, the

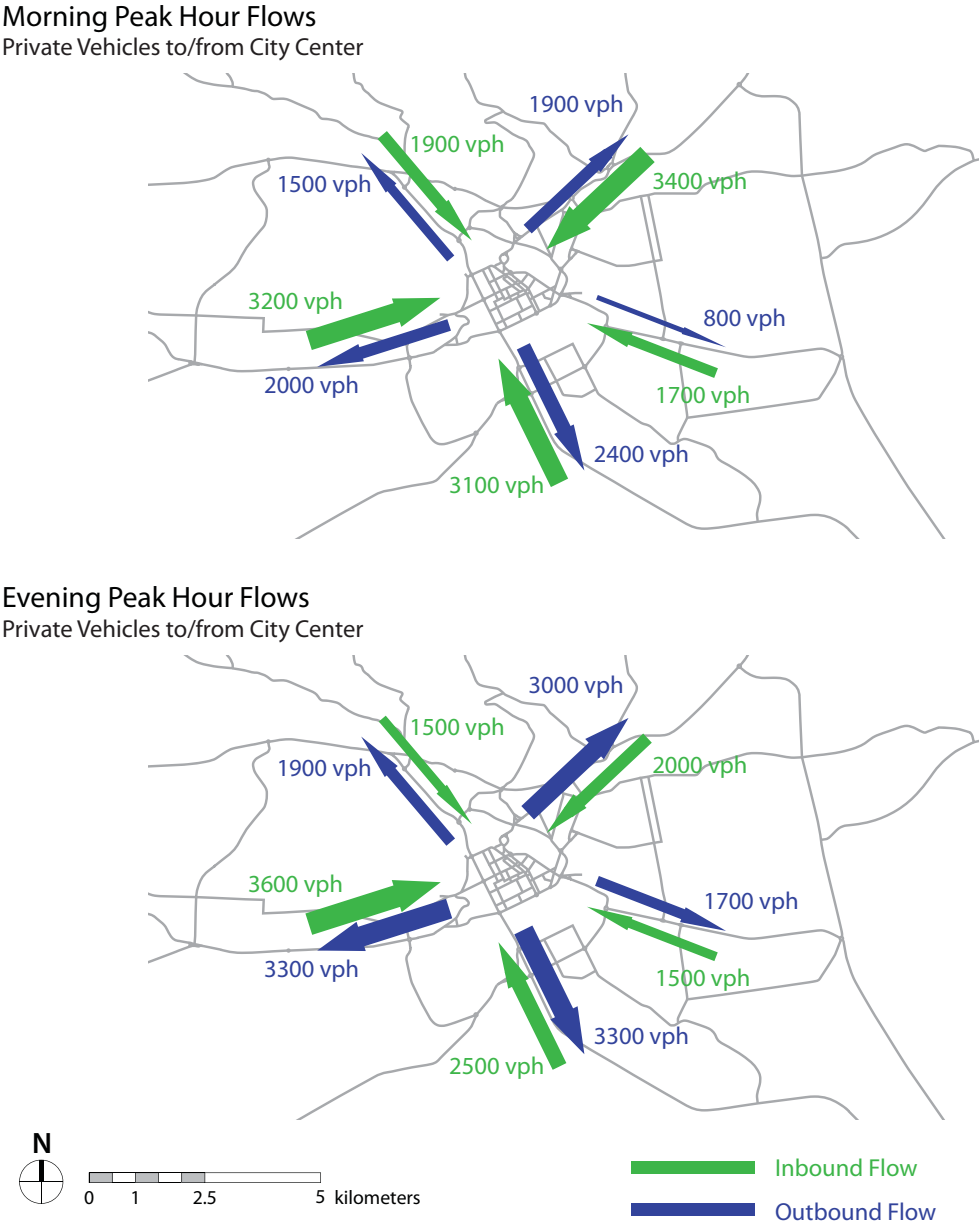


Figure 6. The origin-destination tables used in simulation were estimated to match aggregate morning and evening peak flows into and out of the CBD, based on intersection flows from the data provided. In the morning, the predominant direction of trips is into the city center, and in the evening, there are large flows in both directions, but more exiting.

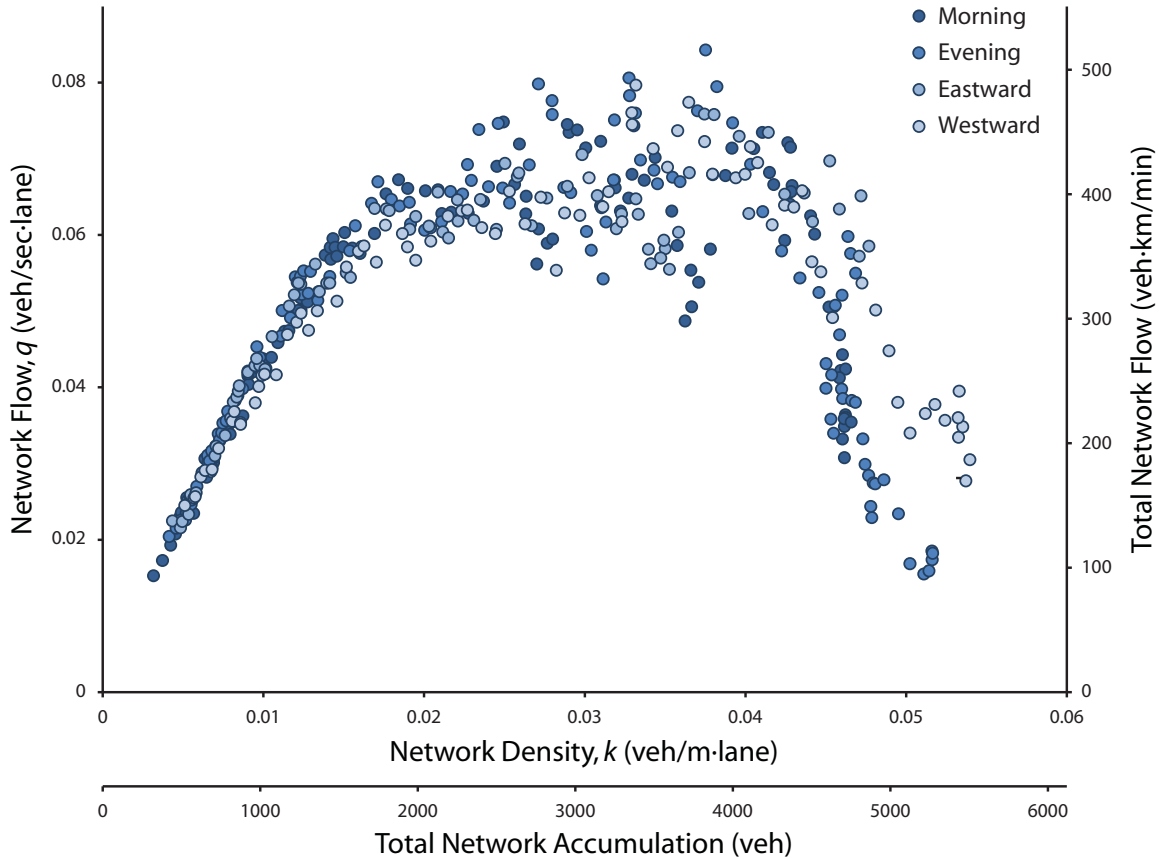


Figure 7. Simulated MFD for central Nairobi with 4 different demand scenarios.

street network in central Nairobi is not homogeneous and most intersections are not signal controlled. Results are presented below.

4.1 Reproducible Relationship Exists

Figure 7 shows that a reproducible macroscopic relationship exists between the number of vehicles on the streets of central Nairobi and the vehicle flows served by the network shown in Figure 8. This relationship is consistent for different demand patterns. The estimated OD table for both the morning and evening peak periods are plotted to show that there is a consistent aggregate network behavior. Other very different OD tables with traffic flowing mostly eastbound or westbound are also plotted on the same figure to show that this MFD applies to the network for a broad range of demand distributions, so it does not matter that we do not have sufficient data to know the demands in Nairobi in great detail.

The shape and size of the MFD is as expected. The uncongested traffic conditions fall consistently along the network average free flow speed up to an effective network capacity. Note that this network average speed is not the cruising speed of traffic on individual links, but the average speed that vehicles experience over the course of a trip including stops at intersections. This speed includes streets with different free flow speeds (i.e. arterials and small side streets), so trips that primarily use major arterials will be faster than this average.

Nairobi Central Business District
Streets in Study Area Included in Simulated Nairobi MFD

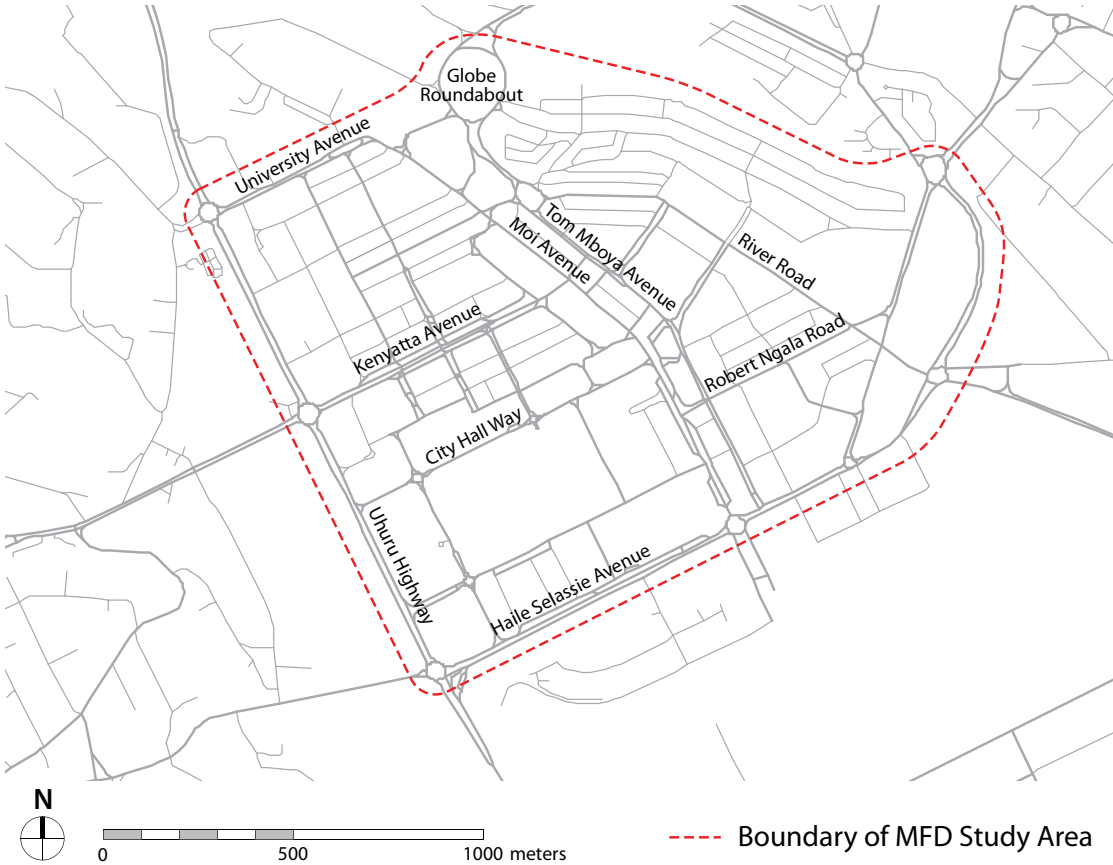


Figure 8. Every street shown within the boundary of Nairobi’s CBD study area is included in the MFD.

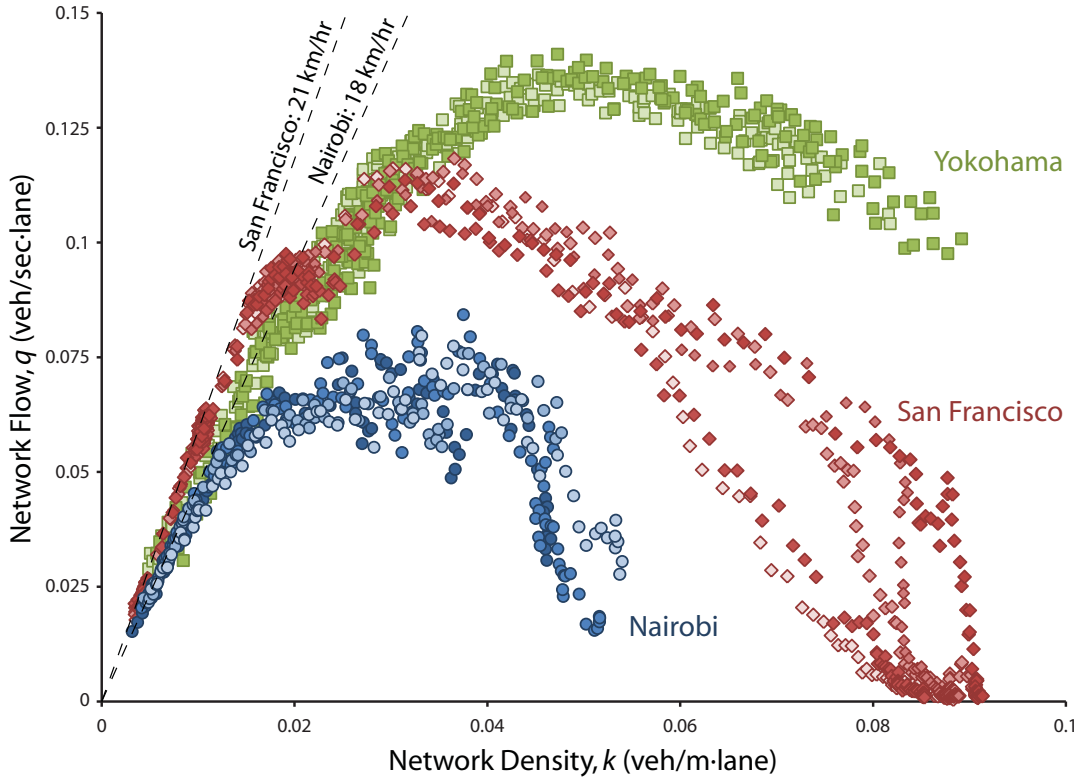


Figure 9. Comparison of central Nairobi with the San Francisco and Yokohama MFDs on a per lane basis.

The network free-flow speed and capacity in Nairobi’s CBD are less than those of San Francisco and Yokohama as shown in Figure 9. This is not surprising, because Nairobi’s streets are not as well connected and the intersections are generally not signal controlled, so the ability of each lane in Nairobi to serve vehicles is expected to be somewhat less than in cities with more infrastructure and advanced traffic control systems. Furthermore, the vehicle fleet contains a large number of matatus which slow traffic by stopping for passengers.

4.2 Some Factors Affecting the MFD

There are changes that can affect the shape of the MFD itself. This relation depends on the ability of the network to move traffic, so the MFD depends on the structure of the street network and how its intersections are controlled. It can also vary with weather conditions. If, for example, rainy weather reduces the free-flow speed of vehicles by approximately 10%, lane discharge capacity by 40%, as well as adding a couple of seconds delay to start-up loss time for vehicles at intersections, the capacity of Nairobi’s intersection will be reduced and this will be reflected in the MFD. Figure 10 shows the results of simulating the same demand scenarios on a network subject to rainy weather effects. Note that in serving the same demands, the network will tend to be more congested and for a longer period of time, as indicated by the center of gravity of the points along the MFDs in the two simulations. Data was not available to make a quantitative comparison of dry and rainy weather network

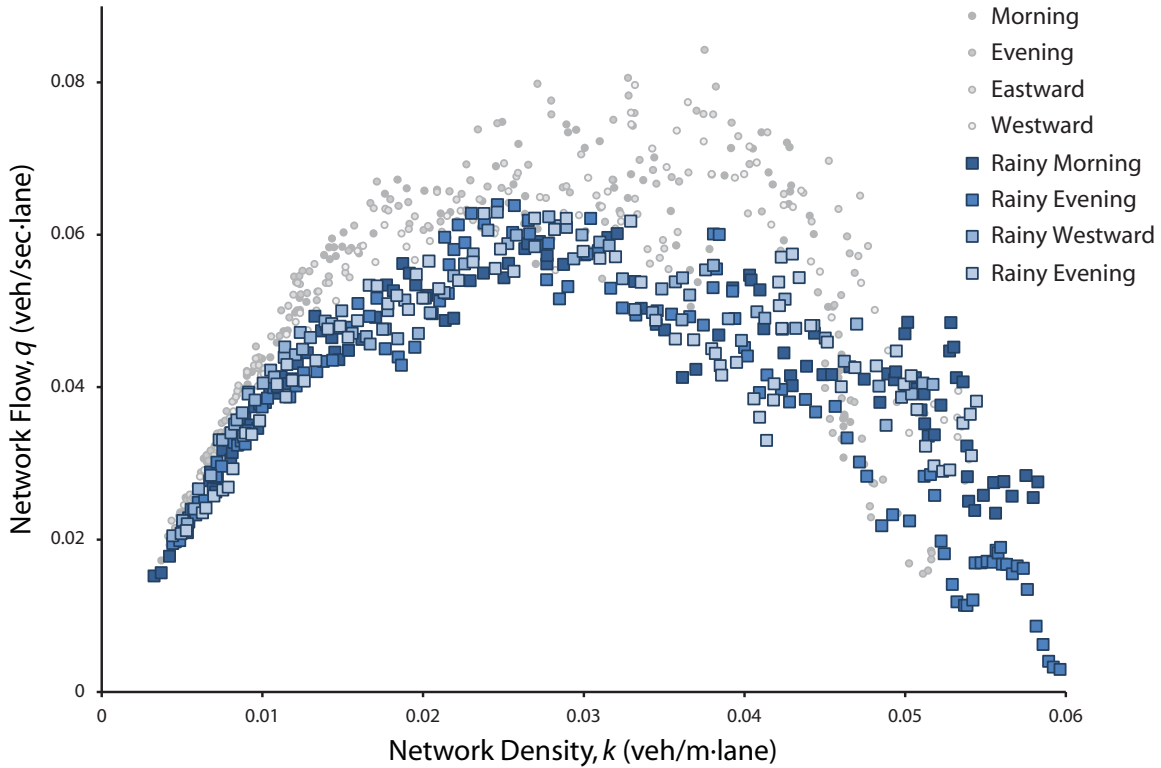


Figure 10. Rainy weather reduces the speed and flow of traffic in the city, so the smaller MFD suggests that traffic conditions will be more congested for the same demand.

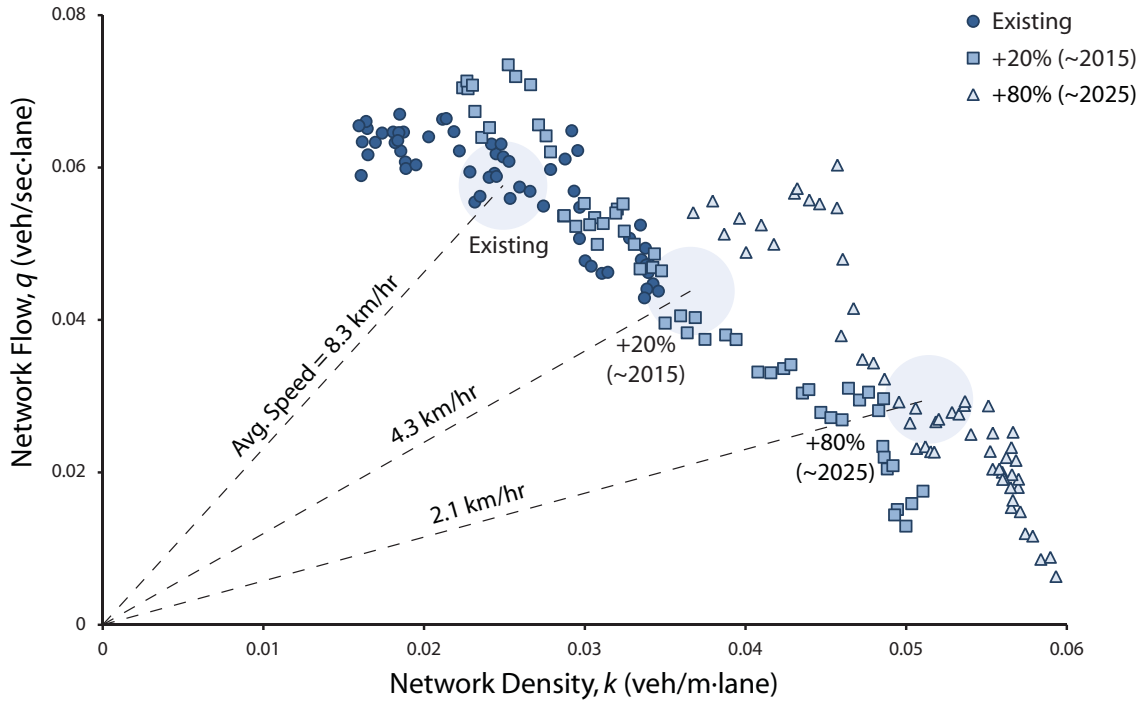
performance, but this example shows qualitatively what the effects of weather can be.

4.3 Effect of Increased Demand

As the population of Nairobi grows, so does the vehicular traffic. Section 4.1 showed the MFD resulting from existing demand patterns scaled from light to heavy traffic in order to show the full range of vehicle accumulations and traffic states. Although growing demand will not change the shape of the MFD, it will change where on the MFD traffic states lie. Therefore, it is meaningful to compare the existing conditions to scenarios with increased demand. A series of scaled up demands were simulated where the proportion of flows for each OD pair remained constant, and the resulting macroscopic traffic conditions are shown in Figure 11. In both of these cases, the accumulation of vehicles on the network is increased and the congested conditions in the city are more extensive. Note that if the demand were to increase by 80%, as is expected if current trends persist to 2025 (Katahira & Engineers International, 2006), it could not be served. In reality, the present rate of traffic growth cannot continue indefinitely, because the street network has finite capacity and will tend to gridlock. Once the city is gridlocked with vehicles, people will be forced to find another way to travel.

Figure 12 shows comparisons of the total vehicle hours traveled with existing conditions and increased demand. The time vehicles spend in the system is important because this reflects fuel consumption and vehicle emissions which matter in aggregate. This value is

Morning Peak Hour (Existing and Future Growth Scenarios)



Evening Peak Hour (Existing and Future Growth Scenarios)

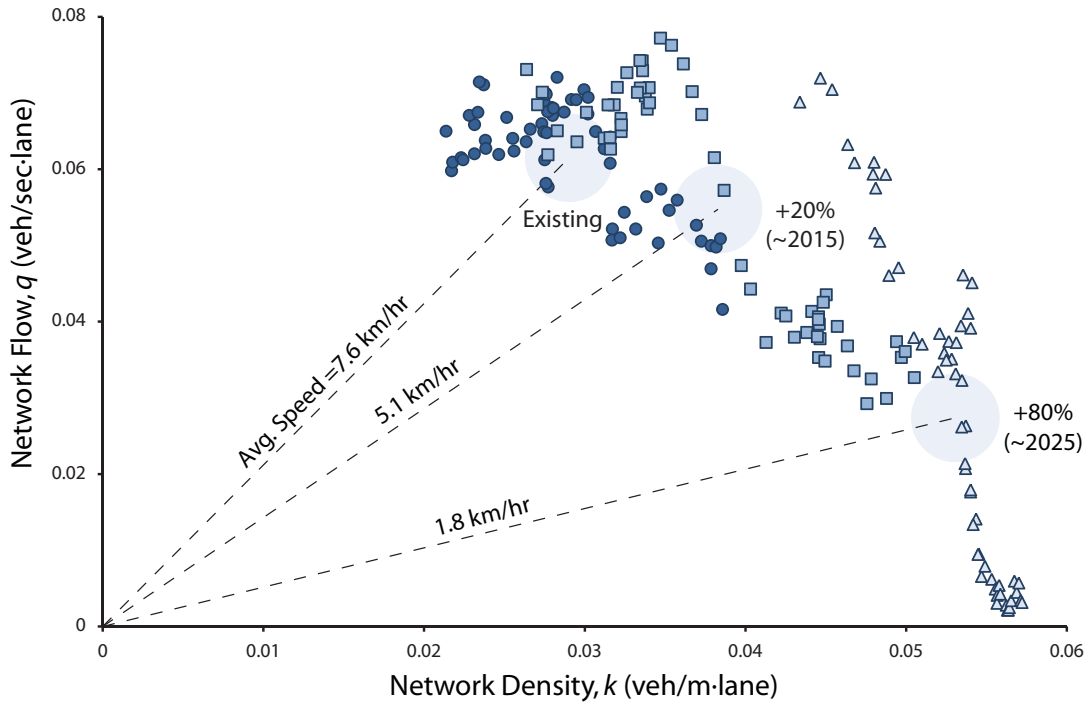


Figure 11. Morning and evening peak hour demand simulated for existing conditions (100%), scaled by 120% (approximately 2015), and scaled by 180% (approximately 2025).

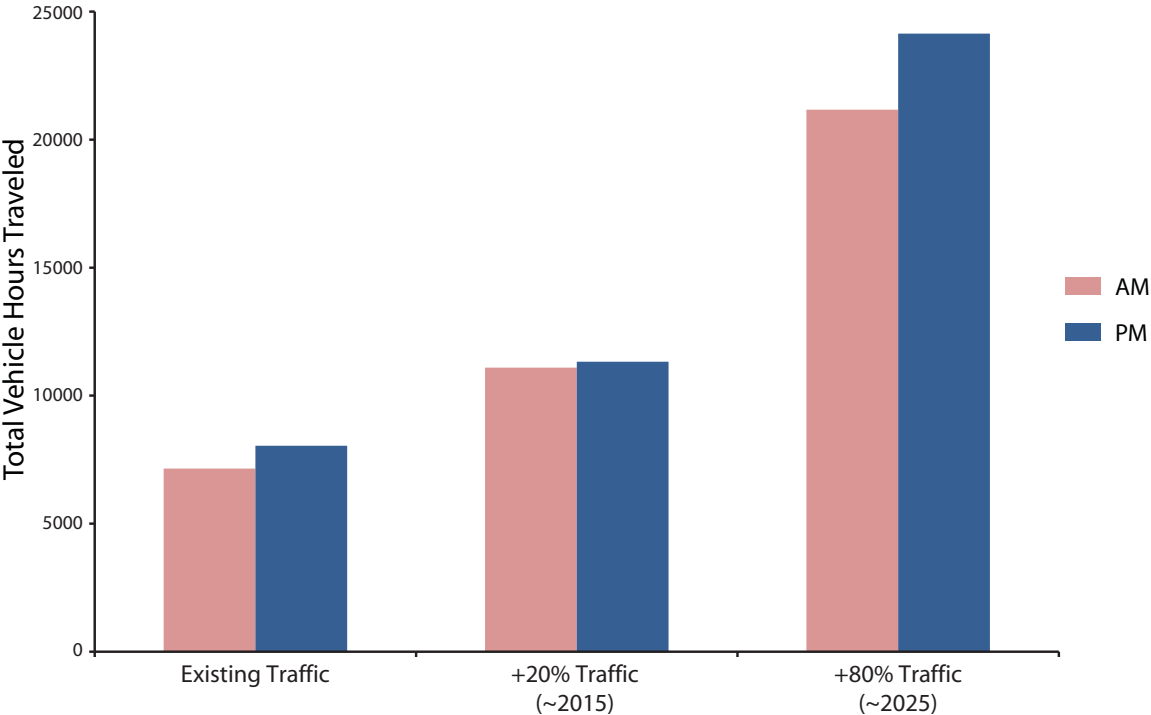


Figure 12. Comparison of total vehicle hours traveled for different demand scenarios in AM and PM peak hours

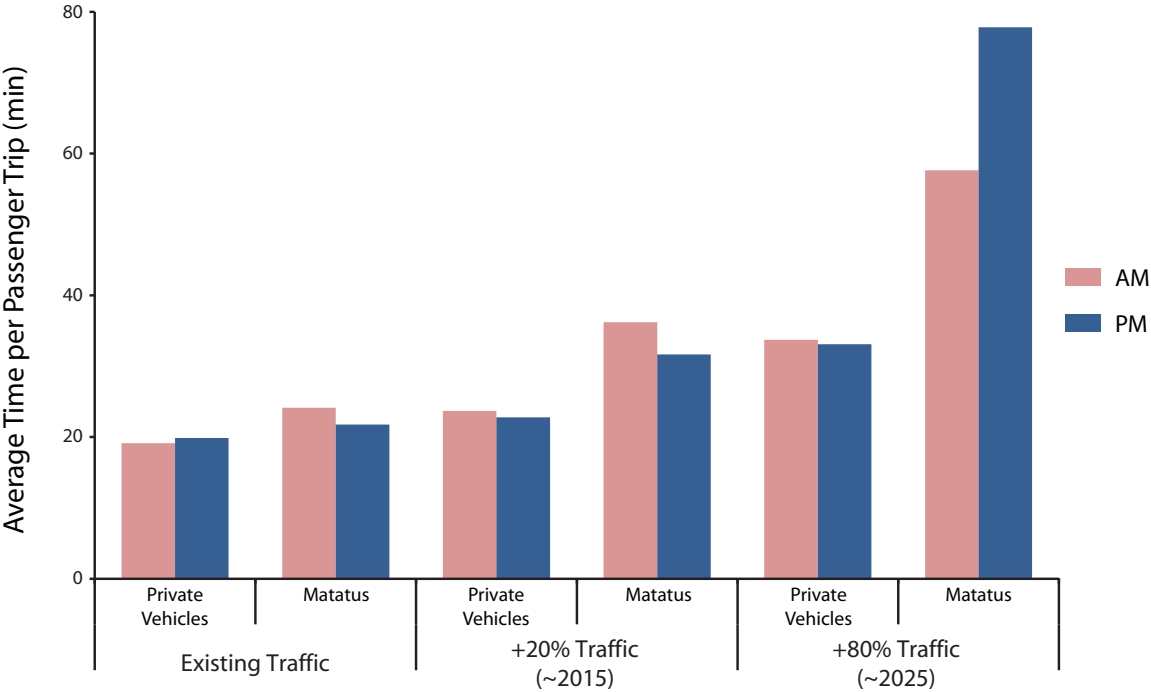


Figure 13. Comparison of average person hours per trip for different demand scenarios

expected to grow faster than the increase in number of trips because congestion will cause each vehicle to spend more time on the road.

The average time per passenger shown in Figure 13 reflects the delay experienced by travelers as a consequence of traffic congestion, and separates the experience of passengers in different vehicle types. The more rapid increase in simulated matatu travel times under congested conditions is due in part to the fact that the simulation assumes that matatus must follow a prescribed route and therefore cannot reroute to bypass congested parts of the network. The average trip duration is averaged across the entire network, and delays in the center are expected to grow more quickly as implied by the falling network average speeds shown in Figure 11. Note the rapid deterioration in the level of service if nothing is done.

5 Problem Diagnosis and Policy Recommendations

The original mission of our project was to illustrate what might happen to Nairobi’s mobility if nothing is done. However, in the process of analysis we were able to identify a number of problems. In the following subsections, we evaluate some cost effective measures intended to address these issues. We start with policies that change where on the MFD traffic conditions occur and conclude with policies that change the shape of the MFD itself.

5.1 Metering Vehicle Entry

The MFD shows that congested traffic conditions occur when vehicle accumulations exceed a critical amount and network flow drops below capacity. This is a waste of the street infrastructure, because a greater network flow could be achieved if the accumulation of vehicles in the center were controlled, and thus the vehicles would travel faster on the network so that they reach their destinations more quickly. Therefore, all passengers using the road network benefit by controlling the vehicle accumulation to prevent congested traffic conditions.

A method used in Zürich, Switzerland, to keep traffic from becoming congested is to adjust the traffic signal timings around the edge of the city center to limit the rate at which vehicles can enter (Ott, 2002). By monitoring the speed of the transit vehicles in the city, traffic controllers only restrict entries when the speed of buses and trams starts to drop due to congestion. In this way, entry to the city center is metered to preserve efficient operation of the street network. Drivers of private vehicles also benefit because traffic in the center does not jam, so despite a short wait to enter, traffic conditions allow them to reach their destinations faster.

In order to use the MFD for real time control strategies, the traffic in the city center must be monitored. An estimate of traffic conditions in Nairobi’s CBD does not require detailed sensor data to be collected on every street. A few vehicle probes indicating the average network speed of traffic is enough to know if traffic is uncongested or where conditions lie on the congested branch of the MFD. Sufficient data for some basic control strategies could be collected by equipping a fleet of vehicles, such as matatus or taxis, with GPS transmitters.

Since all traffic entering Nairobi’s CBD must pass through one of six gateway interchanges, it would not be difficult to equip these entrances to the city center with traffic signals in order to meter entering vehicles. However, experimentation with metering in the simulation revealed that this policy may be of limited effectiveness in Nairobi, because the

limited number of gateways to the CBD is already a physical constraint on the rate at which vehicles enter. More restrictive metering of vehicles entering the city will reduce congestion in center, but may cause large queues on inbound routes.

The properties of the road network suggest that there will be greater traffic congestion in the evening when queues from vehicles trying to leave the city center spill back into the CBD. This is consistent with the data from JICA which shows that congested conditions in the center are more extensive during the evening peak than in the morning. This is illustrated visually in Figure 14 which summarizes the location of congestion in Nairobi based on traffic speeds reported by JICA and also recreated in the simulation. This suggests that metering vehicle entry during the evening commute would be ineffective.

5.2 Techniques for Evening Commute

In the morning, methods of restricting vehicle entry to the center can limit congestion. However, in the evening because trips originate in the center, it is difficult to limit the accumulation of vehicles in the network using traffic metering because the generation of trips inside the city fills the streets with enough vehicles to jam the system.

One approach to reducing evening congestion is to spread peak demand. This could be accomplished by staggering work hours (through incentives to employers) or implementing a variable pricing strategy for parking or transit use (incentives for employees). Spreading the peak demand reduces the rate at which trips are generated in the CBD. By controlling the number of vehicles in the system, the exiting flow of vehicles from the center can be maintained at maximum so that trips are served as quickly as possible. The necessary reduction in peak vehicle trip generation could also be accomplished by shifting trips to modes that carry more passengers. The provision of more attractive public transport options can reduce vehicle demand overall, thereby reducing congestion and benefiting all road users.

5.3 Intersection Operations and Sensitivity of MFD

The previous sections discuss policies that change where on the MFD the traffic conditions lie. Traffic in Nairobi can also be affected by changes to the shape of the MFD itself by changing how the network is controlled internally, not just on the perimeter. The shape of the MFD is very sensitive to how intersections are controlled and their ability to serve vehicles. This is not surprising because the MFD describes the collective ability of all the streets in the network to carry vehicle flow, and the flow that a street can carry depends on the capacity of its intersections. In this section, we look at the operation of intersections with particular emphasis on traffic circles, and the effect they have on traffic congestion in Nairobi. The conclusions apply to both the control of intersections within Nairobi's CBD and on the radial roads leading from surrounding communities to the city center.

5.3.1 Spillback on Traffic Circles

Most of the intersections of major roads in Nairobi are controlled with traffic circles. For low traffic demands, traffic circles have the advantage of not requiring electronic signals to serve flows from multiple approaches. A problem with traffic circles is that they are susceptible to jamming in all directions from queue spillbacks when the network becomes congested. This undesirable effect occurs because the traffic circle serves all directions simultaneously on the same circular section of road. As illustrated in Figure 15, if a queue from another part of the network spills back to an exit from the traffic circle, vehicles will fill the entire circle

Traffic Congestion in Nairobi
Streets with Speeds Under 20 km/hr

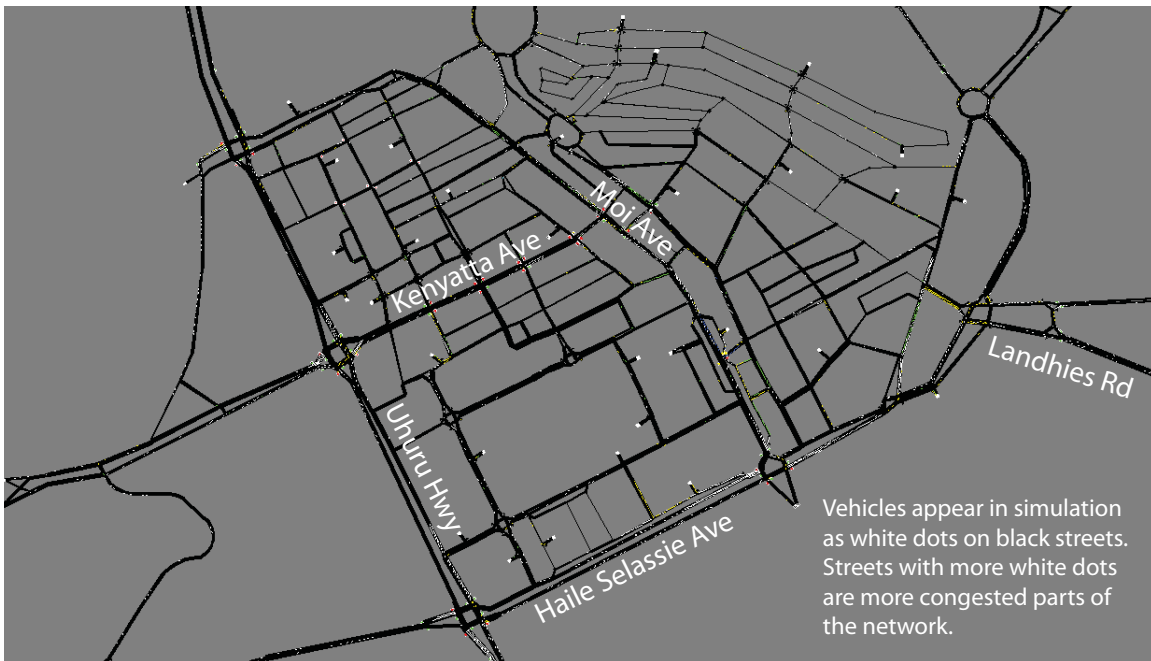
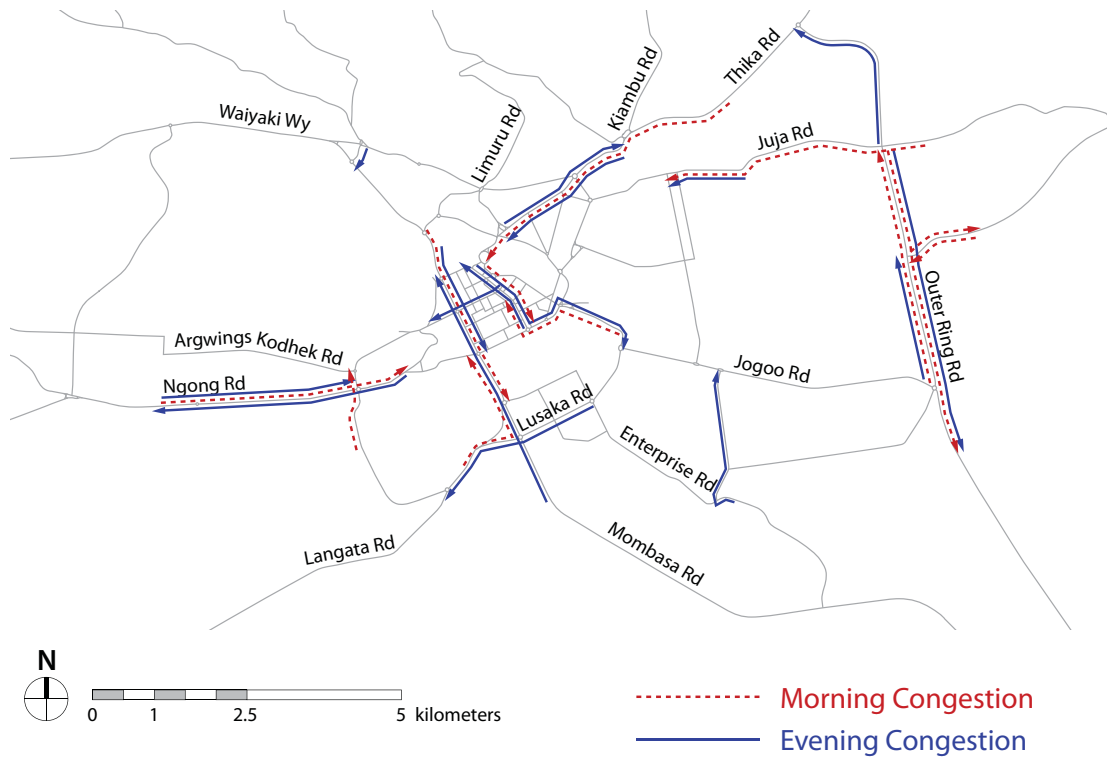


Figure 14. Queues in the simulation emanate from busy intersections along major roads similar to the reported patterns of congestion in Kathira & Engineers International (2006).

blocking all approaches. This is in contrast to a signal-controlled cross intersection where only the approach upstream of the intersection is blocked, and traffic headed in the crossing direction is not impeded. The traffic approaching from the direction of the queue spillback (top of Figure 15) will always be able to discharge into any of the possible downstream approaches, whereas a traffic circle can jam completely even if all drivers follow traffic laws.

Figure 16 shows that the phenomenon of spillback queues blocking traffic circles is not only theoretical but occurs today in Nairobi. Traffic circles tend to spread congestion faster than if intersections were signal controlled. This problem is especially debilitating at the few traffic circles through which all traffic entering and exiting the CBD must flow. If queues of traffic entering the city in the morning back up to traffic circles upstream, vehicles exiting the city center can also be blocked. In the evening, the jamming of a traffic circle further reduces the rate at which trips can depart the city center. Consequently, vehicles accumulate more quickly and contribute to widespread gridlock in the city center. Therefore, it is important that critical intersections are designed to prevent this kind of locking, and that road use policies do not cause queues of traffic to spill back into traffic circles.

5.3.2 Signalized Traffic Circles

Another disadvantage of traffic circles is that they cannot be controlled by signals as effectively as ordinary intersections because of the complexity of the vehicle paths (discussed in Section 5.3.2). A few of the busiest traffic circles on the Uhuru Highway are supplemented with signal controls. From video of the intersection of Uhuru Highway and Kenyatta Avenue, we can see that the signals are timed to give each approach one quarter of the cycle. The 2-minute cycle length is very long, however, and by using traffic signals to control vehicles entering the traffic circle, the intersection's capacity is much less than if the streets crossed directly.³ A standard signal controlled intersection allows opposing directions of traffic to flow simultaneously so that each approach could be served for nearly half the cycle time.

The difference in intersection capacities is illustrated in Figure 17 with a comparison of the existing signalized traffic circle control and a signal controlled intersection. In order to improve the capacity of the existing street infrastructure, we recommend focusing on the operation of intersections, and in particular considering the conversion of major traffic circles into signalized intersections.

Another feature of signalized intersections which does not appear to be used currently as a traffic control strategy is to vary the signal times for different times of the day. This could be used to restrict entry to the center during times of day when the CBD is likely to be congested and to increase the capacity of routes exiting the city center in order to control vehicle accumulations. With some monitoring of traffic conditions in real time, the signals could be controlled dynamically in response to actual vehicle accumulations in the city center.

5.4 Adding Infrastructure

As explained in Section 2.3, the lack of redundant links in the network means that traffic cannot reroute around congested streets. The result is that compared to other cities,

³If signals are not properly set, they can create gridlock in traffic circles by allocating priority poorly. This problem was not observed in the video of Uhuru Highway and Kenyatta Avenue.

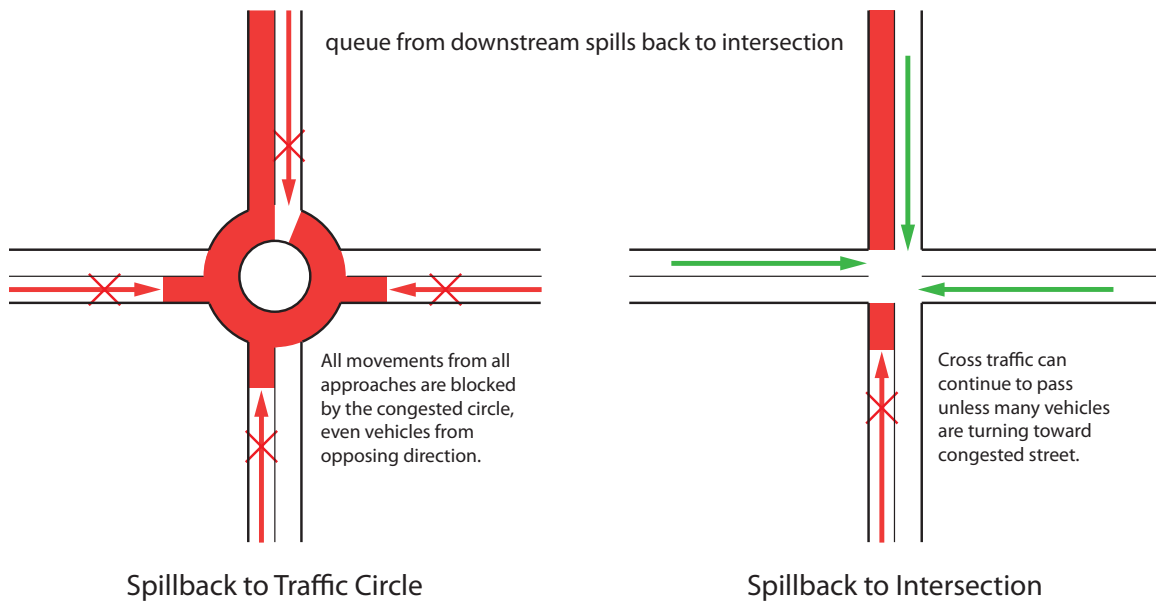


Figure 15. Comparison of the effects of a queue spillback in a traffic circle and intersection. Spillbacks block all traffic in traffic circles but only some of the movements at standard intersections.



Figure 16. Example of spillback jam blocking all approaches in an aerial photo of the intersection of Haile Selassie Avenue and Race Course Road (Source: Google Earth)

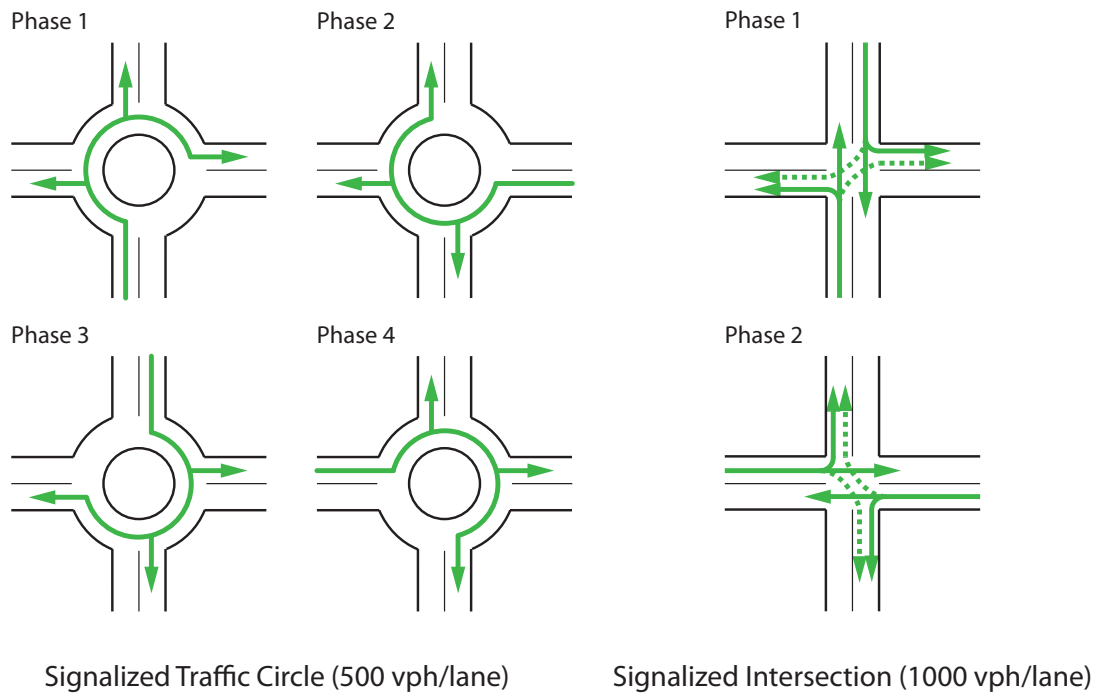


Figure 17. A signalized traffic circle gives each approach its own phase, so each lane is served for only one quarter of the cycle. A signalized intersection serves opposing approaches simultaneously so that each lane is served for nearly half of the cycle. Estimated lane capacities shown are consistent with observed flows in Nairobi.

Table 3. Simulated Effect of Dedicated Lanes for Matatus and Private vehicles in AM and PM peak hours

	Measure of Performance	Mixed	Dedicated	% Change
Morning	Network Total VHT	7122	7249	2
	Matatu Routes (min. for route)	15.1	14.6	-3
Evening	Network Total VHT	8386	8875	6
	Matatu Routes (min. for route)	15.4	16.4	6

Nairobi’s street network can serve fewer vehicles in total but also fewer vehicles per lane (see Figure 9). Strategically adding redundant lanes to the network so that drivers are able to choose alternative routes will not only increase network capacity by the number of lanes added. Redundancy will also increase the capacity of all lanes in the network by distributing traffic more evenly.

Another factor restricting the capacity of Nairobi’s street network, although not incorporated in the simulation model, is the presence of pedestrians who use the streets for transport and commerce. Providing pedestrian facilities will increase the capacity of intersections and roads. For both safety and efficiency, transport in Nairobi would be improved by expanding sidewalks to provide space for pedestrians apart from motorized traffic.

5.5 Dedicated Matatu Lanes

For cities such as Nairobi, where a large number of residents use some form of public transport, the focus of transportation policy should be on passenger throughput as opposed to vehicle throughput. One policy option that would require relatively little new infrastructure is dedicated lanes for buses or matatus. Figure 18 shows how one of the lanes used by all traffic could be converted into a lane for exclusive use by buses or matatus which carry the majority of motor vehicle passengers. This research analyzed the effect of a dedicated matatu lane outside the CBD on the Waiyaki Way–Chiromo Road–Uhuru Highway corridor on sections where the arterial has 3 lanes. This corridor runs from the northwest of the city to the center, and a potential dedicated matatu lane is analyzed for the stretch between Lower Kabete Road and University Way. The morning analysis considered a dedicated lane and the effects on traffic heading toward the CBD, and the evening analysis looked at a dedicated lane and effects on traffic leaving the center of Nairobi. The simulation was performed with matatus, but the same principles apply to dedicated lanes for buses or bus rapid transit.

5.5.1 Morning Commute

During the morning commute, the simulation was performed with an inbound matatu lane and the results are shown in Table 3. The effect on traffic across the Nairobi street network in terms of vehicle hours traveled is small, but benefits are shown for matatu operations. The simulation data for the matatu routes is reported as travel time for the entire route which includes the corridor of interest and a small segment with the CBD.

The reduction in travel time by matatu routes using the dedicated lane is small but shared by more passengers than the private vehicle commuters who experience increased travel times on the corridor. If matatus carry enough passengers, then the time savings can outweigh the increased delays. There are approximately twice as many matatu passengers

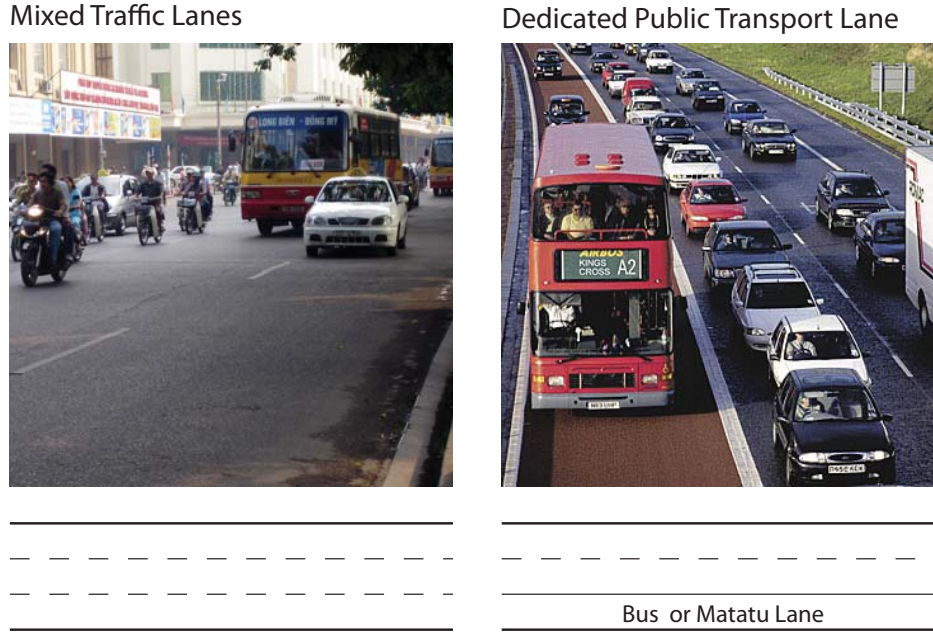


Figure 18. Traffic lanes can be shared among all modes (left) or dedicated to buses or matatus (right) which carry many more passengers per vehicle.

as private vehicle users in the Waiyaki–Chiromo–Uhuru corridor (Aligula et al., 2005), so data from this simulation resulted in a net increase in passenger travel time. Nevertheless, with sufficient numbers of passengers using public transport, or with decreased congestion in the center of the city, it is possible to improve traffic conditions in Nairobi with the use of dedicated lanes.

A drawback of dedicating a lane of traffic to matatus is that less space remains for the queues of private vehicles. Figure 19 shows that queues approaching the intersection of Uhuru Highway and University Way grow longer if a lane is dedicated to matatus. These snapshots of the simulation were taken with the same demand and at the same time point in the simulation. The same flow of private vehicles is squeezed onto fewer lanes so the queue must be longer. This is problematic if the queues block intersections upstream (as described in Section 5.3.1) but this is not likely to happen in the morning commute unless queues from traffic entering the city are already very long.

5.5.2 Evening Commute

During the evening commute, the outbound matatu lane was the focus of the analysis. As can be seen in Table 3, dedicated matatu lanes worsen the system during the evening commute. Similar to metering the evening commute, the dedicated matatu lanes cause queues of automobiles to spill back into the city center and block traffic circle exits which increases system-wide delay. Since blocks in the CBD are short, this negative effect occurs easily. Furthermore, congestion in the center delays both matatus and automobiles because access to key traffic circles is limited. The travel time data for matatus in Table 3 shows an increase because this value includes the extra time spent within the CBD.

As described in Sections 5.2 and 5.3, the evening commute can be improved by changing key traffic circles to signalized intersections so that capacity for exiting vehicles is increased.



Figure 19. Queues on Uhuru Highway approaching University Way grow longer if a lane is dedicated to matatus, because less space is available on the street for the same number of private vehicles.

This would also negate some of the harm associated with the reduction in capacity for automobiles. If matatu lanes are to truly benefit matatus, then dedicated lanes may need to be extended into the center as dedicated matatu streets so that high capacity vehicles are not blocked by the increased congestion in the center.

6 Discussion and Future Work

This report outlines an approach to use simulation to derive the macroscopic relation between vehicle accumulation and network outflow at the neighborhood level based on the street network and traffic operation. The results presented in the previous sections are qualitatively applicable to Nairobi because the model and simulation are approximate. Although the precise traffic speeds and network capacity may differ in Nairobi, the general findings from the model apply to cities that share characteristics with Nairobi such as a poorly connected, asymmetric network. Other large cities with limited transport infrastructure and a high number of informal transit vehicles may benefit from similar policy interventions.

Nairobi's traffic is hindered by insufficient infrastructure, and improvements in the operation of overstructure such as buses and matatus require improvements to the road network itself. Viable transport policies rely on having at least enough infrastructure to carry the demand on efficient modes like public transport.

6.1 Caveats of the Model

Microsimulation has many drawbacks. Such models are highly data intensive and require extensive analysis to ensure that the results are realistic (Daganzo et al., 2007). Our study did not include detailed origin destination information or specific knowledge on matatu operations. Estimates of status quo traffic volumes and congestion levels could be improved with additional data. Furthermore, the microsimulation software is designed for the North American setting, so heavy modifications are required to represent conditions in Nairobi, and it is not possible to capture the traffic behavior exactly. Furthermore, matatu operations differ from western bus operations, so even after calibration, the model may not be fully capturing the interaction effects between matatus and other vehicles.

6.2 Future Studies and Monitoring

Despite the limitations of simulation, the study has benefits. Because the results are interpreted on a macroscopic or neighborhood level, they are robust for different demand patterns (so the lack of detailed demand data is not a problem) and the actual MFD for Nairobi should not differ significantly from the simulated one. So, the simulation can be used to analyze policies such as those.

In addition to metering traffic and signaling intersections, improved connectivity could also increase traffic flows significantly. By adding a few key links to the city, the highly peaked traffic of Nairobi can be better served. Other less costly policy measures that could be analyzed for Nairobi is the use of one-way streets in the CBD to more efficiently move traffic and the banning of right-hand turns at key intersections. The model can also be used to analyze the potential benefit of bus rapid transit (BRT) and limiting the entries of vehicles into the downtown area. Moreover, all of these strategies are synergistic so that they can be combined as joint strategies to reduce congestion.

It is important to note that in all of these scenarios, the simulation tool can help to compare the aggregated effects of policies at the neighborhood level, but it is more important to monitor actual conditions on the streets of Nairobi. An MFD describing actual conditions in Nairobi could be estimated by collecting data on real traffic conditions using methods such as vehicle probes. A fleet of vehicles such as matatus can be equipped with GPS equipment just as taxis were used as traffic probes in Yokohama (Geroliminis and Daganzo, 2008). This approach is less problematic than the intensive data collection required for microsimulation, and can provide an indication of how much the simulated MFD differs from actual conditions in the city. By monitoring the performance of Nairobi's street network and taking measures to increase traffic flows, the system can be improved.

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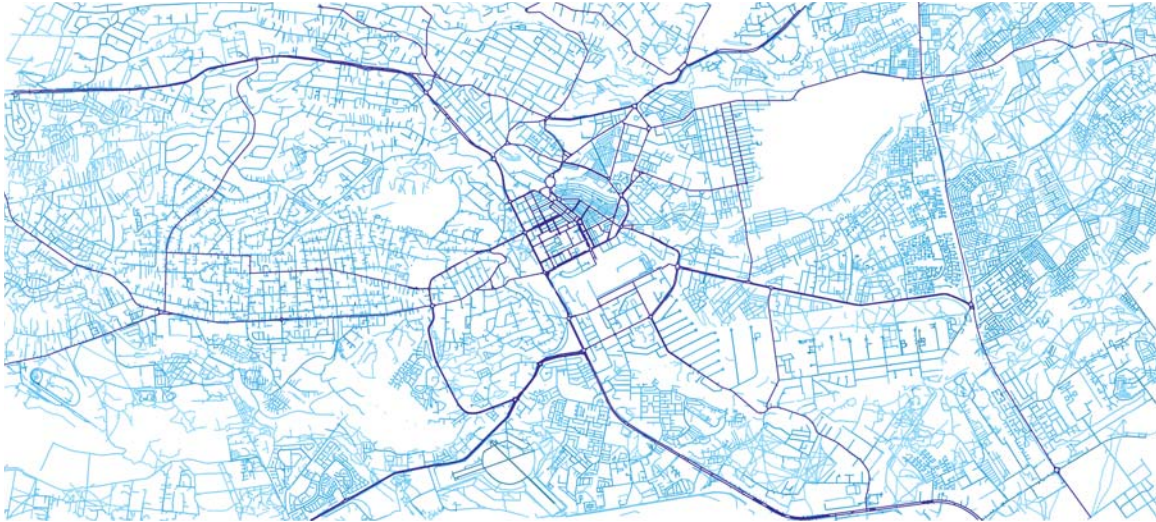
A Data Sources

Table 4. List of Input Data Sources

	Data	Source
Streets	Scale map of Nairobi streets including street categories	Columbia University CSUD GIS Map
	Number of lanes for each street	Estimated from GIS Map, Aerial photos from Google Earth, Windows Live
	Block length	GIS Map
	Free flow speed	Estimated from data, JICA
	Jam spacing	Aerial photos
	Lane capacity	Estimated from data provided
Intersections	Map of intersections by category	JICA
	Description of each intersection/Type of control	JICA
	Signal phases/cycle time	City Council of Nairobi
	Traffic circle diameter	Aerial photos
	Traffic circle lanes	Aerial photos
OD Zones	Map of OD zones showing locations on street map	JICA, Aerial photos
	Map of parking	JICA, Aerial photos
	OD flows by time of day (morning peak, evening peak, off-peak)	Estimated from cordon counts
Public Transport	Map of matatu routes	JICA
	Matatu terminals	JICA, Aerial photos
	Matatu frequencies on each route by time of day	JICA passenger flows and waybill occupancy data
	Matatu daily passenger flows	JICA
	Matatu size	KIPPRA
System Perf.	Traffic counts for representative streets and intersections by time of day	Data provided, JICA
	Average speed of traffic	JICA
	Travel by time of day	Cordon counts

B Street Network Modeled in Microsimulation

Although the simulation study focused on identifying macroscopic traffic patterns in central Nairobi, the simulation covered a larger area of the city. All streets in central Nairobi were included in the model in order to capture the effects of the street hierarchy. Outside the city center, major arterials which carry the vast majority of motor vehicle traffic in Nairobi were included. These are the streets which carry the majority of traffic to and from the city center and the routes of most matatus. Figure 20 shows the street network in the simulation model. This network was calibrated and loaded with origin-destination demand tables as described in Section 3.



Streets on GIS Map



Streets in Simulation Model

Figure 20. This snapshot of the road network in the model shows all the streets that are included in the simulation runs.

C Incremental and Stochastic Traffic Assignment

As described in Section 3.4, demand in CORSIM is based on the vehicle entry flows at origin (or generation) nodes and the proportion of vehicles making each turn movement at intersections. In this way, vehicles in the simulation do not keep track of where they came from or are going, but make turns occur with the correct frequency at each intersection to generate the correct traffic patterns on the network. One method of entering demand into CORSIM is to specify the entry flows and turn percents directly, as these may be measured directly through extensive data collection.

An alternative method, and the one adopted in this study, is to specify an origin-destination (OD) table from which the equivalent entry flows and turn percents can be determined. The default traffic assignment feature in CORSIM can only accommodate a static OD table. The traffic patterns are then determined using either FHWA or Davidson impedance functions which approximate travel times as increasing functions of traffic flow. The traffic assignment algorithm then iterates to find user equilibrium. This one time assignment does not capture the dynamics of traffic congestion, so traffic can not reroute itself as parts of the network become congested.

In order to simulate route choice in a more realistic way, CORSIM's traffic assignment process was modified with scripts to achieve dynamic stochastic traffic assignment. This process involves reassigning traffic to the network at action points which fall at fixed time intervals over the course of the simulation so that drivers can respond to existing traffic conditions as we would expect in reality. This alternating process of assigning traffic, simulating, and then modifying the traffic assignment is illustrated in Figure 21. The assignment script uses Burrell's incremental method of implementing stochastic traffic assignment (Burrell, 1968). An added benefit of this method is that the OD table can change at each time period, so CORSIM can be used to simulate demand described by a time dependent OD table.

Burrell's method assigns traffic at each time step in several increments with random variations in link travel times to avoid all-or-nothing effects. In this way, traffic will be spread across routes with very similar travel times. The traffic assignment procedure uses CORSIM's traffic assignment feature. The effects of congestion are incorporated by using observed link speeds at each action point for the assigning traffic for the following time period. (This is done by modifying the parameters of the FHWA function so that link speeds are independent of traffic volume.)

The simulation process shown in Figure 21 involves the use of scripts to convert demand and observed traffic conditions into traffic assignment values which CORSIM can use in simulation. To simulate a street network and time dependent OD table, the link free flow speeds and OD demand for the first time period are fed into the script which then uses CORSIM's traffic assignment tool (modified as described above) to create entry flows and turn proportions so that traffic patterns in the simulation will match those intended by the stochastic assignment.

Following the first time period, the script extracts observed link speeds which take into account delays associated with queues on congested parts of the network. Then, demand from the OD table associated with the second time period is assigned using the same process and the actual link speeds. The resulting entry flows and turn proportions are applied at the simulation continues in through the second time period.

This process is repeated for as many time periods as are specified for the simulation. The parameters for this dynamic stochastic traffic assignment modification are the number

and length of each time period, the number of slices into which each OD table is cut to perform stochastic traffic assignment, and the magnitude of random variations applied to link speeds to avoid all-or-nothing effects. Shorter time periods and more slices used for the stochastic assignment, the better the results should be, but also the more computationally intensive the simulation becomes.

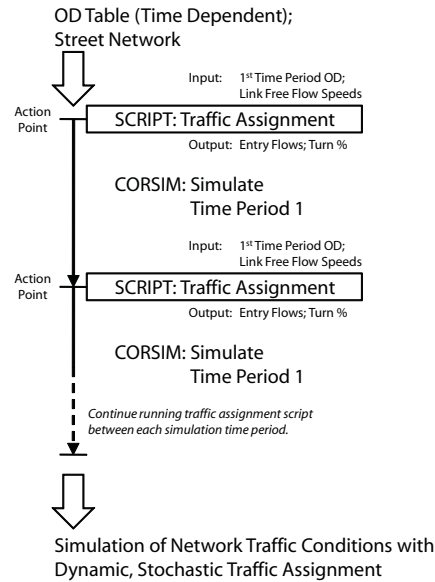


Figure 21. Modification to CORSIM to perform dynamic stochastic traffic assignment with a time-dependent OD table.