UNIVERSITY OF NAIROBI

SCHOOL OF ENGINEERING

FREIGHT TRAVEL TIME RELIABILITY ON THE NORTHERN CORRIDOR: A CASE STUDY OF THE ROAD SEGMENT IN NAIROBI

By:

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A thesis submitted in partial fulfillment for the Degree of Master of Science in Civil Engineering (Transportation Engineering) in the Department of Civil and Construction Engineering in the University of Nairobi

November, 2017

DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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To all striving against many odds for better living societies.

ACKNOWLEDGEMENTS

ABSTRACT

More than common congestion, transport reliability is emerging as an issue of greater concern on freight corridors. It has been estimated that costs associated with unpredictable travel form the bulk of the logistics costs of freight transport on the Northern Corridor, against much lesser direct delay costs. To assist the course of reliability on the corridor, this study evaluated freight travel time reliability on a key logistics stage section, the Northern Corridor Road segment in Nairobi. Applying a modelling approach to measurement with freight travel time data collected along the road, the travel time reliability measures planning time and buffer time were compared with the travel time measure average travel time over time for trip scheduling purposes and the travel time reliability measure reliability index was compared with the travel time measure mean travel rate over time for performance evaluation purposes. The results indicated that freight travel time reliability trends are inconsistent with freight travel time trends on the segment. From the trends, the ideal and unideal freight travel periods were identified and it was indicated that it is over four times more beneficial to transport freight during periods of high reliability than during periods of low reliability. The segment also performs dismally with freight reliability index values ranging from 100% to 400% compared to an acceptable threshold of 100% and compared to more or less similar function roads. It was also determined that the study adds to previous congestion studies of the road segment with pointing out the need to treat unexpected delay much as the previous studies pointed out the need to treat expected delay. Further, shortcomings on the segment were prioritized for improvement. It was indicated that providing the trip scheduling information from the study to users through the website of the agency responsible for management of the road segment, with accessibility enabled on mobile devices, would improve the reliability of their travel plans. The influence factors of the segment freight travel time and freight travel time reliability performance were identified as the mainly commute use of it; traffic incidents and roadway abuse coupled with inadequate traffic control. Possible improvements measures were therefore determined as truck-only facilities; an incident management programme and a ramp metering control system, these in addition to traffic separation strategies; traffic signs; signal-controlled junctions and traffic rules enforcement that have already been proposed in the previous studies of the road segment.

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ACRONYMS

ADT	-	Average Daily traffic
ADUS	-	Archived Data User Service
ATIS	-	Advanced Traveler Information System
ATRI	-	American Transportation Research Institute
AVI	-	Automatic Vehicle Identification
AVL	-	Advanced Vehicle Location
BRT	-	Bus Rapid Transit
BTI	-	Buffer Time Index
CBD	-	Central Business District
DWH	-	Data Warehouse
DMI	-	Distance Measuring Instrument
DRC	-	Democratic Republic of Congo
EIRR	-	Economic Internal Rate of Return
Eqn.	-	Equation
FDOT	-	Florida Department of Transportation
FHWA	-	Federal Highway Administration
GPS	-	Global Positioning System
HGV(s)	-	Heavy Goods Vehicle(s)
ICD	-	Inland Container Depot
ITS	-	Intelligent Transportation System
JICA	-	Japan International Cooperation Agency
JIT	-	Just-in-time
JKIA	-	Jomo Kenyatta International Airport
KeNHA	-	Kenya National Highways Authority
KSC	-	Kenya Shippers Council
LOS	-	Level(s) of Service
MI	-	Misery Index
NCTIP	-	Northern Corridor Transport Improvement Project
NMT	-	Non-motorized Traffic

PORTAL	-	Portland Oregon Transportation Archive Listing
PCU(s)	-	Passenger Car Unit(s)
PSV(s)	-	Public Service Vehicle(s)
PTI	-	Planning Time Index
RI	-	Reliability Index
SGR	-	Standard Gauge Railway
TTCANC	-	Transit Transport Coordination Authority of the Northern Corridor
TI	-	Travel Time Index
TTI	-	Texas Transportation Institute
UNES	-	University of Nairobi Enterprises and Services
US	-	United States
V/C	-	Volume-to-capacity
VMT	-	Vehicle Miles Travelled
VOC(s)	-	Vehicle Operating Cost(s)

1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Efficient movement of freight through transport corridors is prerequisite to effective trade and economic development. Where major constraints to movement exist, business is curtailed for such groups as freight carriers, shippers, suppliers and retailers, resulting in tremendous economic losses. Of particular concern are congestion situations that occur along the freight corridors, resulting in slow and often unpredictable freight movement patterns. Against this backdrop, a trucking company for example has to worry not only about incurring more expenses in fuelling vehicles, in maintenance costs and in extra payments for crew caught up in traffic while making deliveries but also about meeting the expectations of shippers, suppliers and retailers who are in turn worrying about incurring more expenses in keeping inventory over the uncertainty of whether goods will be delivered on time and the potential of losing customers dissatisfied with services. On a larger scale, these problems mean slow economic growth for countries and regions and the inability to compete in major international markets, particularly those employing just-in-time (JIT) management techniques that require goods to be where they need to be on time, in the right amount and undamaged.

In many parts of the world, it is now increasingly being recognized that one of the most important needs of the freight industry is a reliable transport system – enabling timely delivery of goods. The need for reliable movement on African trade and transit corridors is even more acute as countries and the sub-regions they exist in grapple with promoting trade and regional integration among themselves and improving their competitive edge within offshore markets. On the Northern Corridor, which is East and Central Africa's busiest and most important trade and transit corridor (Transit Transport Co-ordination Authority of the Northern Corridor (TTCANC), 2013, para. 1) this need is greatly manifested in the high costs attached to unpredictable travel through the corridor. The indirect delay costs – including costs related to additional cargo dwell time and the opportunity costs of extra inventory held due to transport unreliability – form the bulk of the logistics costs of freight transport on the corridor at 42% and are much higher than the direct delay costs which stand at 2% (*Figure 1.1*).
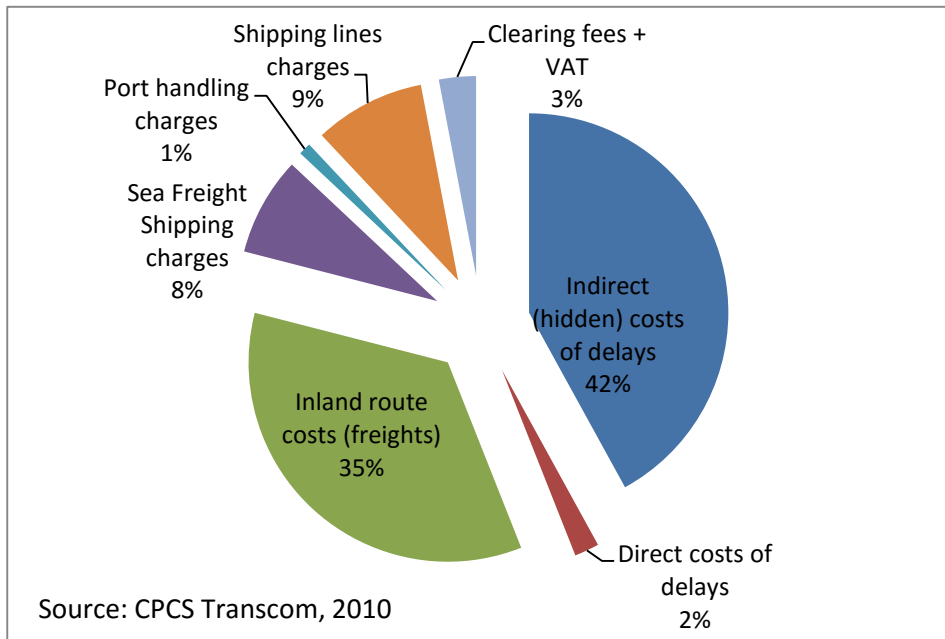
Figure 1.1: Northern Corridor logistics costs structure

In Kenya, the Kenya Shippers Council (KSC) is one of the freight industry stakeholders that have increasingly advocated for a reliable transport system on the Northern Corridor (Langat, 2010), seeing as the country stands to gain or lose most from the performance of the corridor with the majority of the cargo transported on it being domestic at over 70% compared to less than 30% belonging to the rest of the countries dependent on the corridor for transit (*Figure 1.2*).
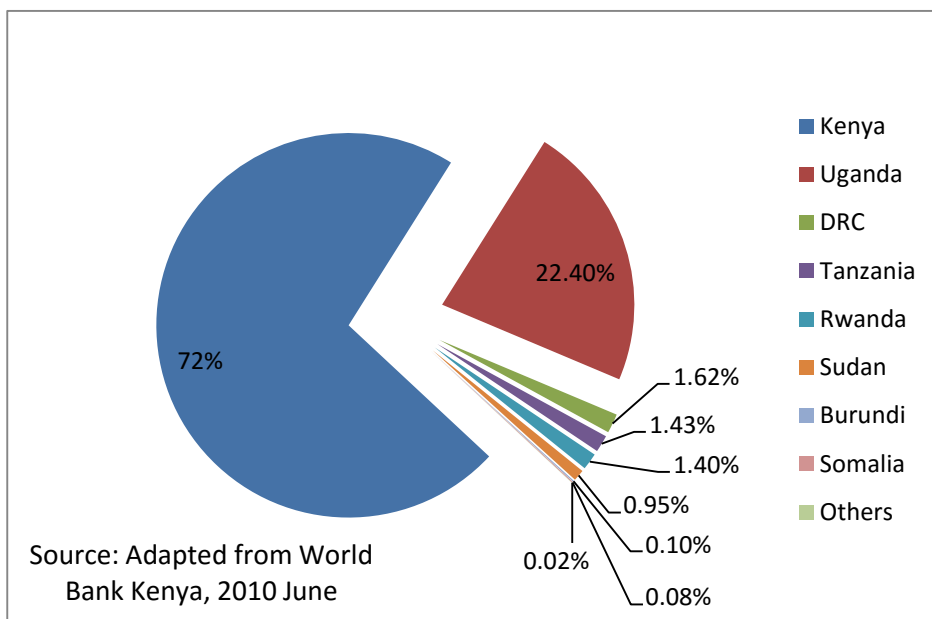
Figure 1.2: Cargo on the Northern Corridor by country of origin/destination

Studies of freight travel time reliability on highly travelled and congestion prone sections of the Northern Corridor such as urban roadway sections could be a significant response to this need. Useful information could be generated with the two-fold goal of providing freight carriers and their customers with a higher degree of certainty on freight haulage times through these sections and providing an advanced basis for designing operational improvement measures at these sections. In the end, this would go a long way in improving the overall reliability performance of the corridor.

1.2 DESCRIPTION OF THE STUDY AREA

This study focused on the Northern Corridor Road segment in Nairobi City, one of the most highly travelled and congestion-prone urban roadway sections of the corridor.

1.2.1 Profile of Nairobi in relation to Northern Corridor freight traffic

Nairobi occupies a strategic position on the Northern Corridor. The city is almost centrally located on the Kenyan portion of the corridor that begins at the port of Mombasa and ends at the Malaba and Busia borders with Uganda (*Map 1.1*).

With this mid-point position, Nairobi provides the perfect environment for stationing of inland cargo facilities along the corridor and accordingly holds an inland container depot (ICD) and a large concentration of break-bulk terminals, where consignments of goods can be broken down for redistribution to the local market – notably oil depots, and warehouses. These facilities in turn attract many industries of manufacturing, processing and commercial goods in the city as they seek easy accessibility to import and export processing zones.

A large percentage of the domestic cargo from or to the port of Mombasa, which as earlier stated constitutes majority of the cargo transported on the Northern Corridor, therefore ends up or originates in Nairobi and much more transference activity happens between Nairobi and other inland parts of the country.

Map 1.1: Relative position of Nairobi on the Northern Corridor portion in Kenya

In addition, almost all of the transit cargo transported on the Northern Corridor must pass through Nairobi en route to beneficiary countries including Uganda, Rwanda, Burundi and the Democratic Republic of Congo (DRC) (*Map 1.2*).

In light of the above, and with road transport accounting for over 70% of all freight transport on the Northern Corridor (International Conference on the Great Lakes Region, 2012, p. 6), it can be seen that the road segment in Nairobi has to carry high volumes of freight traffic every day. Japan International Cooperation Agency (JICA) and Padeco Company Limited (2011) obtained data from the Kenya National Highways Authority (KeNHA) showing that the average daily truck volume between Mombasa and Nairobi is 1,428 trucks per day with that between Nairobi and Nakuru being 4,144 trucks per day, the highest daily truck volume to be found anywhere on the Northern Corridor Road (Table 3-9).

Map 1.2: Northern Corridor transit route to Uganda, Rwanda, Burundi and DRC

Source: Transit Transport Coordination Authority of the Northern Corridor (TTCANC), c2012

1.2.2 Profile of road segment in Nairobi in relation to general traffic

The Northern Corridor Road segment in Nairobi stretches about 26 kilometres across the city from the South Eastern to the Western ends. According to the city's road naming system, the segment is divided into four sections: Mombasa Road, Uhuru Highway, Chiromo Road and Waiyaki Way.

Apart from performing the role of freight routes, these road sections also serve as some of the most important primary distributors within the city, providing for movement to and from major activity centres, as well as together providing a general transit route between the South East of the city and the West. The individual profiles of the road sections are as discussed below:

1. *Mombasa Road*

Mombasa Road covers the 10.8-kilometre road section from the city boundary on the South East to the Lusaka Roundabout towards the Central Business District (CBD) (*Map 1.3*). It traverses majorly high activity commercial and residential areas and also provides connection to the city's industrial zone and the ICD. These areas contribute most of the traffic on Mombasa Road via its Lusaka, Likoni, Enterprise and Airport North Roads arterials and local distributors such as Popo, Kapiti and East Gate Roads, with daily movements between them and the CBD and between their own selves. Mombasa Road is also the main access to the country's most important airport, the Jomo Kenyatta International Airport (JKIA) and also provides connection to such popular city locations as the Wilson Airport and the Nairobi National Park via its Lang'ata Road arterial, all of which attract considerable traffic onto Mombasa Road.

The daily total traffic volume on the road has been found to exceed 70,000 vehicles per day over most of its length and although the links cross-section of 3-lane dual carriageway with shoulders and separated pedestrian walkways on some sections operates from level of service (LOS) B to C depending on section, the major junctions along the road operate generally at LOS F (GIBB Africa Ltd. & Associated Consultants of Ghana, 2015, May; COWI A/S, Otieno Odongo & Partners Consulting Engineers, & QUTEP Ltd., 2012, October).

Map 1.3: Mombasa Road (A104) in Nairobi and its environs

2. *Uhuru Highway*

Uhuru Highway covers the approximately 3.7-kilometre road section between the Lusaka Roundabout and the Museum Hill Interchange (*Map 1.4*). This road section basically traverses the CBD, which is the city's commercial hub and administrative centre. Traffic is attracted onto Uhuru highway from all parts of the city as it tries to find its way to the activity centres in the CBD and vice versa via arterials such as Haile Selassie Avenue, Kenyatta Avenue, University Way and Museum Hill Road and local distributors such as Bunyala Road, Harambee Avenue, City Hall Way and State House Road. Some of the important locations in the vicinity of Uhuru Highway that attract traffic onto the road include government offices located along Harambee Avenue and City Hall Way and those accessed via Kenyatta Avenue towards the West; the country's premier tertiary institution, the University of Nairobi, located along University Way and the Nyayo National Stadium located on the West of the Lusaka Roundabout, where many local and international sports and other events are held. Further considering that the road network in the city is composed mainly of radial routes connecting surrounding regions to the CBD with few circumferential routes, even traffic transiting the CBD to peripheral areas most likely finds its way to Uhuru Highway at one time or another.

The daily total traffic volume on the road has been found to exceed 70,000 vehicles per day over most of its length (COWI A/S, Otieno Odongo & Partners Consulting Engineers, & QUTEP Ltd., 2012, May) and although the links cross-section of 3-lane dual carriageway with shoulders and separated pedestrian walkways operates from LOS A to B depending on section, the major junctions along the road save for the newly constructed Museum Hill Interchange operate generally at LOS F (COWI A/S, et al., 2012, October).

KEY

Main Study Road	
Arterial Road	
Local Distributor	
Roundabout	
Interchange	
T-Junction	
Place Marker	

RESIDENTIAL AREAS

State House Road

University Way

Utalii St.

Nairobi Central

CBD

Market St.

Nyerere Road

City Hall Way

Haile Selassie Avenue

Kenyatta Avenue

Harambee Avenue

ADMINISTRATIVE CENTRES

Nairobi

RAILWAY STATION

Uhuru Highway, Nairobi, Kenya

COMMERCIAL/ADMINISTRATIVE CENTRES

Bunyala Road

Aerodrome Road

Lusaka Road

Lang'ata Rd

Kilimani

© 2012 Google
Image © 2012 DigitalGlobe
Image © 2012 GeoEye

1°17'25.98" S 36°49'03.24" E elev 1672 m

Map Source: Google Earth, 2012 (labeling by Author)

Map 1.4: Uhuru Highway (A104) in Nairobi and its environs

3. *Chiromo Road*

Chiromo Road covers the 1.6-kilometre road section from the Museum Hill Interchange to the Westlands Roundabout, where Rhapta Road and a link of the Parklands Road connect to the study road (*Map 1.5*). It traverses the mixed development Westlands Region combining commercial activity and residential areas. These areas contribute considerable traffic onto Chiromo Road via its Riverside Drive and Parklands Road arterials and via local distributors such as Rhapta Road, with daily movements between them and the CBD, between them and the Western regions and between their own selves.

The daily total traffic volume on the road has been found to exceed 46,000 vehicles per day (COWI A/S, et al., 2012, May) with the 3-lane dual carriageway links of the road operating from LOS A to B depending on section and the Westlands Roundabout operating at LOS F (COWI A/S, et al., 2012, October).

Map 1.5: Chiromo Road (A104) in Nairobi and its environs

4. *Waiyaki Way*

Waiyaki Way covers the approximately 10.0-kilometre road section from the Westlands Roundabout to the city boundary on the West (*Map 1.6*). It traverses partly the mixed development commercial/residential Westlands Region and partly a primarily residential zone with a notable concentration of research centres and market places on the Western outskirts of the city. These areas contribute most of the traffic onto Waiyaki Way via arterials such as James Gichuru Road, Naivasha Road and Kapenguria Road and local distributors such as Kaptagat Road, with daily movements between them and the CBD including the areas in-between.

The daily total traffic volume on Waiyaki Way has been found to range between 39,000 and slightly over 45,000 vehicles per day (COWI A/S, et al., 2012, May; ESER Project & Engineering Co. Inc. & Botek Bosphorus Technical Consulting Co., 2015, June) and although the links cross-section of 2-lane dual carriageway with shoulders and service roads on sections operates from LOS A to B depending on section, major junctions along the road including the Parklands Road Junction and the James Gichuru Road Junction operate at LOS F (COWI A/S, et al., 2012, October).
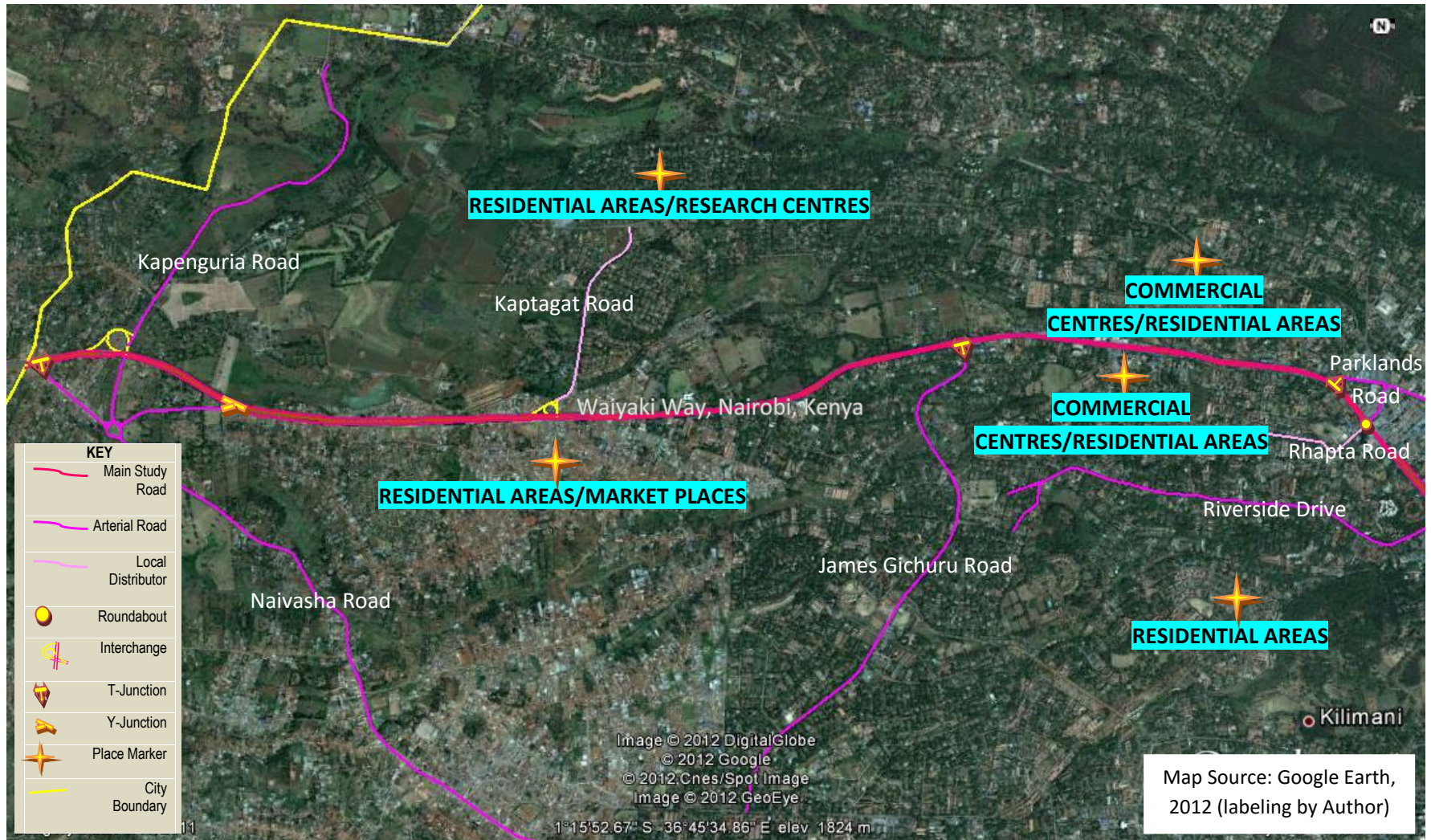
Map 1.6: Waiyaki Way (A104) in Nairobi and its environs

1.3 PROBLEM STATEMENT

It can well be argued that freight carriers on the Northern Corridor are accustomed to congestion on the road segment in Nairobi and they plan for the delays they are likely to encounter in the course of travel through the road segment, either by adjusting their schedules or by budgeting extra time to allow for delays. Their plans basically have to be based on their own experience of travelling through the segment as no other source of information regarding travel times on the road segment is readily available to them.

This is a rather unfortunate situation because the freight carriers may then only be able to plan to a considerable extent for delays due to congestion situations resulting from regular sources such as "rush hour" travel (*Plate 1.1*). Usually, it is possible for common travelers of a particular route to tell the relative timings and sizes of congestion situations occasioned by such regular sources, making it somewhat easy to predict the amounts of delays likely to be suffered on their account.

Source: Access Kenya Group, 2012

Plate 1.1: Evening peak traffic on part of Uhuru Highway
(an example of regular source of congestion on the road section)

What is more difficult for the freight carriers however, is to be able to tell the delays they are likely to suffer due to congestion situations resulting from irregular sources and to sufficiently plan for these delays. Some typical irregular congestion sources on urban roadways include fluctuations in traffic demand that occur from day to day; traffic incidents including accidents, vehicle breakdowns, debris in the travel lanes and events that occur on the shoulders, roadside or further off the roadway such as a fire in a building next to the road; traffic control malfunction; road works; extreme weather and special events in the vicinity of the road that cause surges in traffic demand such as a sports tournament held in a stadium nearby (Cambridge Systematics Inc. & Texas Transportation Institute (TTI), 2005, Chapter 2).

Any of these events can be expected to affect traffic movement on the Northern Corridor Road segment in Nairobi and could occur in complex interaction with one another and also in combination with regular congestion sources or otherwise. For instance, one day may be characterized by normal traffic; good weather; and no incidents, with another being characterized by heavier than normal traffic; heavy rains; and a severe crash during a peak period and with yet another day being characterized by normal traffic; good weather; and a severe crash during a peak period. To make the congestion picture even more complex, one congestion source can be the catalyst of another, such as heavier than normal traffic leading to occurrence of several minor accidents attributable to drivers' frustration with the situation.

In the face of this randomness, it is not easy from the current position of freight carriers to determine what buffer to factor into travel schedules to cover congestion from irregular sources. This is more so because irregular congestion sources tend to be non-recurring events that the freight carriers cannot easily expect and therefore consciously plan for. Yet ironically, congestion resulting from these non-recurring events is known to contribute even over 50% of the total delays on a route or trip (Vorungati, Boyles, & Waller, 2008) particularly where effective management of the events is lacking such as on this road segment. A good example is the case of a traffic accident that occurred on Mombasa Road during the mid-morning hours on 12th August, 2012 (*Plate 1.2*).

Plate 1.2: Traffic accident on Mombasa Road on 12th August, 2012
(ineffective management of the non-recurring congestion source is evident)

With this part of the road blocked not only by the vehicles involved but also by the visible sea of onlookers and with the possibly considerable time it took to clear the incident in light of the obstructions caused to emergency response efforts, it is anybody's guess the extent of the resultant congestion upstream of the incident and how much this contributed to the delays suffered by freight carriers and other road users at the time.

The effect then is that the freight carriers plan their schedules from a rather uninformed point of view with the implication that they make huge errors. This means that their travel time predictions and hence their delay countering efforts with regards to travelling through the Northern Corridor Road segment in Nairobi remain greatly unreliable.

On the other hand, travel time estimation studies carried out so far on the road segment have not properly accounted for the effects of congestion resulting from irregular sources on overall travel times. The trend has usually been to express travel times in terms of simple averages for all times, based on data collected during what is termed typical representative day(s).

An illustration by the TTI and Cambridge Systematics Inc. of how travel times have been communicated in studies in the United States (US) against the actual travel times experienced by travelers (*Figure 1.3*) gives a good picture also of the situation with studies done on the Northern Corridor Road segment in Nairobi. What is evident from a comparison of the two graphs in the figure is that simple averages camouflage the fact that travel times vary greatly over time as an effect of congestion caused by day to day fluctuations in traffic demand and other irregular sources. This is even assuming that sufficient data has been used to develop suitable average measures.

The first implication then is that if it was thought to provide these average results to freight carriers in a bid to aid their schedule planning, with the possible deviations from average practically left unexplained, the only certainty they could have in regard to organizing their schedules around the simple average travel times is that of being early more or less half of the time and late more or less half of the other time. For freight carriers' purposes, this is not desirable and they would rather in that case rely on their own experience.

Source: Texas Transportation Institute (TTI) and Cambridge Systematics Inc., 2006
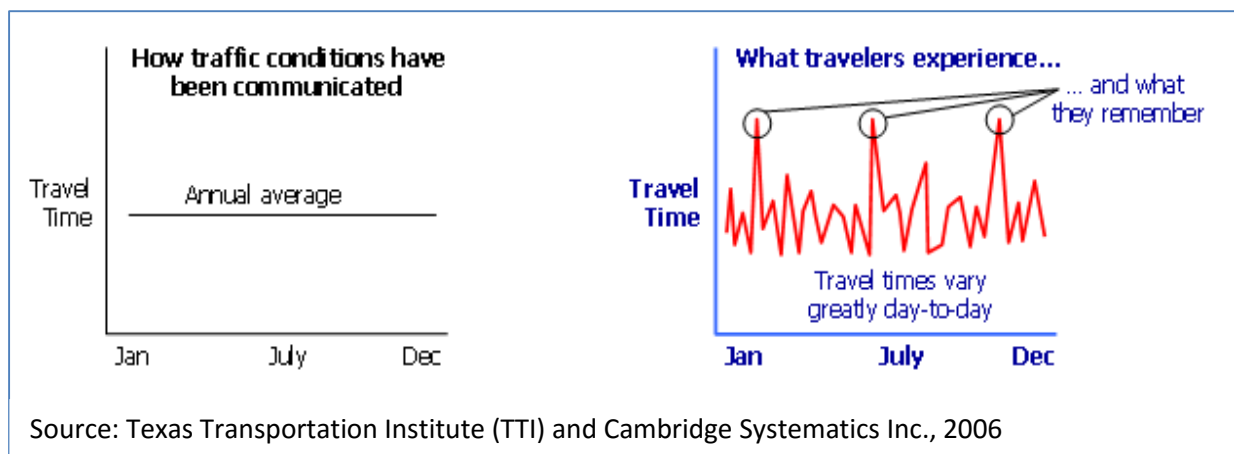
Figure 1.3: Expression of travel time in studies against actual travel time experiences

The second implication is that without the quantification and explanation of variations in travel time on the Northern Corridor Road segment in Nairobi, transport planners and policy makers have not yet achieved sufficient diagnosis of the congestion situation on the segment particularly from the users' perspective, and are not likely to achieve sufficient evaluation of the mitigation strategies they have thought to employ or are employing. For one, they are not able to express how reliable or unreliable the transport system is in terms of travel time, which for users as it has been made clear determines more if they save or lose money than whether there is congestion at all or not. They are also not able to tell other facts of interest such as which specific sections of the system experience the most unreliable travel times and therefore need the most attention and without being able to tell these, they cannot measure the improvement benefits that users are really after.

Thus, while the infrastructural improvements currently being proposed and undertaken for the Northern Corridor Road segment in Nairobi on the basis of evaluations that have relied on the average travel time along with congestion measures such as volume-to-capacity (V/C) ratio and average delay may be justified, it cannot be said for sure that freight carriers' will enjoy the benefits of reliable travel times through the improved segment.

1.4 RESEARCH QUESTIONS

In light of the above problems, this study sought to address the following questions:

1. Can variations in travel time be quantified and explained to establish travel time reliability?
2. Can freight travel time reliability measures for the Northern Corridor Road Segment in Nairobi be determined and can conclusions be drawn about the segment's performance from this information?
3. Can freight carriers obtain and use the freight travel time reliability information to improve their schedule planning?
4. Could reliability needs have been overlooked in the proposed improvements on the segment and are there alternative/additional improvements that may be useful?

1.5 OBJECTIVES OF THE STUDY

The main objective of this study therefore was to measure and evaluate freight travel time reliability on the Northern Corridor Road segment in Nairobi and to demonstrate how this information can be used to facilitate reliable movement on the segment.

It is envisaged that this approach can be applied to promoting reliable movement on highly travelled and congestion-prone urban and similar roadway sections of the corridor.

Specifically, the study was intended to:

1. Examine a method of quantifying and explaining variations in travel time to establish travel time reliability;
2. Compute freight travel time reliability measures for the Northern Corridor Road Segment in Nairobi and evaluate the segment's performance in light of this information;
3. Indicate how freight carriers may obtain and use the freight travel time reliability information to improve their schedule planning;
4. Assess the proposed improvements on the segment in view of its reliability performance and recommend alternative/additional improvement measures.

1.6 SCOPE AND LIMITATIONS OF THE STUDY

The scope of this study was to measure and evaluate freight travel time reliability on the Northern Corridor Road segment in Nairobi, encompassing the road stretch from the JKIA Turnoff to the Naivasha Road Junction, following examination of a method of quantifying and explaining variations in travel time to establish travel time reliability. The study also sought to give only in principle how freight carriers can obtain and use this information rather than to design an information system. Further, only principles for infrastructure and service improvements are presented rather than detailed designs and economic evaluations.

A limitation of the study was in the distinct assessment of freight travel time reliability on the Northern Corridor Road segment in Nairobi without reference to other connecting chains of the corridor transport logistics system that would also impact its reliability performance. If reliable movement on the segment is to be very well promoted, then a more comprehensive study using appropriate methods to assess reliability and identify improvement needs within the other connecting chains and to sufficiently combine interactions with these features on the road segment would be necessary. In line with this limitation, it can be noted that by the time of completion of the study, the new Southern Bypass that tees off the road segment was operational and taking on a significant percentage of freight traffic that previously traversed the segment. No further detailed measurements of freight travel time reliability were carried out in this respect, though a spot check of the measured freight travel times against observed freight travel times along the affected section of the study road at the later time was undertaken and evaluated. Further, only possible contributions of the Southern Bypass to freight travel time reliability on the overall Northern Corridor Route in Nairobi were considered.

There were also several limitations inherent in the methodology adopted for the study. One is that freight travel time reliability was modelled only on the factor of variation over time, with other variability factors being used to infer the validity of the travel time estimates obtained and for largely qualitative analysis of their influence on freight travel time reliability on the segment. Additional quantitative analysis of the effects of these other variability factors on freight travel time reliability would have enabled a more comprehensive influence analysis. Other limitations included the assumptions made in selecting the distribution of freight travel times, in sectioning the road segment for the study and in selecting the data collection month, which are discussed in more detail in subsequent sections.

1.7 JUSTIFICATION OF THE STUDY

As international goods markets modernize and the need to enhance transportation service on the Northern Corridor to suit these markets becomes more apparent, the call is on transport planners and policy makers to respond to this need accordingly.

Currently, the freight industry is placing much emphasis on timeliness of deliveries and order fulfillments, which has brought to the fore the highly unreliable state of the Northern Corridor transport system and the need to focus more attention on addressing this aspect.

Reliability assessment must now take centre stage in transportation studies and in the decision process for transport projects and programmes. Particularly for roadway sections of the corridor severely affected by sources of unpredictable travel, travel time reliability measurement and evaluation could answer pertinent performance questions. Urban roadway sections such as the road segment in Nairobi and other highly travelled and congestion prone roadway sections, as they suffer significant congestion resulting from irregular sources, would especially benefit from an additional means of managing and alleviating congestion that also facilitates reliable movement.

By this way, transport planners and policy makers can be assured of not only instituting projects and programmes that will satisfy user requirements on the Northern Corridor, but also of better targeting scarce resources towards achieving optimal transport solutions.

2. LITERATURE REVIEW

2.1 THE CONCEPT OF TRAVEL TIME RELIABILITY MEASUREMENT

Travel time reliability measurement is still an emerging concept that is taking on many different forms even as research on the concept is going on in several parts of the world. One clear fact though is that the basic feature of travel time reliability measurement is its being a means of quantifying and explaining the variations associated with travel time in a manner that can express how reliable travel time is. The differences evident in the various researches lie in the definitions that have been attached to the phrase 'travel time reliability' and consequently the indices that have been used to express travel time reliability. The measurement techniques are also different, though they are all based on analyzing travel time distributions in the form of either observed frequency distributions or approximated probability distributions obtained from a large amount of travel time data.

Following initial studies that have formed the basis for development of original travel time reliability definitions, indices and techniques of measurement, further studies have in turn been conducted to critically examine the relevance and accuracy of these definitions, indices and measurement techniques, often leading to new definitions, indices and techniques. The merits and demerits of each definition, index and technique are well documented. However, the challenge for researchers seeking an application approach of the concept remains that there is not yet a single agreed upon travel time reliability measure. One can only examine the available body of research and determine the relevant measures for their purposes.

2.2 REVIEW OF TRAVEL TIME RELIABILITY MEASURES

Broadly, the developed travel time reliability measures so far can be classified into probabilistic and statistical measures (Tu, Lint, & Zuylen, 2006). Probabilistic measures have in common that travel time reliability is defined and often indexed by a probability expression, with calculation of the probability that travel time will conform to certain specified tolerances deemed as acceptable to users within the travel environment being the main feature. Obviously, probabilistic measures are based on

analyzing travel time distributions modelled by probability which enables treatment of travel time rightly as a random variable. Their disadvantage though is that the acceptable tolerances that guide measurement are usually determined by heuristics which renders them subjective and it cannot therefore be guaranteed that the results of measurement will be optimal. Even when user perception studies are adopted to inform the tolerances as suggested by Al-Deek and Emam (2006), it is not lost that users tend to have many different psychological responses to the travel environment with estimates of travel time experiences being highly subjective (Carrion, 2013) and there is still great chance that unrealistic expectations would then be taken as the bases for measurement. Hence due to this primary rationale of establishing conformity to so-called acceptable tolerances, probabilistic measures on overall are not very practical to the goal of providing users with what to actually expect of the travel environment. Furthermore, it is not easy to explain how users may use the probabilities. However, these probabilistic interpretations are seen as useful performance indicators particularly when comparing with set targets and as more subjective traveler-specific factors in trip choice analyses (Lint & Zuylen, 2005; Tu, et al., 2006).

Statistical measures on the other hand largely express travel time reliability in terms of quantities derived from the travel time distribution. The quantities are derivable as well with the probability distributions as with the frequency distributions and because of this direct measurement from the travel time distribution, statistical measures can be argued to be more factual and objective compared to their counterpart. Further objectivity is dependent on the quality of the statistics used in the measure. Thus statistical measures fit well the role of providing reliable travel time information in so far as they are well understood by users, while still working well as performance indicators.

Of the probabilistic measures, Asakura and Kashiwadani in their 1991 study (as cited in Higatani, et al., 2009, p. 3) initially defined travel time reliability as *the probability that a trip between a given origin and destination pair can be made successfully within a given time interval and a specified level of service*, the main performance indicators examined being the specified travel time and the specified network service. Al-Deek and Emam (2006) adopted this concept in developing their methodology for estimating

travel time reliability and capacity reliability under the effects of travel demand variation and link capacity degradation, but sought to give a definition that clearly describes the time interval and the level of service to be examined. They gave their definition of travel time reliability as *the probability that the expected travel time at degraded capacity is less than the link free flow travel time plus an acceptable tolerance, which is related to the level of service that should be maintained despite the capacity degradation (or is the level of tolerance the public is willing to accept for link travel time reliability).* In line with the fact that failure was clearly described in their definition, the authors expressed travel time reliability in terms of the engineering failure rate or hazard rate function, as follows:

$$R(Ti) \ = \ e^{-\int_0^{Ti} \lambda(Ti)dT} \hspace{3cm} (\textit{Eqn. 2.1})$$

where $R(Ti)$ is the reliability function for link i in a particular network,

$\lambda(Ti)$ is the failure (hazard) rate function and is in this case dependent on the probability distribution function employed and relates the free flow travel time and the acceptable upper limit of travel time.

The clear advantage of this latter definition over the former is that it is more specific and considerably reduces the analyst's heuristic load of determining acceptable tolerances. On the other hand, a notable strength common to the two measures is that they emphasize choosing the acceptable travel time tolerance in relation to the facility level of service, which as Al-Deek and Emam (2006) point out: "…is sensitive to users' perspective since it reflects that an increase in segment travel time should always result in less travel time reliability" (p. 1). However, what these measures do not do is that they do not explicitly address the important aspect of travel time reliability that is its evident variability over time. As Tu et al. (2006) suggest, the assumption with the measures may be that the underlying travel time distribution on which measurement is based sufficiently accounts for day of week differences and differentiates peak and off-peak hours of the day. However, their research found that considerable differences have been established between travel time distributions on different weekdays and more so within the time periods of day such as peak hours, which discounts this assumption.

Tu et al. (2006) instead advocated that travel time reliability should be considered as a function of both time of day and day of week and gave their definition of travel time reliability as *the probability that a certain trip can be made successfully within a specified time interval as a function of departure time (in terms of time of day and day of week).* Expressing the specified time interval in terms of an upper threshold travel time, they gave the equation of reliability as follows:

$$R(\alpha) = \Pr(t_r \leq \alpha \times t_r^*|_{TOD,DOW})$$
(Eqn. 2.2)

where $R(\alpha)$ is the reliability function,

t_r is the actual travel time for a given trip,

$\alpha \times t_r^*$ is the threshold of travel time with $\alpha \geq 1$ and t_r^* equal to for example free flow travel time,

TOD represents time of day on which the trip has started and

DOW represents day of week on which the trip is made.

Hence different time threshold parameters, particularly the value α, must be chosen and tested for distinct departure times defined by the time of day and day of week.

It is clear then that the choice of acceptable tolerances for use with any of the probabilistic measures must be an elaborate process if all important aspects to interpreting travel time reliability are to be taken into account. This only emphasizes the susceptibility to errors of probabilistic measures and the need for great care when using them.

Further notable is that the above measures define travel time reliability as specific to a trip or link, meaning that they consider that travel time reliability varies across different routes/sections of route. However, the implication then is that the measures do not lend themselves to comparison between different routes/sections of route and would not suit such a purpose of performance evaluation as comparison between routes/sections of route of different lengths.

Of the statistical measures, they are further distinguished as statistical range measures, buffer time measures, tardy trip measures and skew-width measures (Lomax, Schrank, & Turner, 2003; Tu, et al., 2006; Transportation Research Board, 2013).

Lomax et al. (2003) describe statistical range measures as those that "…use standard deviation statistics to present an estimate of the range of transportation conditions that might be experienced by travelers" (p. 10). Typically, the standard deviation is combined with the average in a number of ways to create measures that indicate the possible spread of travel times around the expected value. These measures are said to appear more as variability measures than reliability measures (Lomax, et al., 2003) as they express the amount of inconsistency in operating conditions rather than the level of consistency that users can expect in transportation service, though of course variability and reliability in this case can be considered synonymous because the amount of variability then indicates the level of reliability/unreliability.

One way that the standard deviation has been combined with the average is the *travel time window concept* that takes the form of *the average travel time plus or minus a factor times the standard deviation* (Lomax, et al., 2003; Tu, et al., 2006) as in the following equation:

$$\textit{Travel time window} = \textit{Average travel time} \pm \textit{Standard deviation} \times f \quad \textit{(Eqn. 2.3)}$$

Using one standard deviation above and below the average for example will vencompass 68% of the days, peak periods or other time periods chosen for analysis. An issue of concern with the travel time window concept though is that since the standard deviation is a symmetrical measure, it is only suitable as argued by Tu et al. (2006) if a normal distribution of travel times is assumed. This is inconsistent with the fact that observed travel time distributions have depicted long tails to the right (Lomax, et al., 2003; Taylor & Susilawati, 2012; Transportation Research Board, 2013). Thus measures defined based on this concept use percentile values as a more robust and meaningful way of combining the effect of expected travel time and its variability. For instance, Chen, Zwet, Varaiya and Skabardonis (2003) recommended the use of the 90th percentile travel time, with travel time reliability then defined as *the difference*

between the 90th percentile travel time and the average travel time. Lam and Small (2001) had earlier adopted a similar approach but used the median travel time instead of the average travel time, so that they defined travel time unreliability by *the difference between the 90th percentile travel time and the median travel time.* The use of the median is definitely more advantageous to the use of the average if it is considered that the median is also less sensitive to outliers.

The above measures still have a common weakness in that they are not length-neutral and therefore cannot be compared between routes or sections of a route with different lengths. Lomax et al. (2003) proposed that one way to deal with this problem is to use travel rate (in time per unit length) in place of travel time within the measurement statistics. A statistical range measure that is however length-neutral and fitting to the goal of comparing travel time reliability on different route/section lengths is the *percent variation.* The percent variation combines the standard deviation and the average of travel times in ratio form, thus removing the trip length from the calculation. The equation for calculation of percent variation is as follows:

$$Percent\ variation\ =\ \frac{Standard\ deviation}{Average\ travel\ time}\ x\ 100\% \qquad\qquad (Eqn.\ 2.4)$$

According to Lomax et al. (2003), travelers could use this measure by multiplying the average travel time by the percent variation in order to determine the time for planning a trip and would be assured of arriving on time on 85% of the trips. Higher values would then indicate less reliability and vice versa. This measure however still suffers from the disadvantages that it is only suitable if a normal distribution of travel times is assumed and its use of the average travel time does not well account for outliers in the travel time data.

All in all, statistical range measures have been said to be effective in explaining the statistical characteristics of a travel time data set (Higatani, et al., 2009) but not very effective at relating to the way travelers make trip decisions or to the view of transport policy makers (Lomax, et al., 2003; TTI & Cambridge Systematics Inc., 2006; Higatani, et al., 2009).

Buffer time measures on the other hand have been described as those that "…indicate the effect of irregular conditions in the form of the amount of extra time that must be allowed for a traveler to achieve their destination in a high percentage of the trips" (Lomax, et al., 2003, p. 10). Unlike statistical range measures, these measures express the level of consistency that users can expect in transportation service and are said to relate particularly well to the way travelers make decisions. According to Lomax et al. (2003), the intuitive travel decision process follows the steps "how far is it?", "when do I need to arrive?", "how bad is the traffic?", "how much time do I need to allow?" and "when should I leave?", with assessment of how much extra time has to be allowed for uncertainty in travel conditions being necessary in the "time allowance" stage (p. 19). Buffer time measures are usually presented as a value in minutes of a particular trip or minutes per unit length or as a percentage of the expected travel time.

The 95th percentile travel time is widely accepted for representing the desired percentage of on-time trips, particularly on freeways, and is the foundation statistic of buffer time measures as when translated simply in commuter terms, it depicts that a trip maker would be late on only one weekday per month (Lomax et al., 2003; TTI & Cambridge Systematics Inc., 2006). It can also be described as indicating "…how bad delay will be on the heaviest travel days" (TTI & Cambridge Systematics Inc., 2006, "Measures of reliability", para. 2) or "…the worst travel time that commuters may experience once per month" (Higatani, et al., 2009, p. 4). The 95th percentile travel time is therefore itself considered one of the buffer time measures and the TTI & Cambridge Systematics Inc. (2006) referred to it as the *planning time*, expressed in equation form as follows:

Planning time = 95th percentile travel time   (Eqn. 2.5)

The planning time can be explained as the total amount of time, including an adequate buffer time, that should be set aside or planned before a trip starts (and will ensure that there is on-time arrival 95% of the time). The *buffer time* is then calculated as the *difference between the 95th percentile travel time and the average travel time*, expressed in equation form as follows:

Buffer time = 95th percentile travel time – Average travel time   (Eqn. 2.6)

The buffer time can be explained as the extra time that should be added to the average travel time when planning a trip to ensure on-time arrival (TTI & Cambridge Systematics Inc., 2006; Higatani, et al., 2009).

Since these two measures are reported in minutes, they are said to be ideally suited for traveler information (TTI & Cambridge Systematics Inc., 2006). However, they are hence not length-neutral and cannot be compared between routes/sections of route of different lengths. This presents problems to the comparison goal of performance evaluation unless travel rate is used in place of travel time within the measurement statistics. Another way of solving this problem is to use one of two or both length-neutral buffer time measures that have been formed by combining the planning time and the buffer time with the free flow travel time and the average travel time respectively in ratio form. In the first instance, the measure is referred to as the *planning time index*. The planning time index is really an expression of how much larger the total travel time (the planning time) is than the travel time in ideal conditions (free flow travel time) and is calculated by the following equation:

$$Planning\ time\ index\ (PTI)\ =\ \frac{95th\ percentile\ travel\ time}{Free\text{-}flow\ travel\ time} \qquad (Eqn.\ 2.7)$$

A large value of the PTI then indicates less reliability and vice versa. In the second instance, the measure is referred to as the *buffer time index*. This describes the size of the buffer time relative to the average travel time and is usually expressed as a percentage as in the following equation:

$$Buffer\ time\ index = \frac{(95th\ percentile\ travel\ time - Average\ travel\ time)}{Average\ travel\ time} \times 100\%$$
$$(BTI)$$
$$(Eqn.\ 2.8)$$

A large BTI value also indicates less reliability and vice versa. The clear difference between the PTI and the BTI is that while the former includes the effects of typical and unexpected delay, the latter only indicates the effects of unexpected delay. The PTI is

seen as particularly useful because it can be compared on similar numeric scales with the travel time index (TI[*]), a measure of average congestion (TTI & Cambridge Systematics Inc., 2006; Rakha, El-Shawarby, & Arafeh, 2010). This is because they both express a measure of travel time relative to the free flow travel time. The TI describes how long it takes to travel during peak hours compared to free flow conditions and is calculated by the following equation:

$$Travel\ time\ index\ (TI)\ =\ \frac{Average\ travel\ time}{Free\ flow\ travel\ time} \qquad (Eqn.\ 2.9)$$

Lyman and Bertini (2008) argued that while the PTI, BTI and TI show approximately similar trends along a roadway, the PTI tends to exaggerate the trends while the BTI is the most conservative measure to use as it tends to dilute the trends along a roadway. This obviously owes to the PTI's referral to ideal conditions and the BTI's usage of average travel time so that it fails to well incorporate fluctuations caused by uncertainty factors. Chu (2011) therefore proposed the *reliability index* as an alternative measure that can improve on the overestimate or underestimate of uncertainty conditions with a right-skewed travel time distribution. The reliability index is similar to the BTI, except it uses the median travel time, which is less sensitive to outliers, in place of the average travel time within the measurement index. The equation of reliability index is given as follows:

$$Reliability\ Index\ (RI) = \frac{95th\ percentile\ travel\ time - Median\ travel\ time}{Median\ travel\ time} \times 100\%$$

$$(Eqn.\ 2.10)$$

Chu (2011) was in fact able to prove that the RI yields smaller values than the PTI and larger values than the BTI, which upholds his argument.

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[*] The travel time index is actually abbreviated as "TTI". However, because this acronym also stands for the Texas Transportation Institute, "TI" has been used to abbreviate the travel time index in this report so as to avoid confusion.

Nevertheless, it is noted that the planning time, the buffer time, the PTI and the BTI remain popular in travel time reliability studies and in the US, which is the pioneer of these studies, have been accepted by the Federal Highway Administration (FHWA) as the measures that have technical merit and can also be easily understood by the non-technical community (TTI & Cambridge Systematics Inc., 2006).

Tardy trip measures differ from the above two discussed categories of statistical measures in that rather than examining the trip time effects of unreliable system performance, they seek to represent unreliability impacts using the amount of late trips (Lomax et al., 2003).

Some tardy trip measures seek to answer the question "how often will a traveler be acceptably/unacceptably late?" based on a chosen threshold that identifies an acceptable late arrival time. This threshold is usually expressed as a percentage of the trip time, an increased time in minutes above the expected time or an absolute value in minutes and is chosen depending on what is deemed acceptable to users. Although considered statistical measures because the threshold time is superimposed directly on the travel time distribution to derive the quantity of measure rather than probability being employed in examining the threshold time, this form of tardy trip measures is allied to probabilistic measures in that it involves testing a determined user acceptable parameter. As with probabilistic measures, the thresholds in the case of these tardy trip measures can only be determined by heuristics or by involving user perception studies, which means that the subjectivity problems associated with probabilistic measures also plague these tardy trip measures. They therefore do not also fit very well the goal of providing users with what to expect of the travel environment and could not easily be explained in trip scheduling terms, but can be helpful in performance evaluation when comparing with set targets. An example of this form of tardy trip measures is the *Florida Reliability Method*, derived from the definition of reliability of a highway system as *the percent of travel on a corridor that takes no longer than the expected travel time plus a certain acceptable additional time* (Florida Department of Transportation (FDOT), 2000). In this method, the expected travel time is taken as the median travel time rather than the average during the period of analysis so as to ensure that it is not influenced by unusual major events that may occur during the period and the acceptable additional time is represented by a percentage above

the expected travel time during the period (FDOT, 2000). Al-Deek and Emam (2006) have expressed the Florida Reliability Method in equation form as follows:

$$R(t) \; = \; P(x \; < X + \; \Delta) \; = P(x \; < TT) \qquad\qquad (Eqn.\ 2.11)$$

where $R(t)$ is the reliability function,

X is the median travel time across the corridor during the period of interest, and

Δ is a percentage of the median travel time during the period of interest, with the FDOT having tested percentages of 5, 10, 15 and 20.

Another measure of similar concept is the *frequency that congestion exceeds some expected threshold*, expressed as the *percent of days or time that travel times exceed a value, X, in minutes* (TTI & Cambridge Systematics Inc., 2006). It can also be referred to simply as *percent congestion*. These two measures like all other statistical measures reported in minutes have the shortcoming that they are not length-neutral and cannot therefore be compared between routes/sections of route of different lengths unless appropriate adjustments are made to use travel rate in place of travel time within the indices.

A tardy trip measure of different form is the *Misery Index*, which focuses on determining the length of delay of the worst trips (Lomax, et al., 2003; Tu, et al., 2006). The Misery index takes the average travel time of the upper 10%, 15% or 20% of trip times and compares it with the average travel time of all trips to express the amount of time beyond the average needed for some amount of the slowest trips. As Lomax et al. (2003) express it, the measure could be thought of as answering the question "how bad are the worst days?" (p. 25). The use of the 20% value for instance might be explained as focusing on the worst day of the week with the index then computed by the following equation:

$$\text{Misery index (MI)} = \frac{\text{(Average travel time of the worst 20\% of trips} - \text{Overall average travel time)}}{\text{Overall average travel time}}$$

The advantage of this measure is that it is length-neutral and therefore can be compared between routes/sections of route of different lengths. However, its use of the average travel time means that it tends to obscure important aspects of the travel time distribution. Another disadvantage of it is that it may not be easily explained in trip scheduling terms.

The last category of statistical measures, skew-width measures, capitalizes on the observation that most travel time distributions are skewed to the right to focus on describing the size and shape of the distribution of the travel times (Transportation Research Board, 2013). Lint and Zuylen (2005) defined a skew measure and a width measure based on median and percentile values noting that these values were more robust than the mean and standard deviation at representing aspects of the travel time distribution.

The *skew* is computed as the *difference between the 90th percentile travel time and the median travel time divided by the difference between the median travel time and the 10th percentile travel time* as in the following equation:

$$\lambda^{skew} = \frac{(T90 - T50)}{(T50 - T10)} \qquad (Eqn.\ 2.13)$$

where *T90*, *T50* and *T10* denote the 90th percentile, the median and the 10th percentile travel times respectively.

The skew is said to be closely related to the MI in representing reliability though more robust in light of its use of the median travel time rather than the average travel time (Lint & Zuylen, 2005). A very small skew value depicts a highly right-skewed distribution while a very large skew value depicts a strongly left-skewed distribution. A large skew value is then interpreted as unreliable. A skew equal to 1 means that the

distribution is symmetric and it therefore becomes necessary to determine the width in order to express reliability. The *width* is computed as the *difference between the 90th percentile travel time and the median travel time divided by the median travel time* as in the following equation:

$$\lambda^{var} = \frac{(T90 - T50)}{T50} \qquad\qquad (Eqn.\ 2.14)$$

where the symbols denote the same travel time values as those of the skew.

The width can be thought of as representing reliability in a much similar way to statistical range measures, with a large width depicting that a large range of travel times may occur within the period of interest and hence there will be low reliability.

The skew and the width are length-neutral measures because they are ratios and as such can be employed for purposes of comparing reliability on routes/sections of route of different lengths. Their disadvantage is that they are not easily explainable in trip scheduling terms.

An important note regarding all of the statistical measures is that they do not in themselves address the variation of travel time reliability over time and must be calculated at different times of day and days of week in order to well capture this aspect (Lomax et al., 2003; Lint & Zuylen, 2005; TTI & Cambridge Systematics Inc., 2006; Higatani, et al., 2009). The advantage is that this can easily be achieved from representative travel time distributions of the different times of day and days of week.

The reviewed travel time reliability measures can be summarized in terms of a suitability matrix gauging strengths, weaknesses and capabilities of each in accordance with the insight gained on aspects that should characterize an all-round good measure (*Table 2.1*).

Table 2.1: Suitability matrix of travel time reliability measures

| Measure | Strength/Weakness Gauge | | | | Capability Gauge | | Suitability |
	Objectivity (with respect to opinion)	Explain ability (with respect to users' purposes)	Representativeness (with respect to reliability aspects/travel time distribution aspects)	Comparability (with respect to route characteristics, particularly length)	Trip Scheduling	Performance Evaluation	
Probabilistic Measures							
Probability that a trip between a given origin and destination pair can be made successfully within a given time interval and a specified level of service	x	x	x	x	x	√	x
Probability that the expected travel time at degraded capacity is less than the link free flow travel time plus an acceptable tolerance, which is related to the level of service that should be maintained despite the capacity degradation	x	x	x	x	x	√	x
Probability that a certain trip can be made successfully within a specified time interval as a function of departure time (in terms of time of day and day of week)	x	x	x	x	x	√	x
Statistical Measures							
1. Statistical Range Measures							
Travel time window	√	x	x	x	x	√	x
Difference between 90th percentile travel time and mean travel time	√	x	x	x	x	√	x
Difference between 90th percentile travel time and median travel time	√	x	√	x	x	√	√
Percent Variation	√	x	x	√	x	√	√

Measure	Strength/Weakness Gauge				Capability Gauge		Suitability
	Objectivity (with respect to opinion)	Explain ability (with respect to users' purposes)	Representativeness (with respect to reliability aspects/travel time distribution aspects)	Comparability (with respect to route characteristics, particularly length)	Trip Scheduling	Performance Evaluation	
2. Buffer Time Measures							
Planning Time	√	√	√	x	√	√	√
Buffer Time	√	√	x	x	√	√	√
Planning Time Index (PTI)	√	x	x	√	x	√	√
Buffer Time Index (BTI)	√	x	x	√	x	√	√
Reliability Index (RI)	√	x	√	√	x	√	√
3. Tardy Trip Measures							
Florida Reliability Method (Percent of travel on a corridor that takes no longer than the expected travel time plus a certain acceptable additional time)	x	x	√	x	x	√	x
Percent congestion	x	x	√	x	x	√	x
Misery Index (MI)	√	x	x	√	x	√	√
4. Skew-Width Measures							
Skew	√	x	√	√	x	√	√
Width	√	x	√	√	x	√	√

KEY: √ - favourable   x - unfavourable

From the matrix, none of the probabilistic measures is deemed suitable on the basis that they are found favourable on only one suitability criterion. On the other hand, at least one measure from each category of the statistical measures is deemed suitable on the basis that they are found favourable on at least three suitability criteria.

The planning time and the buffer time are the only measures found fit for trip scheduling applications. For performance evaluation purposes, any one of the buffer time measures (that is, the planning time, the buffer time, the PTI, the BTI and the RI), the MI, the skew, the width, the percent variation and the difference between the 90th percentile travel time and the median travel time can adequately be applied depending on the goal of evaluation.

2.3 INPUTS OF TRAVEL TIME RELIABILITY MODELLING

As has already been discussed, travel time reliability is usually measured through analyzing either observed travel time distributions or approximated probability travel time distributions. The use of probability distributions is preferable because it enables treatment of travel time as a random variable and produces better and longer serving predictions (Lomax et al., 2003; Lint & Zuylen, 2005). As long as probability distributions are used then, the process entails modelling travel time reliability. The primary inputs of the modelling process that should be considered carefully are the travel time data sample and the probability distribution function. Other inputs of the model are the factors on which it can be conditioned, the departure time in terms of time of day and day of week being the most basic. If it is desired to produce a more elaborate model that gives more insight, then the model conditioning can be extended to other time periods such as month of year and/or to any or several other variability factors such as the irregular congestion sources on urban roadways.

2.3.1 The travel time data sample

An adequate sample of travel time data for modelling is that which estimates the variability of travel time from day to day and/or across different times of day with reasonable degree of accuracy and on this aspect in fact, modelling travel time reliability is no different from measuring through observed travel time distributions.

Elsewhere in the Chapter it has been hinted that the adequate sample is essentially a large one. Of note is that the period of time over which data is collected is important rather than the number of vehicle units observed. However, collecting data over a long period of time also increases the chances of obtaining an adequate vehicle sample size on roadways to cater for other aspects of variability such as the ranges in driving patterns and the different vehicle types.

Generally, at least one month of data collection has been recommended for ensuring the adequate sample. Specifically, in the *Travel Time Data Collection Handbook* prepared for the FHWA, Turner, Eisele, Benz and Holdener (1998) suggested that collection of data over twenty weekdays (evenly distributed over the associated five days of the week) will give sufficient representation of variability across weekdays, with sampling during weekend days in the month giving an adequate representation of weekend trip times (p. 38). The FDOT (2000) recommended an optimum data collection period of six weeks with data collected at intervals of five minutes or less in order to capture variability across small time intervals, and a minimum data collection period of four weeks with data collected at fifteen-minute intervals (p. 2). Toppen and Wunderlich (2003) found that ninety days was an optimum data collection period for estimating travel time variability, though twenty days would give them an adequate sample for this application (Section 4.2).

Larger samples would be necessary for studying such aspects as trends across months or years and could certainly ensure that the estimated travel time variability across smaller time periods is much closer to the true variability, though would not necessarily mean a significant increase in the level of accuracy of measurement.

2.3.2 The probability distribution function

A probability distribution function must be used that adequately fits the observed travel time data in order to enable accurate modelling. As has also been mentioned elsewhere in the Chapter, most observed travel time distributions have been found to be skewed to the right. On this basis, several probability density functions able to represent skew have been tested on travel time data.

The log-normal distribution has been found appropriate in many cases and is widely accepted, with Lomax et al. (2003), stating that "Travel time distributions…are typically "log-normal"" (p. 16) and the Cambridge Systematics Inc., TTI, University of Washington and Dowling Associates (2003) also stating that "The log-normal distribution is the closest traditional statistical distribution that describes the distribution of travel times" (p. 155). Susilawati, Taylor and Somenahalli (2010) after conducting goodness of fit tests with the normal and the log-normal distributions also found that travel times did not follow the normal distribution but did follow the log-normal distribution in some cases. Further, Chu (2011) conducted goodness of fit tests with the gamma, largest extreme value, log-logistic, log-normal and Weibull distributions and found that the log-normal distribution gave a good fit to roadway travel times in cases of a large volume of mixed traffic flow.

Chu (2011) also found that the log-logistic distribution gave a better fit to travel times in cases where there were greater variations in travel times (which happened on roadways when congestion was not so heavy) and was consistent with the theoretical fact that the log-logistic distribution has heavier tails than the log-normal distribution. Taylor and Susilawati (2012) have also suggested the Burr distribution as more appropriate for significant skewness, stating that it has a flexible shape and the ability to describe the very long upper tails (and hence significant skewness) often seen in observed distributions of travel time variations.

Thus, while the log-normal distribution remains a strong choice especially for heavily congested roadway study sections, conducting goodness of fit tests to establish the best fitting distribution between the log-normal distribution and a longer-tailed distribution in specific cases would be more appropriate.

2.4 TRAVEL TIME DATA COLLECTION TECHNIQUES IN TRAVEL TIME RELIABILITY MEASUREMENT

Travel time data for travel time reliability measurement may be collected by any of the well-established travel time data collection techniques depending on their availability and applicability within the study context. Also especially important to consider in choosing a technique is how well it is able to capture travel time variability in the study

area. Several researchers have examined the appropriateness of various roadway techniques and their associated instruments and their works can give good guidance as to the selection of a suitable technique.

The travel time data collection techniques can be classified as follows:

1. Extrapolation from inductive loops and other point sensors
2. Active probe vehicle techniques
3. License plate matching techniques
4. Passive probe vehicle techniques

The first class of techniques typically measures volume and lane occupancy data, and speed data to a lesser degree of accuracy. Ground truth travel times must then be estimated from these types of data. Since sensors are usually closely spaced along a roadway (optimum length of 9 metres according to Turner et al. (1998)), these techniques also constrain measurement to small road segments. Algorithms would then be needed to aggregate small segment data in order to estimate travel times over long segments/corridors/routes (Figliozzi, et al., 2011). Hence with this secondary production of travel time data, this class of techniques does not give the most accurate travel time data (Lomax, et al., 2003; Toppen & Wunderlich, 2003) which is especially necessary for travel time reliability measurement. Further, point detection devices have been shown to be unreliable for estimating travel times in cases of heavy congestion where speeds are low (Turner, et al., 1998; Toppen & Wunderlich, 2003). Loops and sensors are also unable in themselves to differentiate between vehicle types and would not fit the purpose of collecting data for a particular category of vehicles such as freight vehicles unless video footage is incorporated. Still, data collection with these techniques is less labourious and they are advantageous for collecting data over a long period or gathering data for continuous monitoring systems.

The second class of techniques allows direct measurement of ground truth travel time as it involves a data collection vehicle driving through the traffic stream in a manner to represent the prevailing driving conditions and depending on the instrumentation used, travel time being recorded at predefined checkpoints or the location of the vehicle being noted at specific time intervals. The reference to them as "active probe vehicle

techniques" is due to the fact that the probe vehicle is specifically in the traffic stream for data collection and no other purpose. With these techniques, ground truth travel time can also be measured over long segments since it is possible to tell the exact time that the probe vehicle passes through the start point of the segment and the exact time it again passes through the end point of the segment. While data can also be easily collected for sub-sections of the long segment/corridor/route, measurement of variability across different days or different times of day is difficult as it is not easy to control on multiple days precisely when the probe vehicle enters the segment for which travel time is required. Further, collection of data over a long period requires the commitment of a significant amount of resources, particularly labour. The categories of active probe vehicle techniques include the average car, the chasing car and the maximum car techniques, with the instruments used in data recording including manual, distance measuring instrument (DMI) and global positioning system (GPS), the latter two being more accurate and requiring less data reduction effort (Turner, et al., 1998; Toppen & Wunderlich, 2003).

The third class of techniques which involves matching vehicle license plates at predefined checkpoints and measuring travel time by the difference in arrival times of the matched plates at consecutive checkpoints is considered particularly appropriate for obtaining ground truth travel time. This is because it allows direct measurement of travel time and can also capture a higher percentage of the traffic stream, thereby sufficiently accounting for ranges in driving patterns and different vehicle types, compared to active probe vehicle techniques which tend to summarize the traffic stream by only one vehicle (Toppen & Wunderlich, 2003). Like the active probe vehicle techniques, these techniques also allow measurement of ground truth travel time over long road segments/corridors/routes as well as over sub-sections of the segment/corridor/route. Their most unique advantage with respect to travel time reliability measurement however is that since the instruments of measurement remain stationed at the same desired locations of the segment/corridor/route under study over the entire data collection period, travel time variability across different days/times can accurately be established as long as the instruments are operational at the same time each day. The data recording instruments that differentiate these techniques include manual, portable computer, video with manual transcription and video with character recognition (Turner, et al, 1998; Toppen & Wunderlich, 2003). The video based

instruments particularly have the advantage of allowing a large percentage of the traffic stream to be captured. Manual observers can only record a sample of the traffic stream especially where high traffic volumes are involved and there is also the possibility of errors occurring due to fatigue. Further, the manual data reduction procedures require considerable effort with Turner et al. (1998) indicating that up to ten hours are required to reduce one hour of data collected. A final disadvantage of these techniques is that collection of data over a long period can require a significant amount of resources.

The fourth class includes such techniques as Advanced Vehicle Location (AVL), Automatic Vehicle Identification (AVI), cellular phone tracking, ground based radio navigation and GPS technologies that are typically intelligent transportation systems (ITS) designed to track vehicles in real-time for such applications as traffic operations monitoring, incident management and route guidance but can provide opportunity for travel time data collection (Turner, et al., 1998; Toppen & Wunderlich, 2003). The fact that the vehicles tracked are in the traffic stream for purposes other than just data collection explains the reference to these techniques as "passive probe vehicle techniques". The techniques are most suitable where the technologies have widely penetrated the market such that a large number of vehicles are equipped with the instruments of measure; otherwise it would be hard to obtain an adequate sample for accurate estimation of ground truth travel time let alone the establishment of travel time variability. Close coordination is usually necessary with the agency responsible for the system operation as authorization must be obtained to track vehicles for data collection and there are also privacy concerns to deal with. Thus these techniques are more easily employable for agency data collection efforts than for small scale research efforts as an agency is more likely to obtain the necessary authorization and deal with the privacy issues. However, if the institutional and privacy challenges can be overcome and there is sufficient market penetration, these techniques offer the advantages that no investment in additional infrastructure for data collection is required; data can easily be collected over a long period or for continuous monitoring applications as long as the probe vehicles continue to travel through the system; and data reduction is less labourious as the data collected is already in electronic format. One thing that may be hard to control with these techniques (with the exception of the GPS technologies) is the desired locations of data collection stations since the

associated infrastructure is already fixed to suit the primary purposes (Turner, et al., 1998).

2.5 REVIEW OF CASE TRAVEL TIME RELIABILITY STUDIES

Travel time reliability studies have most notably been conducted in developed countries such as the US, Japan, the Netherlands and Australia and in emerging countries such as Taiwan, where travel time reliability is now recognized as an important information tool to travelers in addition to being a key indicator of transportation performance and a problem diagnostic tool. The studies demonstrate the value of travel time reliability in design and operation of Advanced Traveler Information Systems (ATIS), in characterization of congestion in transport systems/networks, in prioritization of system/network shortcomings and in evaluation and appraisal of mitigation projects and programmes.

Some of the studies are reviewed here below in accordance with the already presented principles of travel time reliability measurement:

1. *Freight Performance Measurement: Travel Time in Freight-Significant Corridors (Mallet, Jones, & Sedor, 2006) - US*

In this pilot comparative study of freight performance initiated by the FHWA, truck performance was analyzed in terms of speed and travel time reliability on five freight significant corridors across the US: Interstate 5, Interstate 10, Interstate 45, Interstate 65 and Interstate 70. The FHWA was able to successfully collaborate with the American Transportation Research Institute (ATRI), technology vendors and freight carriers to collect data for the study using AVL equipment aboard approximately 250,000 trucks nationwide over a period of one year (2005). Speed and travel time reliability were measured in terms of average truck speed and BTI (with travel rate being used instead of travel time in the statistics of measure) respectively across different months of the year for each corridor.

A comparison of the corridors' average truck speeds showed that trucks moved the slowest on Interstate 5 while a comparison of the BTIs showed that travel times were

most unreliable on Interstate 45, having the highest BTI values (rising up to 45% in the month of June) and which themselves fluctuate greatly throughout the year. The study was the first step in the FHWA's goal of developing a long-term freight performance monitoring system that could avail information first to relevant transportation agencies across the US for better informing their decisions on management of freight transport systems and aiding their prioritization of investment towards capital improvements, and second to freight carriers, shippers and other industry stakeholders for better informing their business decisions and strategies towards improving productivity.

The following can be noted about this study:

- Since the method of data collection used allows direct measurement of travel time and there was a high level of market penetration as evidenced by the number of probes involved, it can be assured that the sample of data obtained was sufficient for accurate estimation of travel time and its variability;
- The period of data collection of one year was obviously chosen in relation to the goal of representing trends across the months of year, though it further affirms the accuracy of the travel time variability estimate. However, while the representation of trends across the months of year may be fit for the goal of performance evaluation, it is not very valuable to the decision process of frequent users and for this purpose, trends across such time periods as time of day and day of week offer better guidance;
- While not explicitly mentioned in the study, there is indication that the analysis was based on observed travel time distributions which means that the random aspect of travel time was not studied. This means that the resulting travel time reliability information would not serve long-term purposes;
- The use of the BTI measure served well the purpose of comparing travel time reliability on the different corridors, with the use of travel rate instead of travel time in the statistics of the index further assuring that corridor lengths had as little effect as possible on the comparisons. However, the BTI still does not account well for the impacts of unusual events on travel times and measures such as the RI, the skew and the width are better in this respect;

- The study well demonstrates the complementary role played by travel time reliability measures in pointing out system shortcomings, in this case clearly indicating the greater economic risks in terms of delay costs posed to freight carriers travelling on Interstate 45 than travelling on Interstate 5 as would have otherwise been assumed.

2. *Using travel time reliability measures to improve regional transportation planning and operations (Lyman & Bertini, 2008) – US*

Lyman and Bertini (2008) described how travel time and its reliability are measured in the city of Portland, Oregon in the US and how the resulting information is used in ATIS and how it can be used for different goals of performance evaluation. Data is continuously collected from sensors located all along the city's transport corridors and transmitted to an Archived Data User Service (ADUS) known as the Portland Oregon Regional Transportation Archive Listing (PORTAL).

PORTAL produces for different corridors automated monthly reports with information such as the mean travel time and the 95th percentile travel time across different times of day, and the percent of monthly readings that were congested, with the simple web allowing users to query the archive for the reports. Thus a user would be able to tell and compare beforehand the planning time and buffer time for their trip across different times of day and/or different routes and choose a most convenient departure time and/or travel route. The authors explained that if users can be induced this way to manage their own travel, then this results not only in more profitable use of time but also in better use of a transport system/network.

PORTAL also allows comparisons over time, such as from month to month and from year to year, which make it possible for transport planners and operations personnel to continuously gauge what and where management and capital improvements are needed, to aid decision making on these and to evaluate benefits where they are applied. For instance, the authors themselves compared the time of day patterns of the TI and the planning time on Interstate 5 from 2004 to 2006. They found that there was slight decrease in the afternoon peak values of the TI in 2006 which they attributed to the incorporation of an improved ramp metering software system in that

year. However, the planning time increased significantly in 2006, which means that the ramp metering improvement was not sufficient to deal with this aspect of travel time.

The authors further undertook an analysis of the relationship between BTI and vehicle miles travelled (VMT) per unit length on several of the city's freeway corridors over time and identified two corridors and directions of travel (Highway 26 East and Interstate 84 West) that greatly served travelers in terms of VMT per unit length and also showed consistently large BTIs as needing the most attention. They concluded that the interchanges between these corridors and Interstate freeways could be bottlenecks, being one reason for the large BTIs and lending importance to bottleneck analysis at these locations.

The following can be noted about this study:

- Although the data collection technique used does not allow direct measurement of travel time and the accuracy of the secondary travel time data produced can be wanting, the advantages of having a continuous ITS data collection and monitoring system – including the facts that information needed for analysis is easily available, samples as large as one requires can be obtained with little effort and the archived data allows a myriad of useful analyses – are clear and could be considered to outweigh this disadvantage of the data collection technique;
- The analysis of data in PORTAL is based on observed travel time distributions and this suffices because data is collected and analyzed continuously which means that the resulting information is always up to date;
- While the percent congestion measure provides the benefit of testing stakeholder expectations and the BTI well allows comparison across different route lengths, these measures still fall short with regards to objectivity in representing travel times;
- The study well demonstrates different valuable applications of travel time reliability. First, it gives a practical example of an ATIS that incorporates travel time reliability measures and describes how it works, and shows the benefits to efficient use of transport systems/networks this in itself offers. It also uses travel

time reliability to carry out a more advanced evaluation of an instituted transport project in a manner that could not be achieved by use of just the average travel time. Lastly, it combines travel time reliability with a spatial congestion measure to effectively prioritize shortcomings within a transport network.

3. Empirical Analysis of Travel Time Reliability Measures in Hanshin Expressway Network (Higatani, et al., 2009) – Japan

Higatani et al. (2009) studied travel time reliability in the Hanshin Expressway Network in a bid to understand the characteristics of congestion in the expressway that accommodates massive flows of commuter and freight traffic – up to 900,000 vehicles per day – in the Hanshin Metropolitan Area of Japan. Focusing on the expressway's five radial routes that connect downtown Osaka City to different suburban areas (Route 11 to Route 15), the authors estimated route travel times from 5-minute interval traffic flow and occupancy data collected by ultrasonic vehicle detectors installed at approximately every 500 metres along the expressway and stored in the Hanshin Expressway's data warehouse (DWH). One full year's data (April 1, 2005 to March 31, 2006) was used to develop probability distributions of travel time at departure times for the downtown bound lane and then the general patterns of the average travel time, the planning time, the buffer time and the BTI across the hours of day determined for each route.

Comparison of the patterns of route average travel times and route planning times showed that apart from Route 11 which had an opposite trend, travel times on the other routes tended to be longer and more time needed to be set aside for trips during the morning peak than during the evening peak. The patterns also showed that the morning peak hours of both measures on Route 12 tended to occur one hour later than on the other routes, this being attributed to its service of freight and business trips more than commuter trips. Also, the peaks of the buffer time and the BTI on the routes tended to occur shortly after the peaks of the average travel time, this implying that the transition hours from peak times to off-peak times were the most unstable to travel in. While Route 11 was established as generally the busiest throughout the day in terms of the average travel time, the patterns of route BTIs showed that Routes 12, 13 and 14 generally had more unreliable travel times throughout the day, with BTIs on Routes

13 and 14 even rising to more than 100%. The conclusion then was that the level of congestion in terms of the average travel time is inconsistent with the uncertainty of travel times and travel time reliability measures are therefore very useful in representing the whole picture of congestion.

The authors also examined the influence of traffic incidents (accidents, road works, vehicle breakdowns, inattentive driving, fallen loads and fire) on travel time reliability on one route (Route 14). Traffic incident data and corresponding travel times were collected from the DHW when the tail of the traffic congestion was on the observed section during three target hours (7:00 - 8:00 a.m., 12:00 - 1:00 p.m. and 5:00 - 6:00 p.m.) of all the weekdays in the fiscal year 2006. Travel times throughout the year's weekdays for each hour were then ranked from the longest to the shortest, with accident, other incident or no incident being noted at corresponding travel times. It was found that the frequency of incidents was lower in the peak hours (7:00 - 8:00 a.m. and 5:00 - 6:00 p.m.) than in the off-peak hour (12:00 - 1:00 p.m.) though incidents were more likely to be the cause of the longest travel times in the peak hours than in the off-peak hour. It was also found that while incidents had no major effect on the average travel times in all the hours, they resulted in significantly larger planning times, buffer times and BTIs compared to when there were no incidents, this instability effect being greatest in the off-peak hour than in the peak hours. The conclusion then was that minimizing the occurrence of traffic incidents using advanced traffic control systems could well improve travel time reliability.

The following can be noted about this study:

- Data was obtained from a continuous ITS data collection and monitoring system, enabling easy gathering of required information in sufficient samples which as has been mentioned previously, outweighs the shortcoming of indirect measurement of travel time inherent of the data collection technique;
- Analysis was based on probability travel time distributions, meaning that the random aspect of travel time was taken into consideration and strong predictions were possible. However, the authors did not mention what

probability distribution function was employed and it is not therefore clear whether travel times were well represented in this respect;

- The routes studied were of similar length, which enabled the authors to compare the average travel times, the planning times and the buffer times on the routes;

- The BTI measure used in performance evaluation has the shortcoming of obscuring effects of unusual events on travel times;

- The study achieved elaborateness in its examination of the influence of traffic incidents on travel time reliability and gave useful insights that could help justify investing in reducing them. It can be noted that effort was made to precisely relate traffic incident effects with travel time and this was made easier by the data collection system used;

- The study well demonstrates the benefits of travel time reliability to holistic understanding of congestion, which would particularly be useful when designing traffic control systems. It also well demonstrates the route and time specificity of travel time reliability, with especially good comparisons given of travel during the peak and off peak periods across the different routes.

4. An Empirical Study to Determine Freight Travel Time at a Major Port (Chu, 2011) – Taiwan

Chu (2011) investigated freight travel time reliability on four urban arterials that provide access to an international sea port, the Kaohsiung Port, in Taiwan, which he described as experiencing "…significant congestion and delays during peak periods due to the large volume of heavy truck and car traffic". The arterials, with LOS ranging from D to F, were divided into seven segments based on the approximately equivalent length of 2.0-3.0 kilometres and the major intersection of arterials. The author was able to collaborate with large trucking companies that already operated GPS fleet tracking systems to obtain 5-minute interval daytime (7:00 a.m. to 7:00 p.m.) travel time and speed data for the segments from GPS equipment aboard 40 heavy duty trucks (3 axles or more) that tended to traverse all the segments two or three times a day. The data was collected over a 3-month weekday period from February to April, 2009.

From the data, it was established that the log-normal distribution best fitted travel times on segments 1, 2 and 3 during the morning peak period (7:00 a.m. to 10:00 a.m.) and the afternoon peak period (4:00 p.m. to 7:00 p.m.) when LOS fell below E and freight movements generated more interactions with a high volume of commuter trips. On the other hand, the log-logistic distribution was found to fit travel times best on all other segments (with LOS D) and on segments 1, 2 and 3 during the midday off-peak period (10:00 a.m. to 4:00 p.m.). The average truck speeds and the travel time reliability measures of PTI, BTI and RI were determined for each segment during the morning peak, the midday off-peak and the afternoon peak periods. While it was found that the average truck speeds on most segments were higher during the midday off-peak than during the other time periods, a comparison of the segment PTIs, BTIs and RIs showed that the additional time required to ensure on-time freight trip arrivals 95% of the time during the midday period was slightly greater than during the afternoon peak period and noticeably greater than during the morning peak period. Ironically though, most freight carriers tended to select the off-peak period for travel to avoid rush-hour congestion.

The author also sought to examine the effects of variance related factors including speed fluctuations, traffic incidents, severe weather, work zones, traffic signal breakdown and special events on route travel time reliability during the midday off-peak period. 3-month historical data of the factors other than speed during the spring season were obtained from the central weather bureau, the traffic control centre and the traffic engineering division. Multiple regression models were then established for relating the logarithmic transformation of travel time and the variance related factors on each route and statistical analysis conducted to screen the significance of the explanatory variables. It emerged that traffic signal breakdown had the most significant effect on travel time reliability during the midday period, followed by traffic incidents, work zones and travel speeds in that order. The conclusion then was that maintaining the continuous operation of traffic signals and functions would greatly improve freight travel time reliability on the port arterials. Another finding was that speed fluctuations and traffic incidents were the common persistent factors of uncertain travel times on all the study arterial segments during the midday period. The variance of travel time particularly showed strong correlation with speed fluctuations and the author concluded that this could owe to aggressive and pessimistic driving behavior from

truckers during this uncertain period motivated by the JIT mentality and called for more research.

The following can be noted about this study:

- The travel time data collection technique used and the fact that 40 probes with the tendency to traverse all the study segments two to three times a day were involved over a period of 3 months makes a good case for the data sample obtained for estimation of travel time and its variability;

- Analysis was based on probability travel time distributions which allowed studying the random aspect of travel time and resulted in strong long-serving predictions. The author also put effort into establishing the best fitting probability distribution function for travel times during different daytime periods, which further assured the accuracy of the travel time reliability measurements;

- The objectivity of the performance evaluation in the study was greatly improved by dividing the arterials into segments of approximately equivalent length and using the RI measure, which provides a more robust representation of travel time distributions;

- The study well established the differences in travel time reliability during the peak and off-peak periods of the day, though as it has previously been stated, there could be inherent differences worth studying within these time periods;

- The study achieved elaborateness in its examination of the influence of several variance related factors on travel time reliability, identifying the factor with the most effect on travel times in the most unreliable daytime period and the factors that were most frequent on the study segments during this period, also giving recommendations on solutions;

- The study well demonstrates the best practices in travel time reliability measurement, from the data collection method used, to the analysis methods employed and the travel time reliability measures adopted.

2.6 REVIEW OF PERFORMANCE AND IMPROVEMENT STUDIES ON THE NORTHERN CORRIDOR

Reliability only now gaining importance on the Northern Corridor, performance and improvement studies have yet to embrace elaborate methodologies of assessing its indicators or using them on the corridor. On the Northern Corridor Road in particular, the V/C ratio remains the measure primarily used for establishing transport bottlenecks, hence usually informing additional capacity requirements within the road infrastructure. The average travel time is then popularly used to evaluate effects of improvements and is also often incorporated into the determination of costs, used also for evaluating improvements or just for assessing the trade performance on the corridor. Rarely have even the forms of reliability measurement carried out on the corridor so far been used to inform improvement decisions or to assess improvement effects on the corridor road, or other corridor elements for that matter, though they have been used significantly to assess current performance. There has not been an attempt to explore expression of reliability for the information of users.

Some of the recent performance and improvement studies on the Northern Corridor are reviewed here below, with examination of the extent to which they have contributed to reflecting performance and achieving improvement particularly with respect to measurement and application of reliability indicators:

1. *Northern Corridor Transport Improvement Project (NCTIP): Monitoring and Evaluation Project (University of Nairobi Enterprises and Services (UNES), Ongoing)*

The University of Nairobi Enterprises and Services (UNES) has since the year 2006 been undertaking monitoring and evaluation of the Northern Corridor Transport Improvement Project (NCTIP), whose key component is the rehabilitation of sections of the Northern Corridor Road in Kenya (UNES, 2010). The parameters for monitoring and evaluation of the rehabilitation listed in the project terms of reference include: the level of utilization and distribution of vehicular traffic along the Northern Corridor Road; travel times within each sub-project section and the entire corridor; and passenger fares and cargo charges and vehicle operating costs. The intent is to measure these

parameters annually/biannually during the rehabilitation period in order to determine changes and be able to estimate impacts after the projects are completed, all towards evaluating the goals of reducing freight and passenger travel times by 25%; reducing the cost of business along the Northern Corridor Road; and enhancing Kenya's role as a regional trade hub.

The project does not include a specific component for the indication of reliability and evaluation of it. Yet this would have been very beneficial considering that reliability has been demonstrated to be at the heart of better trade facilitation on the corridor, with costs of unreliability currently affecting most adversely the logistics costs of transporting goods through it.

2. *Freight Rate Determinants along the Northern Corridor Road (Oyier, 2009)*

For his thesis requirements, Oyier (2009) undertook development of a model for calculating freight rates on the Northern Corridor Road, recognizing that the absence of a well-defined method of estimating costs of transporting goods through the corridor left this aspect to the forces of market supply and demand which was detrimental to end users. Like most other land transport cost models, the model places great emphasis on sensitivity of freight rates to vehicle operating costs (VOCs), with other significant inputs of the model being travel distance and cargo weight. Cargo time value in the model is based on the average travel time along the roadway while assumptions such as to the effect that there are minimal delays at weighbridges, border posts and police checks along the road were made in its development.

As has already been demonstrated, the average travel time does not capture the effects of uncertainty factors on travel times. Further, delays and particularly unreliability delays that result from uncertainty factors account for the largest percentage of the logistics costs of transporting goods on the corridor. Hence the model suffers a limitation in the minimization of the value of delays and reliability, and would likely not give users an accurate reflection of the costs they could incur from transporting goods through the Northern Corridor Road.

Some of the improvement recommendations made from this study were that sections of the road that experienced repeated changes in alignment should be realigned to shorten the distance covered and lower the VOCs and that the maximum cargo weight limit should be strictly enforced at weighbridges to prevent high VOCs. Again, without a comprehensive consideration of reliability, it remains debatable that these improvements would provide optimal benefits to users.

3. **Analytical Comparative Transport Cost Study along the Northern Corridor Region (CPSC Transcom Limited, 2010)**

This study was carried out with the objectives of quantifying and analyzing the total transport logistics costs on the Northern Corridor, proposing appropriate policy and other measures for lowering the costs and improving trade performance on the corridor. The authors undertook to quantify the various cost components including fixed costs of shipments (sea freight and shipping line charges; port handling charges and clearance fees), transportation costs by the modes of road; rail; pipeline and inland waterways (including VOCs and tariffs charged by transporters), transit overheads (custom procedure costs; forwarding agents and middlemen costs; bribes and facilitation payments) and delay costs including direct and indirect delay costs. They then compared the road transportation costs from the port of Mombasa to main destinations such as Nairobi; Kampala and Kigali, the operating costs by the different transport modes and the total logistics costs with those of other similar trade and transport systems around the world.

The methodology of costs determination was by review of existing studies and extensive questionnaire interviews with stakeholders including public authorities, transporters, shippers, freight forwarders, clearing agents, shipping lines and stakeholder associations and verification by conducting a trial run through the corridor for measurement of all physical barriers and delays. The indirect delay costs associated with unreliable movement and processes along the corridor were in particular determined by applying the "revealed preference" methodology whereby transporters and shippers were asked of their "willingness to pay" to avoid such aspects as transport unreliability; road accidents and insecurity, manifested mainly as opportunity costs of extra inventory held. It is from this study that it has been

determined that indirect delay costs form the bulk of the logistics costs of transport on the Northern Corridor (*Figure 1.2*). Stakeholders were also asked to prioritize a set of policy and other measures proposed by the authors from their review studies, which then formed the basis for development of the improvement recommendations.

The consideration of the effects of corridor reliability on business costs distinguishes this study from previous cost studies and is a great achievement towards capturing all trade influence factors. However, estimation from users' perceptions as has previously been indicated is subjective and does not guarantee optimal results. Even the trial run through the corridor, while perhaps able to measure common delays, is not capable of well capturing effects of uncertainty factors that cause unreliability. It is recognized that this methodology was probably chosen as a practical quick way of determining overall corridor measures, but applying methodologies appropriate to measuring actual process, logistics stage or section specific cost factors would have been more beneficial to giving accurate information and especially to prioritizing improvements. This lack of specificity of the study may explain why it exhibits no comprehensible relation of the proposed improvements to the performance cost measures employed. It remains therefore debatable that the improvements proposed would provide optimal benefits.

Although not an intent of this study, it can also be noted that the measure and expression of reliability as the percentage overall indirect costs relative to other cost components does not suit provision of information to users that can induce them to manage their own travel and other business decisions, this being another effective means through which trade competitiveness on the corridor can be improved.

4. ***Northern Corridor Infrastructure Master Plan (Louis Berger, 2011, May); East African Transport Strategy and Regional Road Sector Development Program (Africon Ltd., 2011, September)***

The above two studies had a mainly infrastructure perspective, focusing on determining additional infrastructure requirements within their scopes through consideration of the physical capacity needed to cater for the envisaged utilization in the projects' time frames. The Northern Corridor Road for instance in both cases was

evaluated in terms of the V/C ratio, with shortcomings identified and prioritized for improvements based on the LOS and the estimated benefits in terms of the economic internal rate of return (EIRR).

The infrastructure perspective alone however is limited with respect to reflecting user experiences and values in the transport system and provides little insight into effects on trade. Without additional evaluation of parameters such as time; cost and reliability of movement and processes in the system, it is near impossible to determine the true worth of improvements and to well prioritize projects and programmes. Besides, while it may be sufficient to assume that the V/C ratio and movement or process time on average have a strong correlation and improvements in V/C ratio will result in significant improvements in average times, it has already been made clear that time reliability does not necessarily follow the same pattern and can therefore provide a very different picture even of infrastructure shortcomings and improvement priorities. Hence, besides not providing user sensitive performance assessment, project and programme decisions made from these studies may not be the ones that can provide optimal benefits.

5. *Corridor Diagnostic Study of the Northern and Central Corridors of East Africa (Nathan Associates Inc., 2012)*

This study was carried out with the objective of providing a technical foundation for the development of an action plan to tackle transport bottlenecks along the two main East African trade routes. It focused on evaluating the corridors' transport logistics chains in terms of freight time, cost (as experienced by shippers) and time reliability and giving recommendations for improvement of these parameters on the corridors.

A software and audit methodology known as FastPath was used to model the current state of the performance parameters for various components of the logistics chains. It was also used to quantify and prioritize identified infrastructural and other operational bottlenecks and potential solutions based on information obtained from review of existing studies and ongoing development projects and programmes; collected data and conducted questionnaire and discussion interviews with stakeholders including shippers; transport service providers; freight forwarders and government entities. For

instance, for the port components, the input information into FastPath pertained to the price, the average time and the maximum and minimum times as analyzed by the authors from the raw information. For the road components, the input information pertained to the price per kilometer, the average trip time, the average wait time, the maximum and minimum speeds and the maximum and minimum wait times by each road transport alternative also as analyzed by the authors from the raw information. FastPath then developed time reliability measures as the range of variations in time with respect to the average time spent in each component analyzed. The resulting component performance measures were later added for the total logistics chains and sub-chains and evaluated also against international benchmarks of whole corridors, of different transport modes and of different logistics chain stages.

The fact that time reliability was incorporated as a parameter of evaluation in this study is a great strength for holistic evaluation from a trade facilitation point of view. Another advantage of the study lies in the fact that bottlenecks and solutions were quantified in terms of the three evaluation parameters, which enabled comprehensive representation, understanding and assessment of impacts. An additional great achievement particularly towards facilitating prioritization of improvements lies in the specificity of evaluation employed, with different processes and sections within the various logistics stages of the corridors having been considered separately. For instance, at the port stage of the logistics chains, the five main elements of the channel, the berth, the yard, customs clearance and the gate were considered in both processing of imports and exports and the yard of the Mombasa Port on the Northern Corridor identified as the most costly and slowest element in processing of imports with the channel and customs clearance sharing the slot of most unreliable. In processing of exports, the yard had the worst performance on all three parameters. Thus it was possible to tell that the focus of improvements should be on enhancing the performance parameters at the yard. The corridor roads on the other hand were evaluated in links between key nodes, being major towns and border posts, such as Mombasa-Nairobi, Nairobi-Eldoret, Eldoret-Webuye, Webuye-Malaba, Malaba-Tororo and Tororo-Kampala on the Northern Corridor, which enabled distinctive evaluation of the road sections as opposed to considering the roads as whole.

However, the study is still limited in the methodology employed to measure the evaluation parameters, which relied extensively on estimations by stakeholders. As previously stated, this approach tends to be subjective. Although the authors cite even distribution of interviews among the stakeholders, cross-checking with available information from actual invoices; published tariffs and discussions with unbiased third parties and physically driving through the corridors as validating the representativeness of the data entered into FastPath, it is difficult to particularly verify time reliability information through the mentioned cross-checking measures. Hence it is debatable that the most accurate reliability results were obtained and that optimal reliability improvements were taken into account. Of note also is that although time reliability was used in assessment of performance and improvement impacts, it is not mentioned in the criteria employed to prioritize projects within the proposed action plan. The criteria include impacts on cost and time and an acceptable EIRR, with road sections also having previously been prioritized based on the LOS, but nothing on time reliability. It would have been beneficial if time reliability had been included, having already been indicated to be the most valuable to business and to work well alongside the other parameters for such prioritization.

A further note is that the measure and expression of reliability in this study would not suit provision of information to users for purposes of managing their travel and other business decisions, though this was not an intent of the study. As has already been mentioned, the measurement of time reliability as the range of variations in time relative to the average time does not relate very well to the way of making trip decisions. Reliability is also classified as good, fair, poor and very poor based on percentage score ranges such as 5 – 100%, 100 – 200%, 200 – 300% and 300 – 500% respectively on the roads, which does not communicate to users for instance in trip scheduling terms.

6. *Consultancy Services for Upgrading the A104 from Likoni Road to James Gichuru Road (COWI A/S, et al., 2012, October); Consultancy Services for Preliminary and Detailed Engineering Design for JKIA Turnoff – Likoni Road (A104) and Links Roads (GIBB Africa Ltd. & Associated Consultants of Ghana, 2015, May); Consultancy Services for Rehabilitation and Capacity Enhancement of A104 from James Gichuru Road Junction to Rironi (A104/B3 Junction) (ESER Project & Engineering Co. Inc. & Botek Bosphorus Technical Consulting Co., 2015, June)*

These studies, focusing specifically on the Northern Corridor Road segment in Nairobi, were carried out with the intention of developing road designs that can carry the envisaged traffic on the segment within the projects' time frames and that can help relieve congestion along the road segment. The capacities of the road components were evaluated based on the V/C ratio, density and average travel speed for the links and average delay and maximum queue length for the junctions, with shortcomings and improvements identified based on the LOS. The improvements were further assessed based on their EIRR impacts.

Thus the studies had a largely infrastructure perspective, with limited reflection of user experiences and values in the system. Further, the evaluation measures employed are not capable of well capturing the effects of irregular congestion causing factors, only possible through such measures as travel time reliability. Hence it is possible that the proposed improvements on the segment including provision of grade separated junctions, addition of carriageway and auxiliary lanes and provision of service roads are not sufficient for the goal of relieving congestion along the road segment.

2.7 STUDY CONTRIBUTION IN VIEW OF PREVIOUS RESEARCH

This study seeks to build on the best practice principles of travel time reliability measurement learnt from research to apply an objective assessment of time reliability on a logistics stage section of the Northern Corridor, being the Northern Corridor Road segment in Nairobi. To this end, measurement is based on obtaining and analyzing

ground truth information and incorporating measures of travel time reliability that have been established to assure objectivity.

The study also endeavours to improve on the usage of reliability indicators on Northern Corridor, by seeking to comprehensively relate travel time reliability to influence factors, to define improvements taking into account travel time reliability and its influence factors and to prioritize shortcomings for improvement also taking into account performance in terms of travel time reliability. Further, the study seeks to express travel time reliability for the purpose of providing traveler information as a first bid of involving users of the Northern Corridor in meaningful management of its transportation service.

Moreover, the study seeks to improve on the holistic assessment and management of congestion on the Northern Corridor Road in Nairobi, this by adding travel time reliability to the evaluation parameters. It is hoped that the same approach can be applied to other similarly problematic roadway sections along the Northern Corridor and indeed on other transportation lines/systems in Kenya.

The study is different from the discussed case travel time reliability studies in this Chapter in that it presents travel time reliability measures across daytime periods both on weekdays and on weekend days.

3. MODELLING FREIGHT TRAVEL TIME RELIABILITY ON THE NORTHERN CORRIDOR ROAD SEGMENT IN NAIROBI

3.1 OVERVIEW

This study sought to measure and evaluate freight travel time reliability on the Northern Corridor Road segment in Nairobi, and to demonstrate how this information can be used to facilitate reliable freight movement on the segment.

The specific objectives of the study were as follows:

1. Examine a method of quantifying and explaining variations in travel time to establish travel time reliability;
2. Compute freight travel time reliability measures for the Northern Corridor Road segment in Nairobi and evaluate the segment's performance in light of this information;
3. Indicate how freight carriers may obtain and use the freight travel time reliability information to improve their schedule planning;
4. Assess the proposed improvements on the segment in view of its reliability performance and recommend alternative/additional improvement measures.

Applying the concept of travel time reliability measurement described in the previous chapter for quantifying and explaining variations in travel time to establish travel time reliability, freight travel time reliability was modelled on the Northern Corridor Road segment in Nairobi in accordance with the benefits of this approach to treating travel time as a random variable and to producing longer serving predictions. Trends of freight travel time and freight travel time reliability measures over time for the days of the week and for distinct sections of the road segment were developed to enable comparison.

The following were considered in model development:

1. Relevant input data;

2. Appropriate probability distribution function;
3. Applicable travel time and travel time reliability measures;
4. Other relevant analysis

3.2 RELEVANT INPUT DATA

The required sets of data were as follows:

- Travel times of heavy goods vehicles (HGVs) on the Northern Corridor Road segment in Nairobi – where HGVs in Kenya are defined as goods vehicles with three (3) or more axles (Bureau for Industrial Cooperation, 2011, Table 3.2) and are recognized as the road freight vehicles in use, including lorries, trucks, tractor-trailer combinations and fuel tankers (Ministry of Transport, 2010, p. 57);
- Site information on irregular congestion causing factors including traffic incidents, traffic control malfunction, road works, extreme weather and special events.

The HGVs' travel time data was the necessary basic input of freight travel time reliability modelling on the road segment. The information on irregular congestion causing factors was needed for screening the travel time data to remove unwanted outliers before it could be incorporated in the modelling process and was later compared with the measured freight travel time reliability on the segment for description of influences.

3.3 APPROPRIATE PROBABILITY DISTRIBUTION FUNCTION

The log-normal distribution, which has proved sufficient in most cases of describing travel time distributions, was adopted for representing the distribution of HGVs' travel times on all sections of the Northern Corridor Road segment in Nairobi across all study time periods. Although this assumption was deemed reasonable on the consideration that almost the entire road segment in Nairobi suffers heavy congestion most of the time, this approach was taken primarily to simplify the study analysis and it is recognized that detailed analysis to determine whether a longer-tailed skew

distribution may in fact have provided a better fit to the HGVs' travel time data in any of the mentioned scenarios would have been more appropriate.

The useful characteristics of the log-normal distribution as learned from Chu (2011) and Thomopoulos and Johnson (2012) are as follows:

Considering a log-normally distributed variable x with mean μ_x and standard deviation σ_x, the variable's natural logarithm,

$$y = \ln(x) \qquad\qquad\qquad\qquad (Eqn.\ 3.1)$$

is normally distributed with mean μ_y and standard deviation σ_y.

The probability density function of the log-normal distribution is defined as follows:

$$f\left(x;\ \mu_y, \sigma_y\right) = \frac{1}{x\sigma_y\sqrt{2\pi}}e^{-\frac{(\ln(x)-\mu_y)^2}{2\sigma_y{}^2}} \qquad for\ x\ \geq 0;\ \mu_y,\ \sigma_y\ > 0 \qquad (Eqn.\ 3.2)$$

If μ_y and σ_y are known for y, the corresponding parameters of x can be defined as follows:

The mean $\mu_x\ =\ e^{\mu_y + \frac{\sigma_y^2}{2}}$ $\qquad\qquad\qquad\qquad (Eqn.\ 3.3)$

The variance $\sigma_x^2\ =\ e^{2\mu_y + \sigma_y^2}\left(e^{\sigma_y^2} - 1\right)$ $\qquad\qquad (Eqn.\ 3.4)$

Similarly, if μ_x and σ_x are known for x, the corresponding parameters of y can be defined as follows:

The mean $\mu_y\ =\ \ln\left(\dfrac{\mu_x^2}{\sqrt{\mu_x^2 + \sigma_x^2}}\right)$ $\qquad\qquad\qquad (Eqn.\ 3.5)$

The variance $\sigma_y^2 = \ln\left(1 + \dfrac{\sigma_x^2}{\mu_x^2}\right)$ $\qquad\qquad\qquad (Eqn.\ 3.6)$

The log-normal distribution can be standardized, in which case the mean of its normal counterpart $\mu_y = 0$. For this case, the parameters of x become:

The mean $\mu_x = e^{\frac{\sigma_y^2}{2}}$ (*Eqn. 3.7*)

The variance $\sigma_x^2 = e^{\sigma_y^2}(e^{\sigma_y^2} - 1)$ (*Eqn. 3.8*)

To transform the log-normally distributed variable into a standardized form represented by the standard log-normal distribution, one way is to find y' so that:

$$y' = y - u_y$$ (*Eqn. 3.9*)

with $\mu_y' = 0$ and $\sigma_y' = \sigma_y$.

Considering that travel times of particular percentile values, including the 50th and 95th percentiles, are important in calculating travel time reliability, a convenient way to express the percentiles is to use the percent point function. In this case, the "critical value" associated with α^{th} percentile point of the standard log-normal distribution is denoted at x_α and corresponds to the value of the log-normally distributed random variable x at which the cumulative distribution function $F(x)$ is equal to α, i.e.:

$$F(x_\alpha) = P(x \leq x_\alpha) = \alpha$$ (*Eqn. 3.10*)

If z_α denotes the value of the standardized normal variate associated with the αth percentile of that distribution, then x_α can be calculated as follows:

$$x_\alpha = e^{\mu_y + z_\alpha \sigma_y}$$ (*Eqn. 3.11*)

The standard normal distribution tables defined by Miller, Freund and Johnson (2000) offer assistance in determining z_α.

3.4 APPLICABLE TRAVEL TIME AND TRAVEL TIME RELIABILITY MEASURES

Having in the previous chapter established the most suitable measures from the accuracy point of view and for trip scheduling and performance evaluation applications, the measures of mean (average) travel time, planning time (*Eqn. 2.5*) and buffer time (*Eqn. 2.6*) were adopted for producing trip scheduling information while the mean travel rate (mean travel time per unit length) and the RI (*Eqn. 2.10*) were adopted for producing performance evaluation information apart from the contribution also made to this by the other three measures.

3.5 OTHER RELEVANT ANALYSIS

The other forms of analysis that were relevant on the HGVs' travel time data were as follows:

3.5.1 Travel time assignment

An algorithm was necessary to assign discrete times to HGVs' travel time data collected within an interval of time. The algorithm developed and used for this study was as described below:

If t_l (in minutes) denotes the length of the time interval of interest and n the total number of observations x within the time interval, then the time t (in minutes) between any two successive observations within the time interval can be estimated by:

$$t = \frac{t_l}{n+1} \qquad\qquad (Eqn.\ 3.12)$$

If t_o denotes the start time of the time interval, the individual observations are then assigned times as follows:

$$x_1, t_o + t;\ x_2, t_o + 2t;\ x_3, t_o + 3t \ldots\ldots\ldots\ldots\ldots\ldots x_n, t_o + nt \qquad (Eqn.\ 3.13)$$

with the assigned times rounded to the nearest whole minute.

The use of $n + 1$ instead of n in *Eqn. 3.12* above is so that the nth assigned time is not always equal to the end time of the time interval.

3.5.2 Sample size test of significance

As mentioned in the previous chapter, vehicle sample sizes are not a major concern when data is collected for measuring travel time reliability since a long period of data collection is involved. However, as an extra measure of accuracy, HGVs' travel time data obtained for this study was checked for significance.

The equations for computing minimum required vehicle sample sizes are as below:

$$Sample\ size, n = (\frac{t \times c.v}{e})^2 \qquad \text{for } n < 30 \qquad\qquad (Eqn.\ 3.14)$$

$$Sample\ size, n = (\frac{z \times c.v}{e})^2 \qquad \text{for } n \geq 30 \qquad\qquad (Eqn.\ 3.15)$$

where t is the t-statistic from the Student's t distribution for (n-1) degrees of freedom and a specified confidence level,

z is the z-statistic from the normal distribution that can substitute the t-statistic if sample sizes approach 30 or more,

$c.v.$ is the coefficient of variation, a measure of relative variability in travel times expressed as a percentage,

e is the relative allowable error in the travel time estimate expressed as a percentage.

From iterative calculations with different sample sizes and estimated coefficient of variation values from exploration of different studies, Turner et al. (1998) used the above *Eqn. 3.14* and *Eqn. 3.15* to develop tables of minimum sample sizes that can be used for checking data collected by different techniques. Borrowing from the authors, a checking table was adopted for this study (*Table 3.1*).

Table 3.1: Minimum vehicle sample sizes

Traffic Density	Average Coefficient of Variation (%)	Sample Sizes (from iterative calculations)		
		90% Confidence, ± 10% Error	95% Confidence, ± 10% Error	95% Confidence, ± 5% Error
Low to moderate traffic, 15- to 30-minute time period	10	4	5	18
Low to moderate traffic, 1- to 2-hour time period	20	12	18	62
Congested traffic, 15- to 30-minute time period	25	18	27	96
Congested traffic, 1- to 2-hour time period	35	34	48	189

Source: Adapted from Turner, Eisele, Benz and Holdener, 1998

4. DATA COLLECTION

4.1 OVERVIEW

A summary of the procedure followed in data collection is illustrated (*Figure 4.1*).

```
                          ┌─────────────────┐
                          │ Initial desk    │
                          │ study           │
                          └─────────────────┘
     ┌────────────────┐   ┌────────────────┐   ┌────────────────┐
     │ Definition of  │   │ Definition of  │   │ Definition of  │
     │ study sections │   │ sampling       │   │ data           │
     │ & data         │   │ periods        │   │ collection     │
     │ collection     │   │                │   │ techniques     │
     └────────────────┘   └────────────────┘   └────────────────┘
                          ┌────────────────┐
                          │ Preliminary    │
                          │ site visit     │
                          └────────────────┘
                          ┌────────────────┐
                          │ Mobilization of│
                          │ data collection│
                          │ resources      │
                          └────────────────┘
  ┌────────────────────┐          ┌────────────────────────┐
  │ Design & production│          │ Engagement & training  │
  │ of data recording  │          │ of personnel           │
  │ forms; sourcing of │          │                        │
  │ equipment          │          │                        │
  └────────────────────┘          └────────────────────────┘
                          ┌────────────────┐
                          │ Pilot study    │
                          └────────────────┘
                          ┌────────────────┐
                          │ Actual data    │
                          │ collection     │
                          └────────────────┘
                    ┌──────────────────────────┐
                    │ Data transcription,      │
                    │ matching of license      │
                    │ plates & reduction       │
                    └──────────────────────────┘
```

Figure 4.1: Illustration of data collection procedure

The individual data collection steps are discussed in detail in the following sections:

4.2 INITIAL DESK STUDY

4.2.1 Definition of study sections and data collection stations

In order to sample data accurately and achieve precise evaluation of freight travel time reliability, the Northern Corridor Road segment in Nairobi was divided into relatively homogenous sections in accordance with sectioning methodologies proposed by Figliozzi et al. (2011) and Turner et al. (1998).

Figliozi et al. (2011) suggested that the most important criterion of division of multi-segment corridors into homogenous sections for travel time studies is change in traffic volume, because the volume of traffic is the key factor associated with congestion (p. 5). They further argued that sectioning should also be considered in the context of land use and other factors such as posted speed limits and the locations of interchanges on freeway corridors. In their *Travel Time Data Collection Handbook*, Turner et al. (1998) added the locations of major junctions and jurisdictional boundaries to the list of factors to consider. The latter authors further advised use of skilled judgment and local knowledge of traffic conditions in defining the sections, also giving guideline of the desirable lengths of urban freeway/expressway study sections as 1.6 to 4.8 kilometres.

The traffic volumes established in 2012 for the portion of the Northern Corridor Road between Likoni Road and James Gichuru Road (COWI A/S, et al., 2012, May) informed sectioning of this portion. Having at the time of the desk study not obtained the latest traffic volume information for the rest of the study segment portions, the land use characteristics of the surrounding areas (as in *Maps 1.3 to 1.6*), judgment of most likely consequent traffic conditions, the locations of major junctions and interchanges and the length guideline already discussed jointly played the major role in sectioning of the portions[†].

[†] 2012 traffic volume information for the rest of the study segment portions was later obtained from GIBB Africa Ltd. & Associated Consultants of Ghana (2015, May) and ESER Project & Engineering Co. Inc. & Botek Bosphorus Technical Consulting Co. (2015, June) and indicated no major discrepancies with the chosen study sections.

The following is a detailed description of the steps followed in sectioning and the resulting study sections:

1. The seven road sub-sections defined by COWI A/S et al. (2012, May) in their road condition survey were consolidated into four sections depending on whether the average daily traffic (ADT) of consecutive sections differed by more than than 10,000 vehicles per day (*Table 4.1*). The ADT difference of 10,000 vehicles per day was assumed in this study to be the significant defining threshold of change in traffic volume, in which case two sections must be considered as being non-homogenous.

2. To achieve a more refined sectioning of the above four consolidated sections, major junctions/interchanges in the vicinity of the start and end kilometer points of each section were identified and designated as the start and end points of the sections, care being taken to ensure that no major transitions in land use occurred with the moving of the start and end points of sections and that the lengths of sections remained within the guideline for urban freeway/expressway study sections. The result was four homogenous sections between Likoni Road Junction and James Gichuru Road Junction (*Table 4.2*).

Table 4.1: Sub-sections of Northern Corridor Road between Likoni Road and James Gichuru Road under road condition survey

	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7
Start (km)	0.0	2.0	3.0	4.5	6.5	7.5	10.5
End (km)	2.0	3.0	4.5	6.5	7.5	10.5	12.0
ADT (including motorcycles)	78,571	39,710	41,382	74,620	69,027	46,639	45,301
Consolidated Sections	Section 1	Section 2		Section 3		Section 4	

Table 4.2: Homogenous sections of the Northern Corridor Road between Likoni Road Junction and James Gichuru Road Junction

Section	Start – End Point along Road Length	Major Land Uses of Surrounding Area	Section Length (km)
Section 1	Likoni Road Junction – Popo/Kapiti Roads Junction	Residential/Commercial with Industrial zone influences	1.17
Section 2	Popo/Kapiti Roads Junction – Haile Selassie Roundabout	Residential/Commercial/Administrative	3.66
Section 3	Haile Selassie Roundabout – Museum Hill Interchange	Commercial (CBD)	2.23
Section 4	Museum Hill Interchange – James Gichuru Road Junction	Residential/Commercial	4.70

3. Considering the remaining portions of the study segment, the land use characteristics of the surrounding areas were examined to identify points of major transition in land use, which would mark section boundaries, also taking into account the locations of major junctions/interchanges that could be associated with the boundaries. Where the initial land use examination could not give a clear distinction of sections or where the resulting sections were longer than the desirable study section lengths, the locations of major junctions/interchanges were used to further refine the sectioning process. Moreover, resulting sections with similar land use characteristics as the previously defined sections between Likoni Road Junction and James Gichuru Road Junction were considered for merging with the defined sections where applicable, depending on how this would affect the length of the final study section. The portions under consideration at this juncture were as follows:

- JKIA Turnoff – Likoni Road Junction
- James Gichuru Road Junction – Naivasha Road Junction

About the first 2.5 kilometres of the JKIA Turnoff – Likoni Road Junction portion traverse the JKIA zone, consisting majorly of open land with a few of the airport

storage facilities. Beyond this, the road portion traverses first a majorly residential/commercial zone up to Enterprise Road followed by a commercial activity area with influences of the industrial zone through the Enterprise and Likoni Roads (see *Map 1.3*). The stretch within airport zone could be considered as one homogenous section. The Airport North Road Junction in the vicinity of its end kilometer point marks an appropriate end point of the section, as it is located just at the transition from airport zone to the next zone of residential/commercial land use. The stretch through the residential/commercial zone could be considered as another homogenous section, with distinct traffic characteristics. The Enterprise Road Junction marks an appropriate end point of this section as it is located almost clearly at the transition from this zone to the next commercial activity area with industrial zone influences. The land use around the last stretch reflects more or less the land use surrounding the previously defined Section 1 in the above Step 2, which is adjacent to it, with both being characterized by commercial activity with influences of the industrial zone. In this sense this stretch could be considered to share similar traffic characteristics as Section 1 and could be merged with Section 1 to form one homogenous section. The lengths of these three sections fall within the desirable study section lengths.

The James Gichuru Road Junction – Naivasha Road Junction portion traverses a primarily residential zone concentrated with research centres and market places (see *Map 1.6*). Based on this, the whole portion could be considered as one homogenous section, except for the fact that its length is much longer than the desirable study section lengths and the presence of the Kaptagat Road Interchange located almost at its mid-point could signify a point of change in traffic characteristics. The Kaptagat Road Interchange could therefore be taken as marking the point of demarcation between two homogenous sections under this portion. The lengths of both these sections fall within the desirable study section lengths.

4. Based on the inferences made in Step 3 above, a total of eight final homogenous study sections were defined for the entire Northern Corridor Road segment in Nairobi (*Table 4.3 and Maps 4.1 to 4.5*).

Following definition of the study sections, data collection stations were located at the start and end points of the sections (*Maps 4.1 to 4.5*) and included one check-point location for each direction of travel at each of the start and end points. The check-points were located on far sides of intersections so that intersection influences could be captured on the travel times of sections following the intersections.

Table 4.3: Homogenous study sections of the Northern Corridor Road segment
in Nairobi

Section	Start – End Point along Road Length	Major Land Uses of Surrounding Area	Section Length (km)
Section 1	JKIA Turnoff – Airport North Road Junction	Airport zone	2.59
Section 2	Airport North Road Junction – Enterprise Road Junction	Residential	2.07
Section 3	Enterprise Road Junction – Popo/Kapiti Roads Junction	Residential/Commercial with Industrial zone influences	3.98
Section 4	Popo/Kapiti Roads Junction – Haile Selassie Roundabout	Residential/Commercial/ Administrative	3.66
Section 5	Haile Selassie Roundabout – Museum Hill Interchange	Commercial (CBD)	2.23
Section 6	Museum Hill Interchange – James Gichuru Road Junction	Residential/Commercial	4.70
Section 7	James Gichuru Road Junction – Kaptagat Road Interchange	Residential with research centres and market places	3.01
Section 8	Kaptagat Road Interchange – Naivasha Road Junction	Residential with research centres and market places	3.79

Map 4.1: Study sections 1, 2 & 3 and station locations 1, 2, 3 & 4
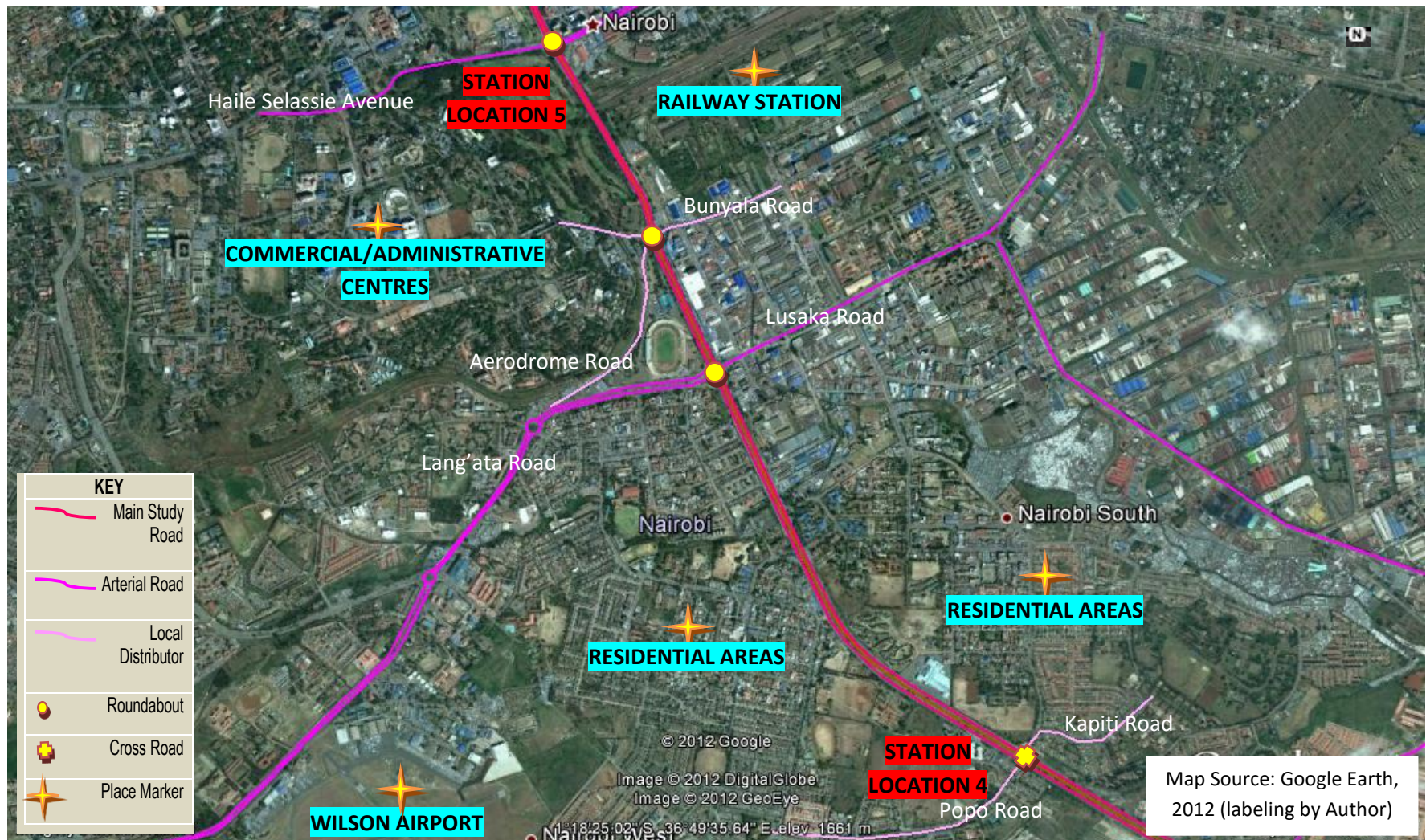
Map 4.2: Study section 4 and station locations 4 & 5
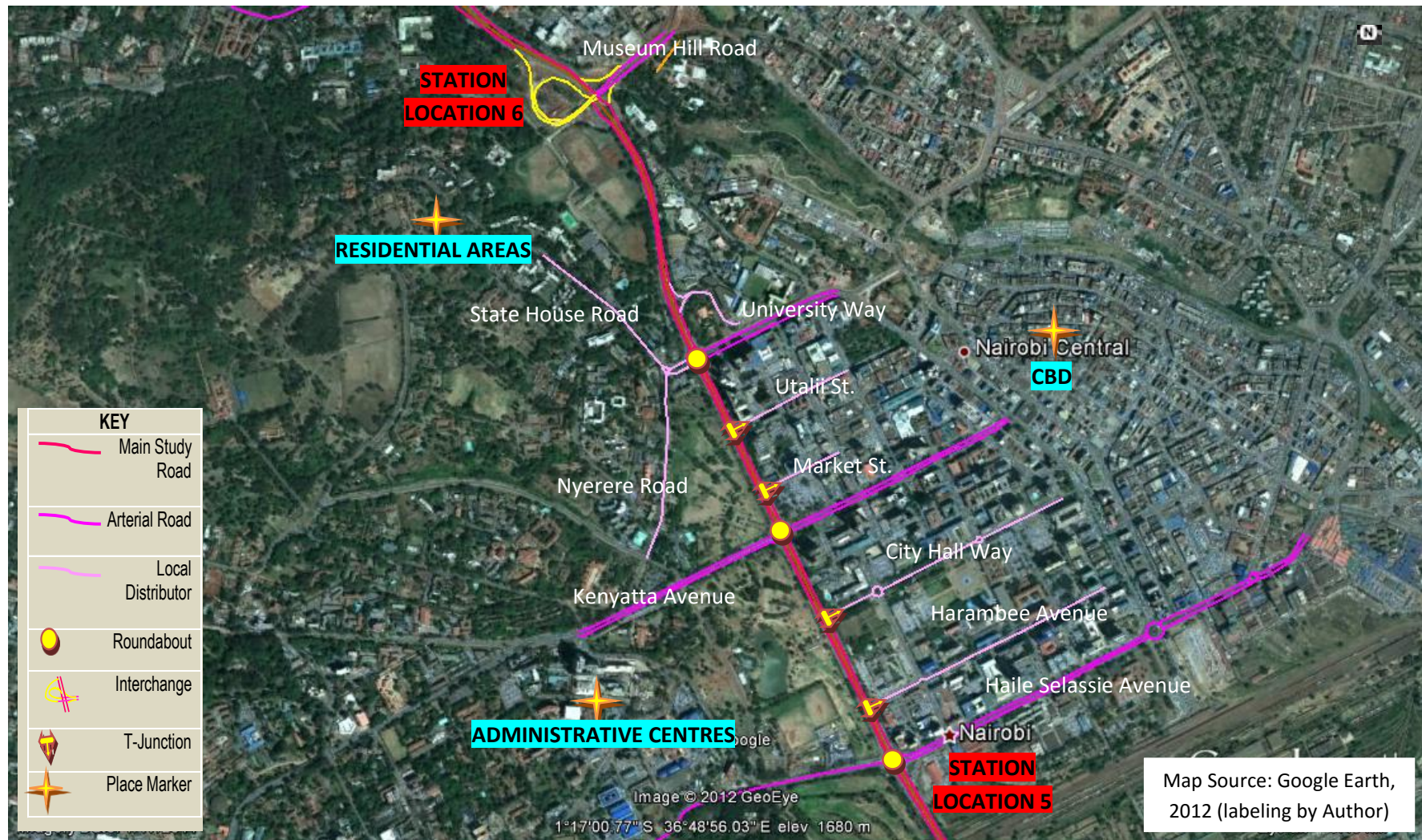
Map 4.3: Study section 5 and station locations 5 & 6

Map 4.4: Study section 6 and station locations 6 & 7

KEY

	Main Study Road
	Arterial Road
	Local Distributor
	Interchange
	T-Junction
	Y-Junction
	Place Marker
	City Boundary

STATION LOCATION 9

STATION LOCATION 8

STATION LOCATION 7

RESIDENTIAL AREAS/RESEARCH CENTRES

RESIDENTIAL AREAS/MARKET CENTRES

Kapenguria Road

Kaptagat Road

Naivasha Road

James Gichuru Road

Image © 2013 DigitalGlobe

Map Source: Google Earth, 2012 (labeling by Author)

Map 4.5: Study sections 7 & 8 and station locations 7, 8 & 9

4.2.2 Definition of sampling periods

Considering the principle that a representative sample of data for travel time reliability measurement involves collection over a considerable number of days, one month (four weeks) was allowed for data collection in keeping with the minimum recommended periods discussed in Chapter 2.

Further, to enable development of the trends of freight travel time and freight travel time reliability measures over time for the days of the week, fifteen-minute intervals throughout the day (7:00 a.m. to 7:00 p.m.) were adopted as sampling periods. This would also ensure capturing and representation of variability across small time intervals as is the recommended best practice.

In selecting the month for data collection, it was assumed that there are only minimal differences in travel conditions on the road segment across the months of year and any particular month would therefore suffice.

4.2.3 Definition of data collection techniques

License plate matching was adopted as the technique for collection of the HGVs' travel time data. As has previously been discussed, license plate matching is very appropriate for collection of travel time data over long segments/corridors/routes as well as sub-sections of the segment/corridor/route and is the best at capturing travel time variability across different days and/or times of day. In addition, since the technique allows capturing a high percentage of the traffic stream, the accuracy of the sample sizes would further be assured.

To minimize on the cost of the study, the manual means was adopted as the instrument for data collection. Site information on irregular congestion causing factors would also obtained manually.

4.3 PRELIMINARY SITE VISIT

A preliminary visit of the study site was conducted from 19th to 20th July, 2013. During the visit, the selected study section boundaries were affirmed to be adequate for the study purposes and the lengths of the study sections as measured during the desk study were confirmed. Actual check-point locations were also selected, for later refining during the pilot study.

4.4 MOBILIZATION OF DATA COLLECTION RESOURCES

4.4.1 Design and production of data recording forms; sourcing of equipment

Two types of data forms were designed and produced as follows:

- License plate recording field sheet; and
- Irregular congestion causing factors occurrence log.

The two form types are shown in *Appendix A* and *Appendix B* respectively.

Stop watches, recording kits, cameras and transportation vehicles were also sourced as equipment for data collection.

4.4.2 Engagement and training of personnel

Twenty seven manual observers were engaged, three for each station, together with two supervisors and two drivers. The data collection team was first sensitized on the study goals, the expected outputs and the potential uses of the information obtained from the study followed by a training on their roles, the field survey procedures and troubleshooting methods.

4.5 PILOT STUDY

A pilot survey was conducted from 30th to 31st July, 2013 with the following aims:

- Orient the data collection team with the study area and traffic conditions;
- Make final choice of vantage and comfortable check-point locations;
- Test the ease of reading and recording license plates within the required time intervals in actual traffic conditions;
- Practice noting irregular congestion causing factors and perceiving resumption of normal traffic conditions after clearance;
- Test troubleshooting methods
- Obtain data for checking license plate matches and the possibility of obtaining representative samples;
- Identify and address any residual data collection issues.

4.6 ACTUAL DATA COLLECTION

Actual data collection was carried out between 1st August, 2013 and 4th September, 2013, ensuring that there were a total of four full weeks with at least four days of data for each day of the week. Pictures of traffic conditions during the period were also taken to aid with later analysis of the data.

4.7 DATA TRANSCRIPTION, MATCHING OF LICENSE PLATES AND REDUCTION

Engaging and training five of the personnel from the data collection team for the exercises, the field data was transcribed into computers on Microsoft Excel workbooks while assigning discrete times to the observed license plates, calculated from *Eqn. 3.12* and *Eqn. 3.13*. License plate matches in each study section and time period were then extracted into separate workbooks, followed by a computation of the difference in arrival times of each license plate between the start and end point of section to determine vehicle travel times.

Data reduction was then performed. The first step involved screening the matched license plate data to remove outliers that could not be explained even by the irregular congestion causing factors observed. This was done by a visual inspection of possible correlation between conspicuously outlying travel times and irregular congestion causing factors observed in corresponding time intervals or adjacent time intervals. A further consideration of the outliers was carried out in the context of the general travel times of other observations in the same time interval and in adjacent time intervals to identify any similarities that could validate the data points. If from this process the outliers could not be accounted for, they were eliminated from the data as they could then be due to vehicles that stopped for rest or refueling or those that rerouted to make deliveries before continuing on the journey through the segment and would not therefore accurately represent travel times. After screening, the data was organized and grouped into samples of freight travel times for each fifteen-minute time interval between 7:00 a.m. and 7:00 p.m. for each day of the week, each study section and each direction of travel together with summaries of the irregular congestion causing factors observed on each day of week in each direction of travel within the fifteen-minute time intervals and study sections. The final task was to replace sample license plate entries with number codes as a measure of privacy protection.

5. RESULTS AND ANALYSIS

5.1 FREIGHT TRAVEL TIME SAMPLES AND IRREGULAR CONGESTION CAUSING FACTORS DATA

A total of 5,953 freight travel time samples were obtained from the data collection process. This data together with the irregular congestion causing factors data also obtained are available in a separate repository.

5.2 VALIDATION OF FREIGHT TRAVEL TIME SAMPLES

The sizes of the freight travel time samples were checked against the minimum sample sizes in *Table 3.1* for a 90% confidence and ±10% error level. This significance level was considered a reasonable compromise between ensuring that data used to provide the study's trip scheduling and performance evaluation information was accurate and recognizing the limitations of the manual means of license plate matching in obtaining the most accurate data.

Out of 5,953 samples, 205 failed the significance test but even so, marginally. This represents 3% of the total number of samples, meaning that 97% of the samples were significant at 90% confidence, ±10% error.

From the above analysis, the sampled data was found reasonably accurate and was therefore accepted for the study.

5.3 FITTING OF FREIGHT TRAVEL TIMES DISTRIBUTION AND CALCULATION OF FREIGHT MEAN TRAVEL TIMES, PLANNING TIMES, BUFFER TIMES, MEAN TRAVEL RATES AND RELIABILITY INDICES (RIs)

The log-normal distribution was fitted to the freight travel time data sets. For each sample, the natural logarithms of the freight travel time variables were calculated as in *Eqn. 3.1* and the sample mean μ_y and standard deviation σ_y determined. The standard

forms of the variables were also calculated as in *Eqn. 3.9* and the sample mean μ_y' and standard deviation σ_y' determined.

The means of the sample distributions were then calculated as in *Eqn. 3.3*, these constituting the sample freight mean travel times.

Determining also z_α for the 50th percentile and the 95th percentile from the standard normal distribution tables, these were incorporated into *Eqn. 3.11* to find the median times and the 95th percentile times respectively for each sample.

The 95th percentile times then constituted the sample freight planning times in accordance with *Eqn. 2.5*.

The sample 95th percentile and mean times were then incorporated into *Eqn. 2.6* to establish sample freight buffer times.

Sample freight mean travel rates were calculated as the sample mean times divided by the appropriate study section length.

Finally, incorporating the 95th percentile and the median times into *Eqn. 2.10* established sample freight RIs.

An illustration of the sample calculations is shown in *Appendix C*.

5.4 ANALYSIS OF TRENDS OF FREIGHT MEAN TRAVEL TIME, PLANNING TIME AND BUFFER TIME

Segment freight mean travel times, planning times and buffer times in each direction of travel were plotted against the time of day for each day of the week to obtain trends for comparison.

5.4.1 Freight mean travel times, planning times and buffer times in North Western (JKIA Turnoff to Naivasha Road Junction) direction

The plots of freight mean travel times, planning times and buffer times are shown for each day of the week (*Figures 5.1 to 5.7*).

Figure 5.1: Freight mean travel times, planning times and buffer times against time of day on Monday (North Western direction)

Figure 5.2: Freight mean travel times, planning times and buffer times against time of day on Tuesday (North Western direction)
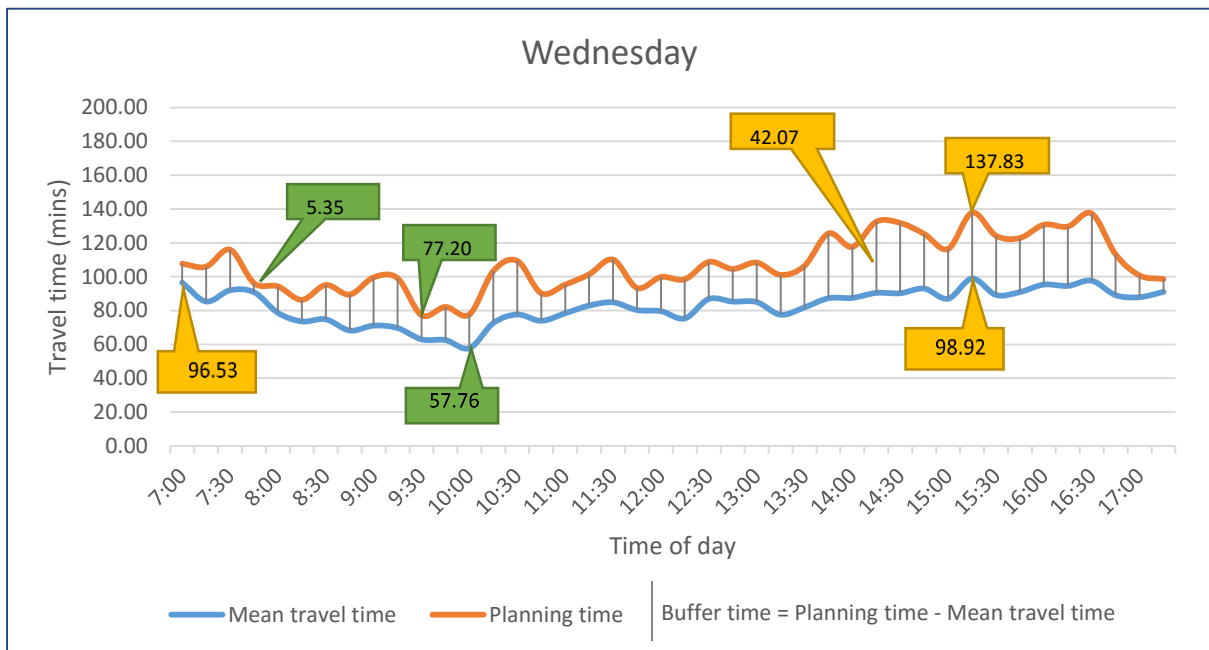
Figure 5.3: Freight mean travel times, planning times and buffer times against time of day on Wednesday (North Western direction)
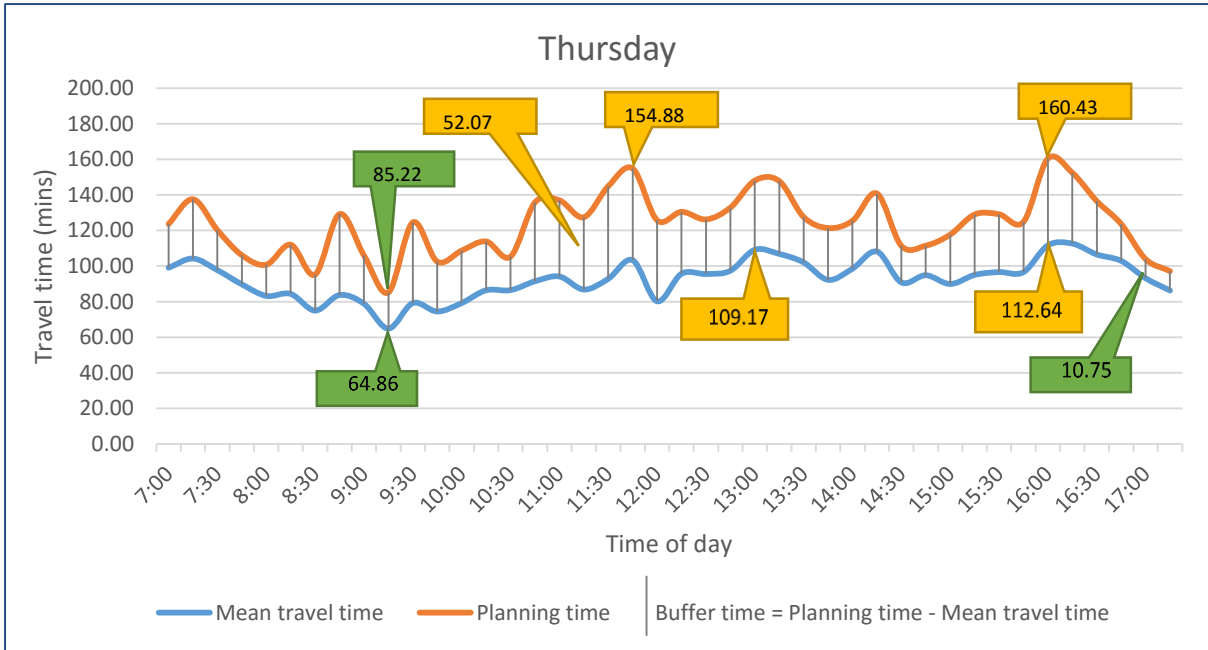
Figure 5.4: Freight mean travel times, planning times and buffer times against time of day on Thursday (North Western direction)
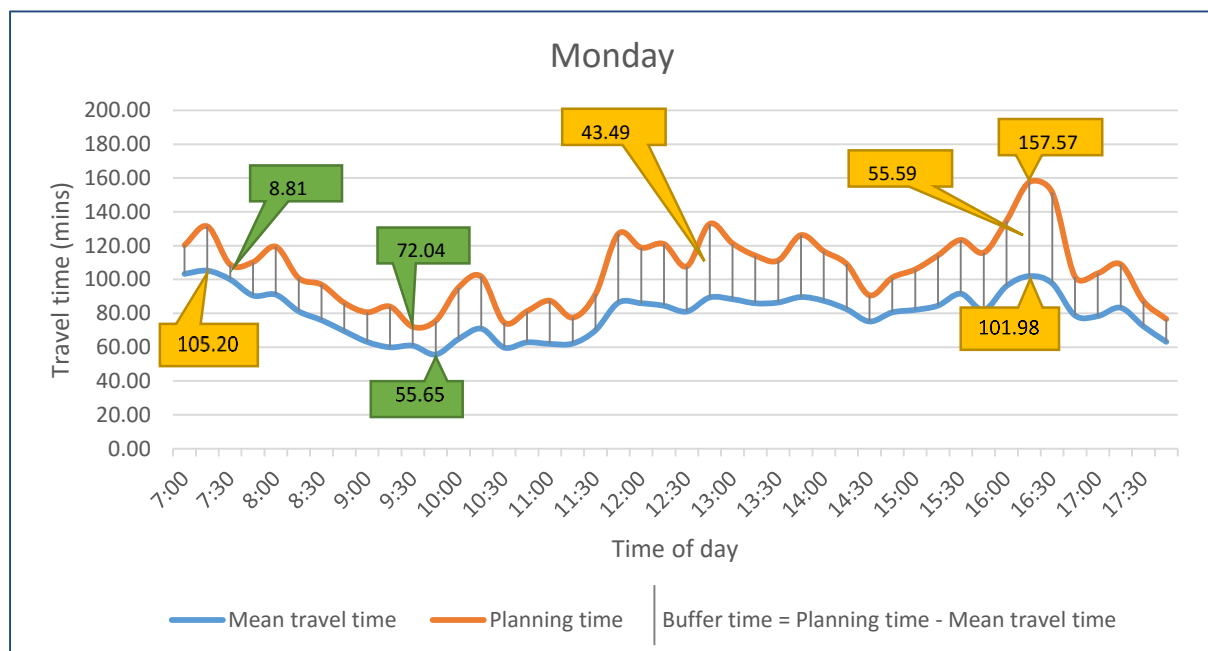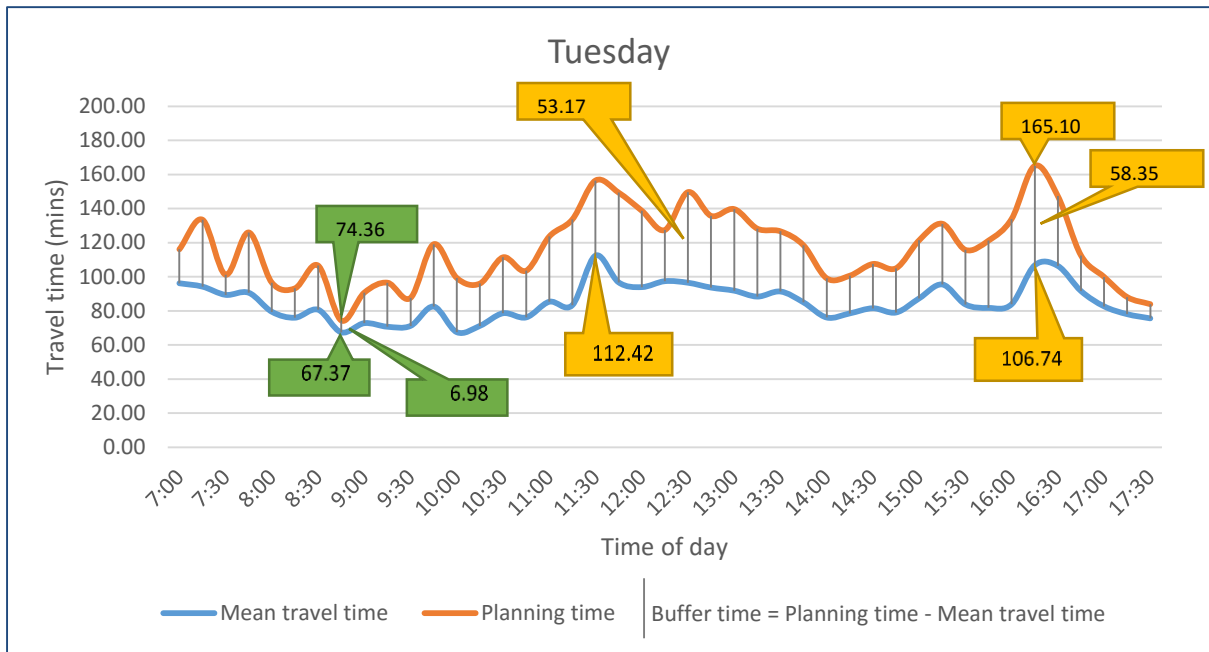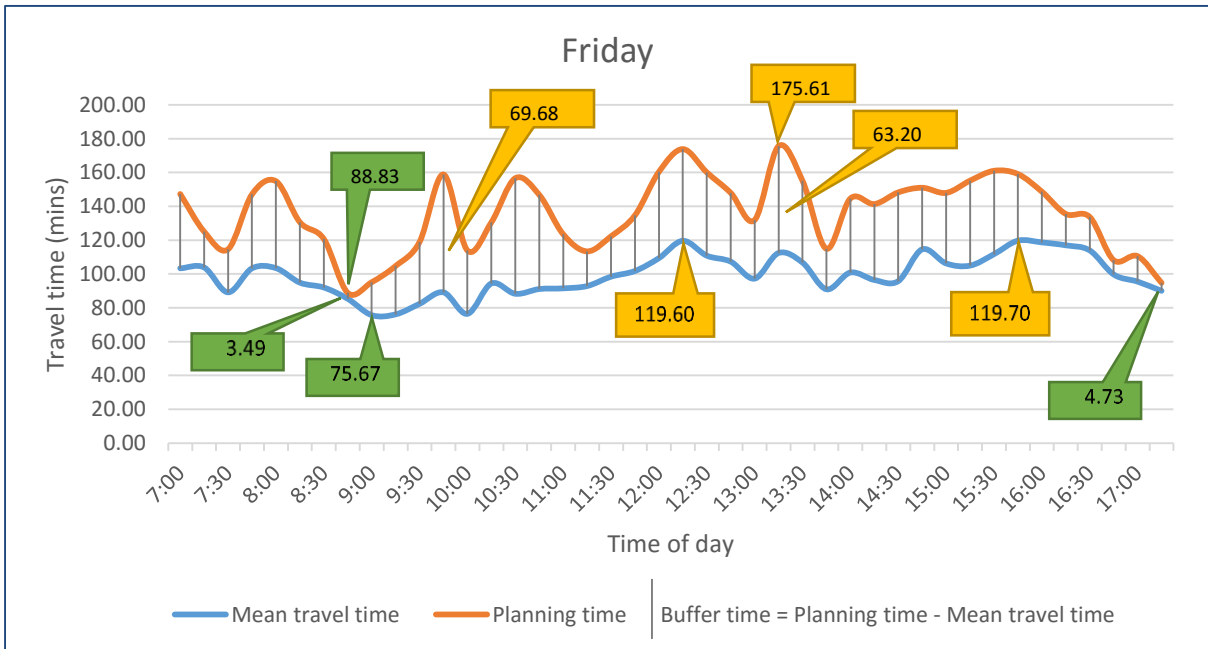

Figure 5.5: Freight mean travel times, planning times and buffer times against time of day on Friday (North Western direction)
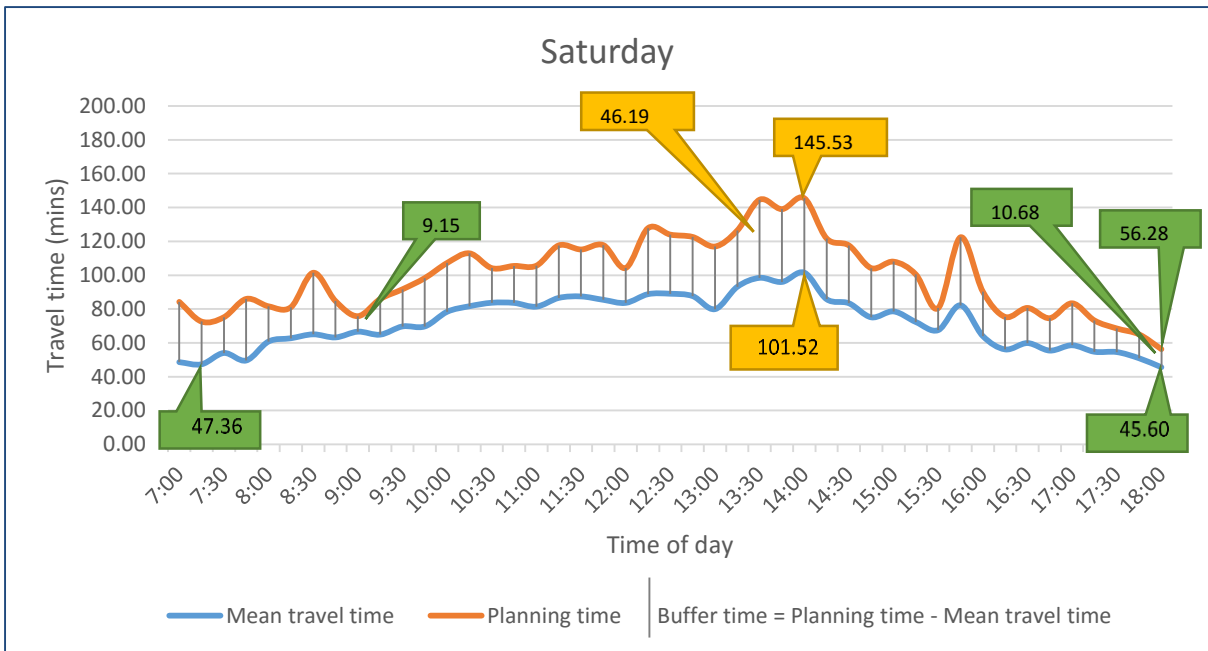
Figure 5.6: Freight mean travel times, planning times and buffer times against time of day on Saturday (North Western direction)
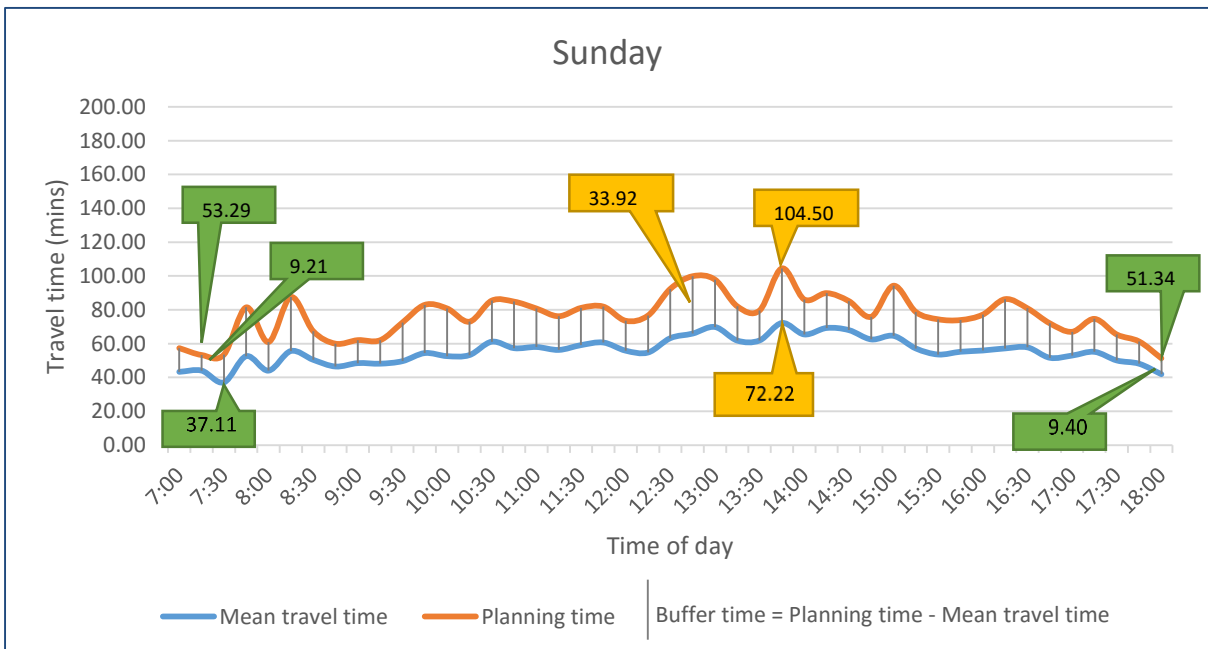
Figure 5.7: Freight mean travel times, planning times and buffer times against time of day on Sunday (North Western direction)

A summary of the trends in the North Western direction is as follows:

1. The day of week across the day patterns of freight mean travel time, freight planning time and freight buffer time tend to differ. In the case of freight mean travel time, Monday exhibits two clear peak periods of the measure in the morning and midday to evening; Tuesday exhibits three clear peak periods of the measure in the morning, midday and evening; Wednesday shows more consistency across the day; and Thursday and Friday show significant variations across the day before a midday peak period is again seen on Saturday followed by more consistency across the day on Sunday. In the case of freight planning time, Monday exhibits three clear peak periods of the measure in the morning, midday and evening; Tuesday exhibits two clear peak periods of the measure in the midday and evening; and increasing variations of the measure across the day are seen from Wednesday to Friday before a midday peak period is again seen on Saturday followed by some noticeable variations across the day on Sunday. In the case of freight buffer time, Monday and Tuesday exhibit two clear peak periods of the measure in the midday and evening; and increasing variations of the measure across the day are seen from Wednesday to Friday before more consistency is seen across the day on Saturday followed by some noticeable variations across the day on Sunday;

2. While there is general similarity in the trends across the day of freight planning time and freight buffer time over the week, the trends of freight mean travel time tend to be rather different;

3. The three measures in the weekdays tend to exhibit the highest values around midday (about 11:30 p.m. – 1:30 p.m.) and early evening (about 4:00 p.m. – 4:30 p.m.), with the lowest values exhibited generally in the mid-morning hours (about 8:00 a.m. – 10:00 a.m.) and the late evening hours (about 4:45 p.m. – end of day). In the weekends, the highest values of the three measures tend to occur around the afternoon hours of about 1:00 p.m. – 2:00 p.m. while the lowest values tend to occur in early morning (about 7:00 a.m. – 7:45 a.m.) and late evening (about 5:30 p.m. – end of day);

4. Friday tends to exhibit significantly higher measure values compared to the rest of the days of the week while Sunday tends to exhibit significantly lower values particularly of freight mean travel time and freight planning time but not

necessarily of freight buffer time. The measure values on Saturday during the midday peak tend to mirror those of Monday, Tuesday, Wednesday and Thursday with the values during the off-peak hours mirroring those of Sunday;

5. When high, freight mean travel time values generally rise above 100 minutes and when low, they rarely fall below 50 minutes. On the other hand, freight planning time values when high generally rise above 140 minutes and rarely fall below 60 minutes when low. The highest buffer time values are generally above 40 minutes with the lowest being generally below 10 minutes.

The above findings indicate the following:

1. Freight travel time reliability trends do not necessarily follow the trends of freight travel time across time and while a certain time may be characterized by a short travel time, it may on the other hand have low reliability with potentially higher costs of the trip than a time of long travel time but with high reliability. This also suggests that careful consideration of both the freight travel time and the freight travel time reliability is a more useful basis of choice of time of travel;

2. The most ideal hours then for undertaking freight travel in the North Western direction in the weekdays are 8:00 a.m. – 10:00 a.m. and 4:45 p.m. – end of day as they are not only short travel time periods but are also well reliable, while the hours that should be avoided are 11:30 p.m. – 1:30 p.m. and 4:00 p.m. – 4:30 p.m. for being long travel time periods and with low reliability. In the weekends, the ideal hours for freight travel are 7:00 a.m. – 7:45 a.m. and 5:30 p.m. – end of day, while the hours that should be avoided are 1:00 p.m. – 2:00 p.m. for the same reasoning as that given for the weekdays;

3. Of the days of the week, Friday is least ideal for freight travel not only because of significantly longer travel times and lower travel time reliability but also because of much less predictability of travel time and travel time reliability across the day. On the other hand, Sunday offers the greatest advantage, having much shorter travel times and higher travel time reliability as well as more consistency of travel across the day;

4. With as much as over 40 minutes or as little as under 10 minutes required as extra time over the freight mean travel time to ensure on time traversal of the road segment 95% of the time, it is over four times more beneficial to undertake

transportation of freight on the road segment during periods of high reliability than during periods of low reliability.

5.4.2 Freight mean travel times, planning times and buffer times in South Eastern (Naivasha Road Junction to JKIA Turnoff) direction

The plots of freight mean travel times, planning times and buffer times are shown for each day of the week (*Figures 5.8 to 5.14*).
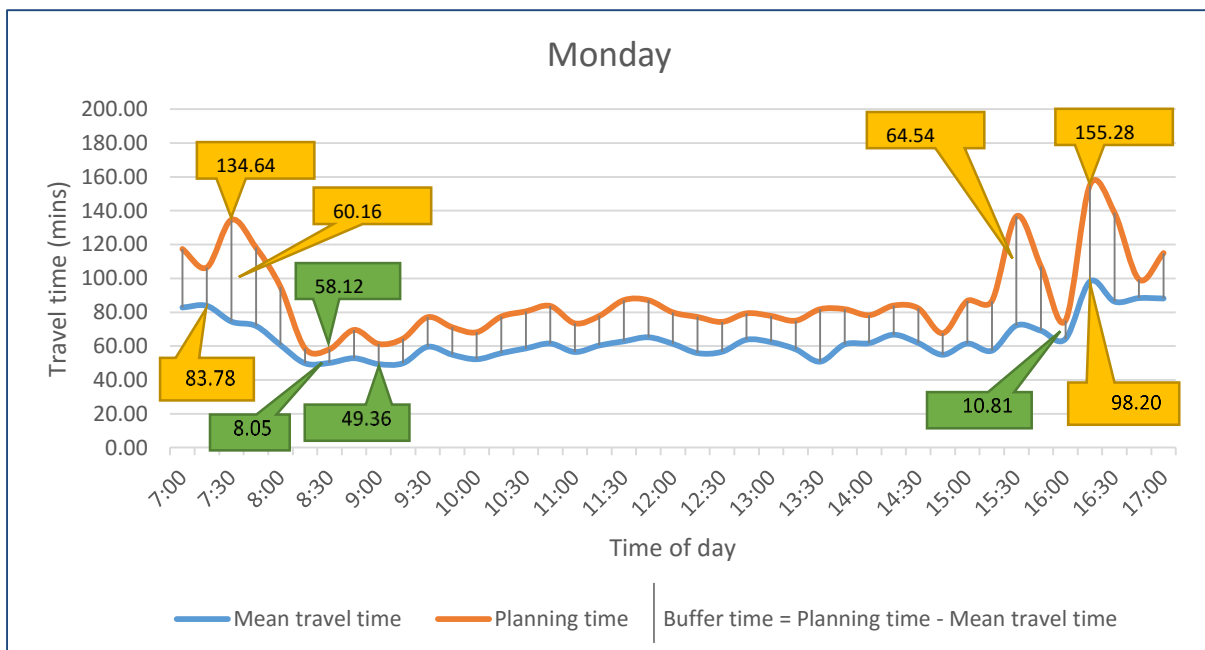
Figure 5.8: Freight mean travel times, planning times and buffer times against time of day on Monday (South Eastern direction)
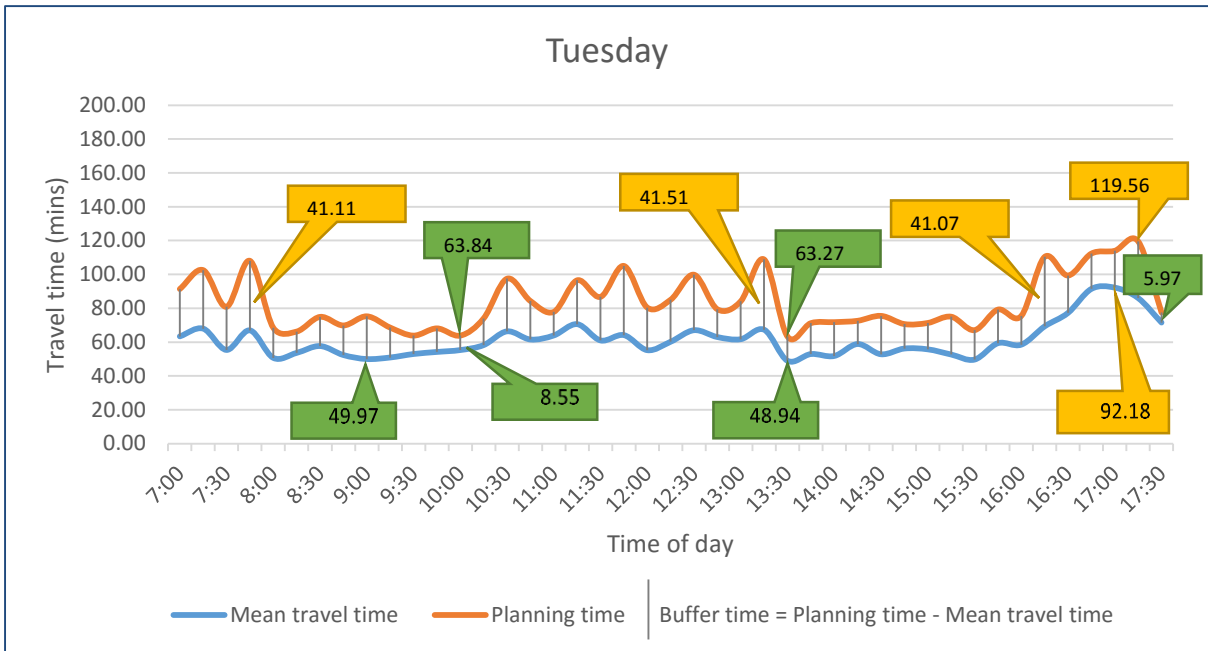
Figure 5.9: Freight mean travel times, planning times and buffer times against time of day on Tuesday (South Eastern direction)
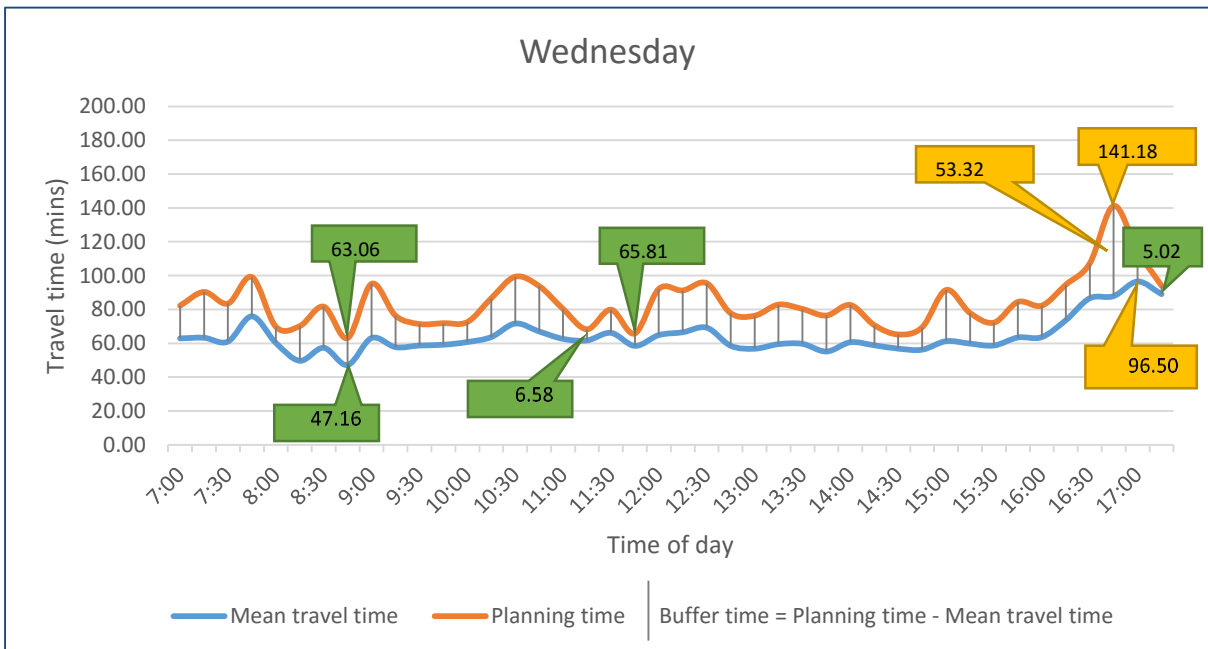
Figure 5.10: Freight mean travel times, planning times and buffer times against time of day on Wednesday (South Eastern direction)
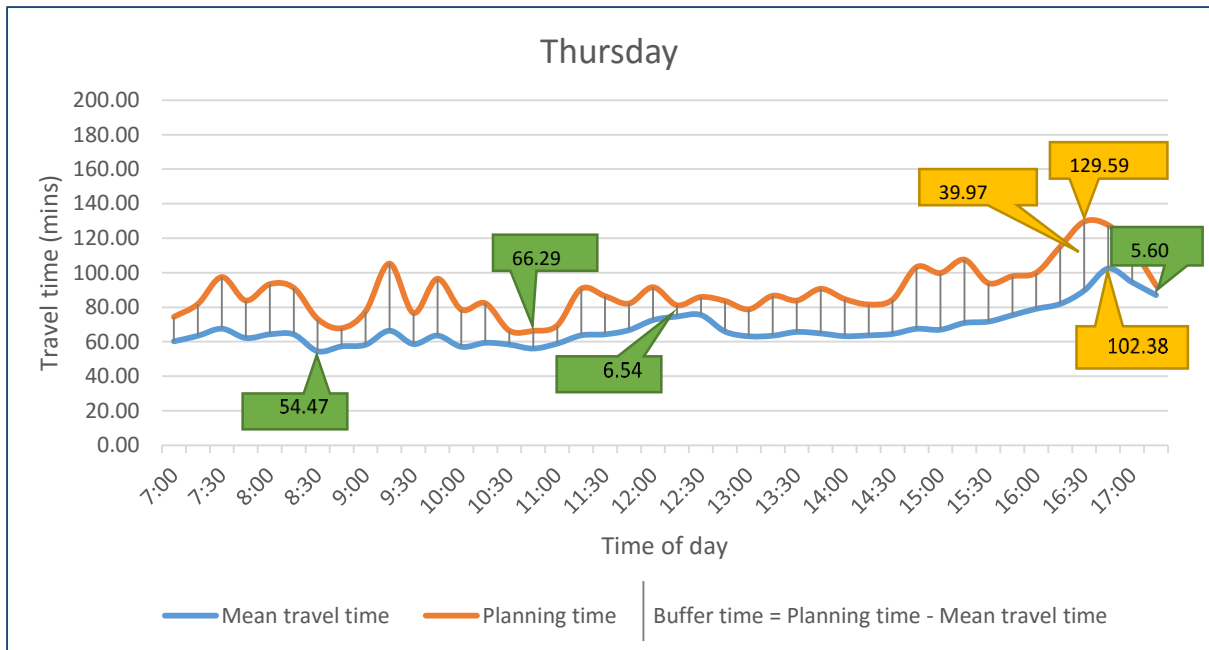
Figure 5.11: Freight mean travel times, planning times and buffer times against time of day on Thursday (South Eastern direction)
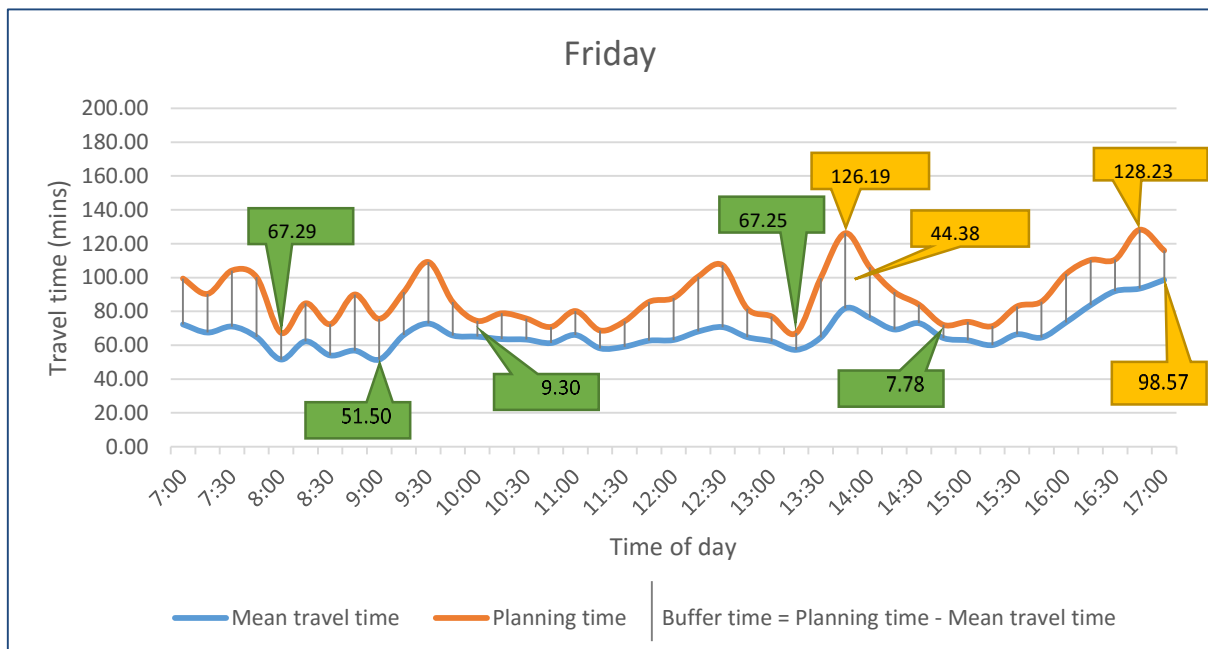
Figure 5.12: Freight mean travel times, planning times and buffer times against time of day on Friday (South Eastern direction)
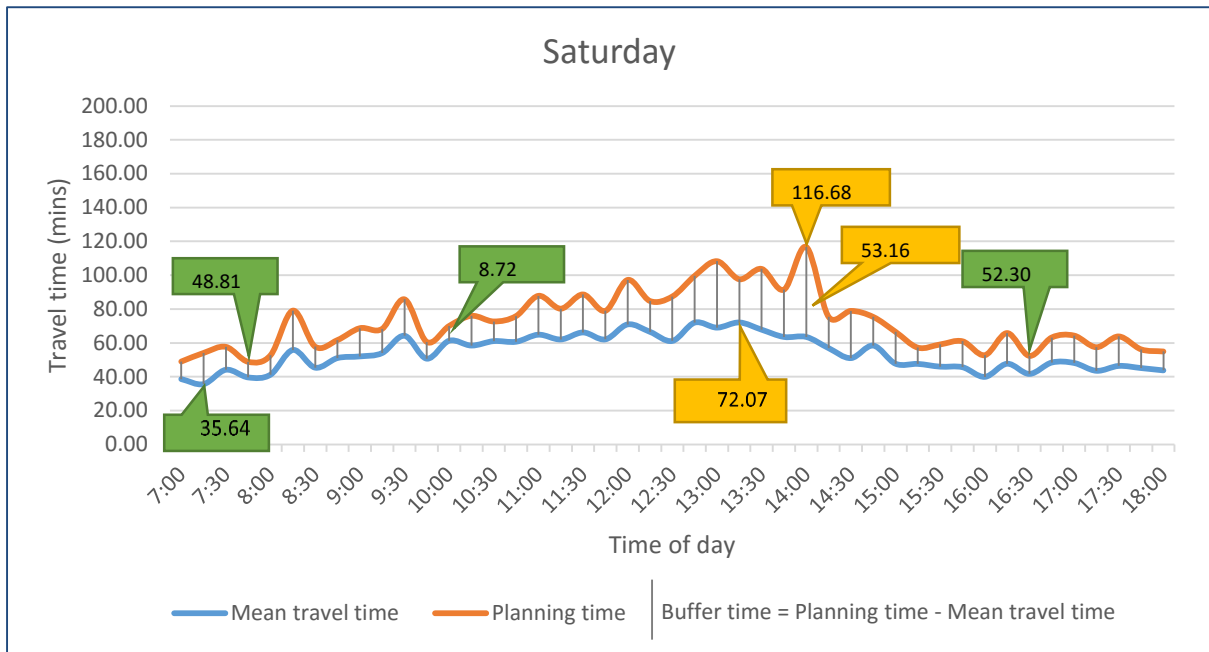
Figure 5.13: Freight mean travel times, planning times and buffer times against time of day on Saturday (South Eastern direction)
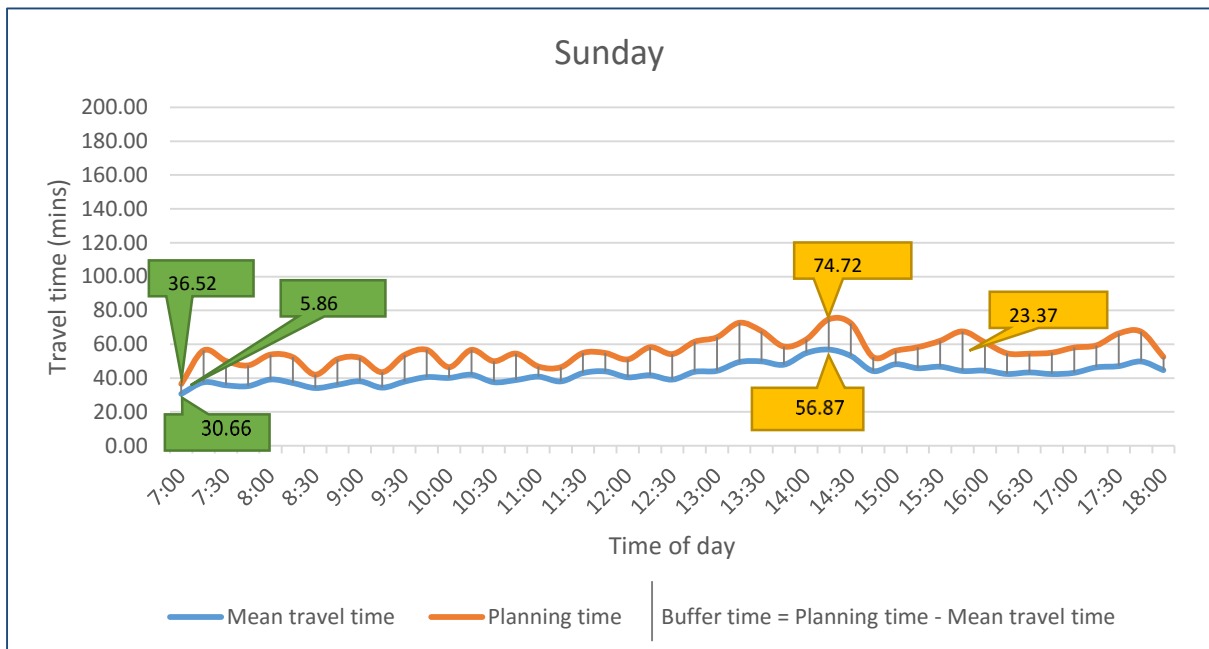
Figure 5.14: Freight mean travel times, planning times and buffer times against time of day on Sunday (South Eastern direction)

A summary of the trends in the South Eastern direction is as follows:

1. The day of week across the day patterns of freight mean travel time, freight planning time and freight buffer time tend to differ. In the case of freight mean travel time, Monday exhibits two clear peak periods of the measure in the morning and in the evening; Tuesday exhibits three clear peak periods of the measure in the morning, midday and evening; and Wednesday, Thursday and Friday exhibit one clear peak period of the measure in the evening before a somewhat midday peak period is seen on Saturday followed by consistency through the day on Sunday. In the case of freight planning time, Monday exhibits two clear peak periods of the measure in the morning and in the evening; Tuesday exhibits three clear peak periods of the measure in the morning, midday and evening; Wednesday and Thursday exhibit one clear peak period of the measure in the evening; and Friday exhibits high variations through the day while Saturday shows some noticeable variations in the first half of the day followed by more consistency through the rest of the day and Sunday shows consistency in the first half of the day followed by some noticeable variations through the rest of the day. In the case of freight buffer time, Monday exhibits two clear peak periods of the measure in the morning and in the evening; Tuesday, Wednesday and Thursday exhibit some noticeable variations through the day; and Friday exhibits high variations through the day before Saturday and Sunday show more consistency through the day;

2. While there is general similarity in the trends of freight planning time and freight buffer time over the week, the trends of freight mean travel time tend to be rather different;

3. The three measures in the weekdays tend to exhibit the highest values in the evening (about 4:00 p.m. – 5:00 p.m.). The lowest values are exhibited generally in the morning hours of about 8:00 a.m. – 9:00 a.m. and about 10:30 a.m. – 12:00 noon, and in the late evening hours after 5:00 p.m. In the weekends, the highest values of the three measures tend to occur around the afternoon hours of about 1:00 p.m. – 2:30 p.m. while the lowest values tend to occur in early morning (about 7:00 a.m. – 8:00 a.m.) and late evening (about 5:30 p.m. – end of day);

4. Sunday tends to exhibit significantly lower values of freight mean travel time and freight planning time compared to the rest of the days of the week but not necessarily of freight buffer time. The measure values on Saturday during the midday peak tend to mirror those of the weekdays with the values during the off-peak hours mirroring those of Sunday;

5. When high, freight mean travel time values generally rise above 90 minutes and when low, they rarely fall below 40 minutes. On the other hand, freight planning time values when high generally rise above 120 minutes and rarely fall below 50 minutes when low. The highest buffer time values are generally above 40 minutes with the lowest being generally below 10 minutes.

The above findings indicate the following:

1. Freight travel time reliability trends do not necessarily follow the trends of freight travel time across time and while a certain time may be characterized by a short travel time, it may on the other hand have low reliability with potentially higher costs of the trip than a time of long travel time but with high reliability. This also suggests that careful consideration of both the freight travel time and the freight travel time reliability is a more useful basis of choice of time of travel;

2. The most ideal hours then for undertaking freight travel in the South Eastern direction in the weekdays are 8:00 a.m. − 9:00 a.m., 10:30 a.m. − 12:00 noon and after 5:00 p.m. as these are not only short travel time periods but are also well reliable, while the hours that should be avoided are 4:00 p.m. − 4:30 p.m. for being long travel time periods and with low reliability. In the weekends, the ideal hours for freight travel are 7:00 a.m. − 8:00 a.m. and 5:30 p.m. − end of day, while the hours that should be avoided are 1:00 p.m. − 2:30 p.m. for the same reasoning as that given for the weekdays;

3. Of the days of the week, freight travel is most ideal on Sunday, having much shorter travel times and higher reliability as well as more consistency of travel across the day;

4. With as much as over 40 minutes or as little as under 10 minutes required as extra time over the freight mean travel time to ensure on time traversal of the road segment 95% of the time, it is over four times more beneficial to undertake

transportation of freight on the road segment during periods of high reliability than during periods of low reliability.

Overall, the two directions of travel show similarity in that:

1. Freight travel time reliability trends do not necessarily follow the trends of freight travel time and careful consideration of both the freight travel time and the freight travel time reliability is a more useful basis of choice of time of travel in either direction;
2. In the weekdays, the hours 8:00 a.m. – 9:00 a.m. and 5:00 p.m. – end of day are most ideal for undertaking freight travel in both directions as they are short travel time periods and well reliable while the hours 4:00 p.m. – 4:30 p.m. should be avoided in both directions for being long travel time periods and with low reliability. In the weekends, the most ideal hours then in both directions are 7:00 a.m. – 7:45 a.m. and 5:30 p.m. – end of day while the hours that should be avoided are 1:00 p.m. – 2:00 p.m.;
3. Sunday is the most ideal day of the week for travel in both directions in terms of freight travel time and freight travel time reliability;
4. It is over four times more beneficial to undertake transportation of freight on the road segment during periods of high reliability than during periods of low reliability in both directions, with as much as over 40 minutes or as little as under 10 minutes required as extra time over the freight mean travel time to ensure on time traversal of the road segment 95% of the time in either case.

On the other hand, the main directional differences are as follows:

1. The time of day and day of week patterns of freight travel time and freight travel time reliability show differences in the directions and the choice of time of travel should therefore take into account directional differences;
2. In the North Western direction, the midday period 11:30 a.m. – 1:30 p.m. also stands out as a period that should be avoided in the weekdays for undertaking freight travel while in the South Eastern direction, the midday period 10:30 a.m. – 12:00 noon also stands out as a suitable period in the weekdays for undertaking freight travel;

3. While Friday stands out in the North Western direction as being least ideal of the days of the week for freight travel due to significantly longer freight travel times and lower freight travel time reliabilities, this is not the case in the South Eastern direction where freight travel time and freight travel time reliability values on Friday compare with those of the rest of the weekdays.

5.5 ANALYSIS OF TRENDS OF FREIGHT MEAN TRAVEL RATE AND RELIABILITY INDEX (RI)

Section freight mean travel rates and RIs in each direction of travel were plotted against the time of day for each day of the week to obtain trends for comparison.

5.5.1 Freight mean travel rates and RIs in North Western (JKIA Turnoff to Naivasha Road Junction) direction

The plots of freight mean travel rates are shown alongside the plots of freight RIs for each day of the week (*Figures 5.15 to 5.21*).
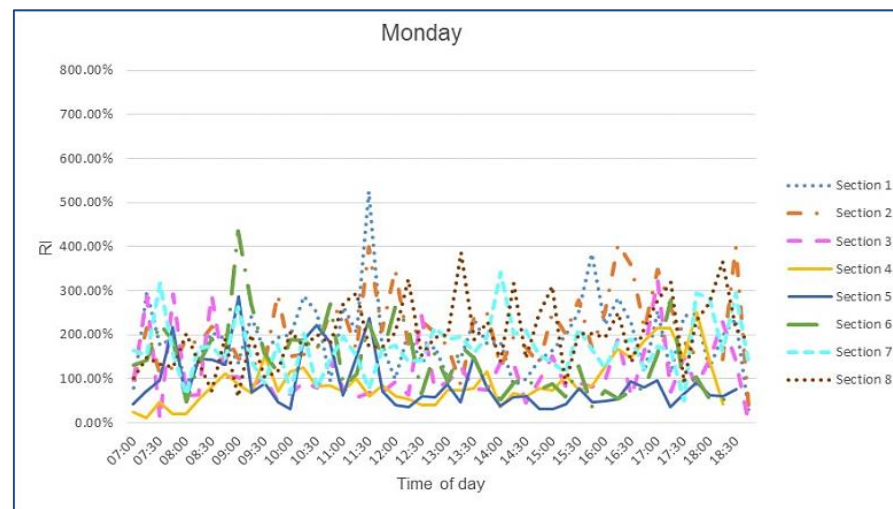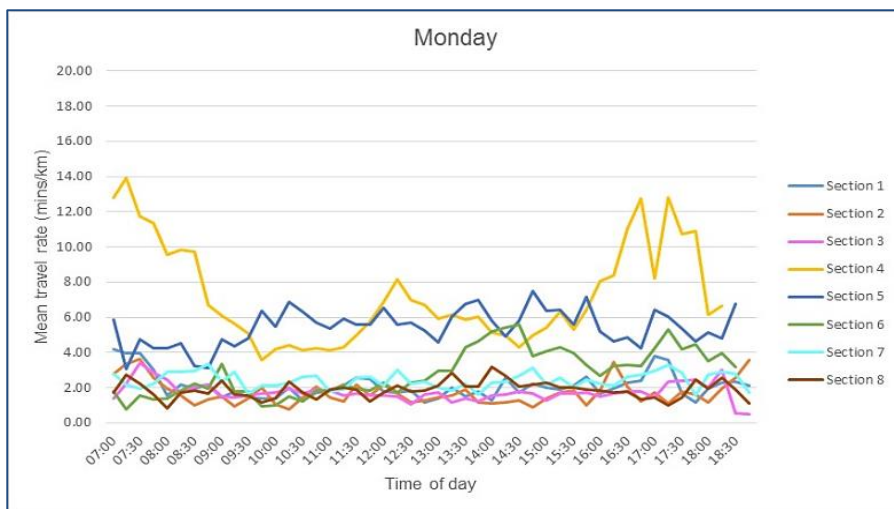
Figure 5.15: Freight mean travel rates and RIs against time of day on Monday (North Western direction)
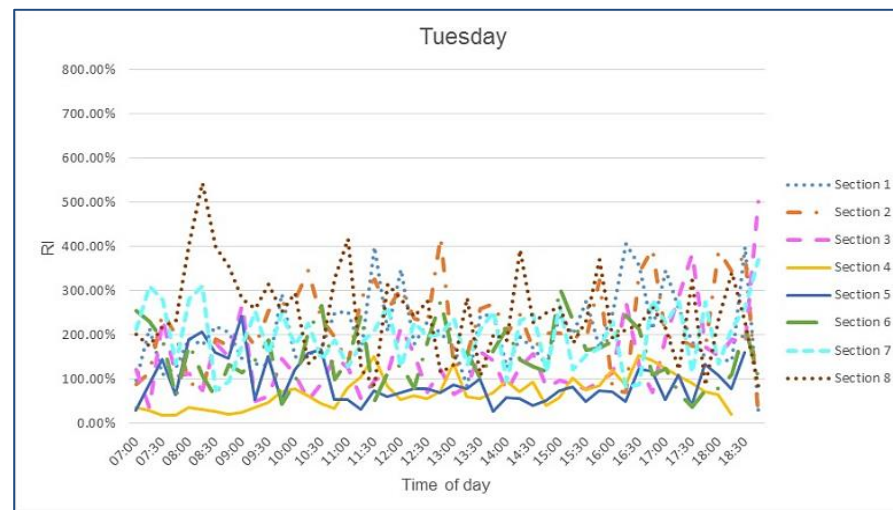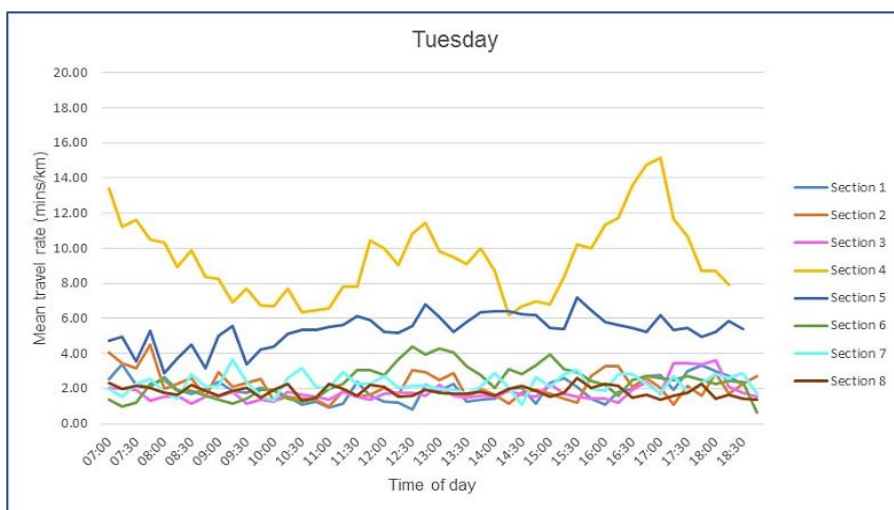
Figure 5.16: Freight mean travel rates and RIs against time of day on Tuesday (North Western direction)

Figure 5.17: Freight mean travel rates and RIs against time of day on Wednesday (North Western direction)

Figure 5.18: Freight mean travel rates and RIs against time of day on Thursday (North Western direction)

Figure 5.19: Freight mean travel rates and RIs against time of day on Friday (North Western direction)

Figure 5.20: Freight mean travel rates and RIs against time of day on Saturday (North Western direction)

Figure 5.21: Freight mean travel rates and RIs against time of day on Sunday (North Western direction)

A summary of the trends in the North Western direction is as follows:

1. The slowest freight mean travel rates occur on Section 4 (Popo/Kapiti Roads Junction to Haile Selassie Roundabout) and on Section 5 (Haile Selassie Roundabout to Museum Hill Interchange) throughout the day, being mainly slower on Section 4 in the weekdays and Saturdays and slower on Section 5 on Sundays. Freight mean travel rates are also relatively slow through most of the weekday afternoons and evenings on Section 6 (Museum Hill Interchange to James Gichuru Road Junction);

2. Clear freight mean travel rate peaks are seen mainly on Section 4 and on Section 6. The peaks in the weekdays on Section 4 generally occur between 7:00 a.m. and 8:00 a.m. in the morning and 4:00 p.m. and 6:00 p.m. in the evening, with freight mean travel rates being slower in the evening peak than in the morning peak. Midday weekday peaks can also be seen on this section on Monday and on Tuesday, generally between 12:00 noon and 2:00 p.m. On Saturday, a midday peak period occurs on the section approximately between 10:30 a.m. and 2:45 p.m. On Sunday however, some general variation is evident in the freight mean travel rates through the day on the section. Section 6 exhibits a more or less consistent travel peak in the weekdays, lasting mostly from 1:00 p.m. through to the evening. In the weekends however, little variation is evident in the freight mean travel rates through the day on the section. The rest of the sections generally exhibit little variation in the freight mean travel rates through the day throughout the week;

3. The freight mean travel rates on Section 4 generally extend to more than 14mins/km at their weekdays and Saturday peaks while extending to more than 6mins/km at the slowest on Sunday. On Section 5, freight mean travel rates generally extend to more than 6mins/km at their slowest while on Section 6, they reach almost 6mins/km at their peaks. Freight mean travel rates on the rest of the sections generally fall between 1min/km and 5mins/km. No significant weekday and weekend distinctions are evident in the values of freight mean travel rates on the sections, except lower values on Sunday on Section 4 compared to the rest of the days;

4. The RIs on Section 4 tend to be the smallest and most stable through the day throughout the week, falling below 100% on most occasions. Except for some

stable periods with RIs less than 100% on Monday, Tuesday and Wednesday, the RIs on Section 5 tend to vary highly and be generally in the range of 100% – 400%. Some of the largest RIs however occur on this section. The very large RIs on the section, mostly above 500%, tend to occur in the morning and in the midday. The RIs on the rest of the sections vary highly through the day on all days of the week and tend to be in the range of 100% – 400%, with some very large RIs also frequently seen on Section 1 (JKIA Turnoff to Airport North Road Junction) mainly in the morning and being mostly above 500% and on Section 2 (Airport North Road Junction to Enterprise Road Junction) mainly in the midday and in the evening and being mostly above 400%. The other sections, save for Section 7 (James Gichuru Road Junction to Kaptagat Road Interchange), also record very large RI values on some days of the week mostly in the mornings and in the evenings. The most extreme RI values occur on Thursday and on Friday.

The above findings indicate the following:

1. Travel time reliability measurement is very useful to holistic understanding of congestion seeing as freight RI trends depict very different patterns and levels of congestion from freight mean travel rate trends along the segment;

2. With freight mean travel rates ranging generally between 1min/km and 5mins/km on most sections of the segment, this translates to general freight average speeds in the region of 20km/hr, suggesting excessive average delays on the segment and reinforcing the need for regular congestion improvements;

3. With freight RI values ranging generally between 100% and 400% and sometimes much larger, the sizes of freight buffers on the road segment are generally double to four times the sizes of freight expected travel times and are sometimes much bigger, suggesting excessive unexpected delays over and above expected delays. This then also suggests that as much, if not more, attention needs to be given to travel time reliability improvements as to improvements of other congestion parameters including V/C ratio, average travel time and average delay on the segment. There is also indication that travel time reliability tends to be lower where travel times are shorter and improvements that result in shorter average travel times without addressing

travel time reliability could lead to more critical congestion in the form of lower travel time reliability;

4. Section 5 (Haile Selassie Roundabout to Museum Hill Interchange) stands out as suffering the greatest effects of congestion, being characterized by slower freight mean travel rates than six other sections and some of the largest and rather varying freight RIs throughout the week. This then suggests that Section 5 should be prioritized for congestion alleviation efforts compared to the other sections. This is more so because it is among the most travelled sections of the segment in terms of traffic volumes, rivalled only by Section 1 (JKIA Turnoff to Airport North Road Junction), Section 2 (Airport North Road Junction to Enterprise Road Junction) and Section 3 (Enterprise Road Junction to Popo/Kapiti Roads Junction) (GIBB Africa Ltd. & Associated Consultants of Ghana, 2015, May; COWI A/S, et al., 2012, October; ESER Project & Engineering Co. Inc. & Botek Bosphorus Technical Consulting Co., 2015, June) and can be expected to continue being highly travelled falling within the CBD;

5. Although Section 4 (Popo/Kapiti Roads Junction to Haile Selassie Roundabout) is the most reliable of all the sections, it suffers much greater effects of regular congestion than the other sections and should also be prioritized for alleviating these effects.

5.5.2 Freight mean travel rates and RIs in South Eastern (Naivasha Road Junction to JKIA Turnoff) direction

The plots of freight mean travel rates are shown against the plots of freight RIs for each day of the week (*Figures 5.22 to 5.28*).
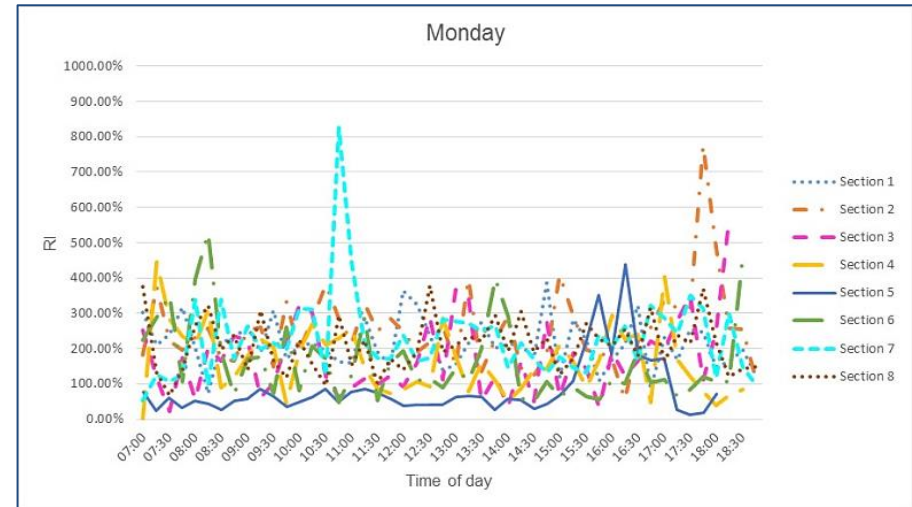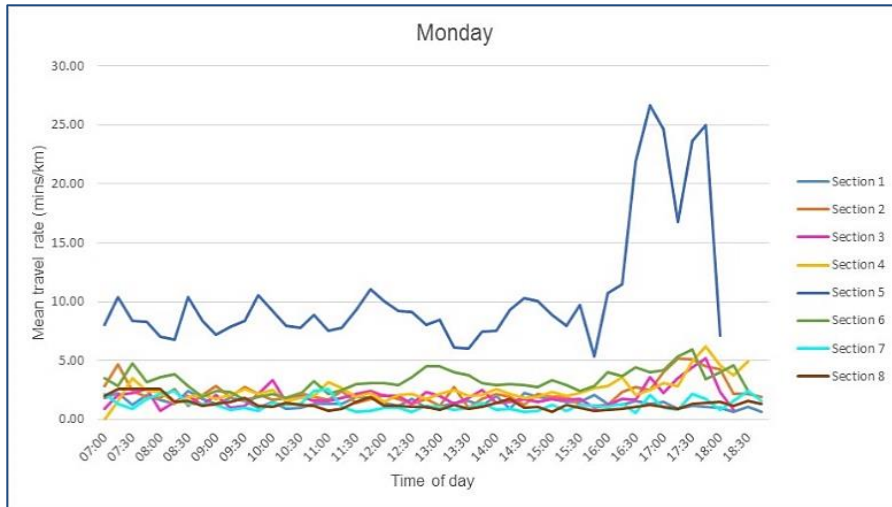
Figure 5.22: Freight mean travel rates and RIs against time of day on Monday (South Eastern direction)
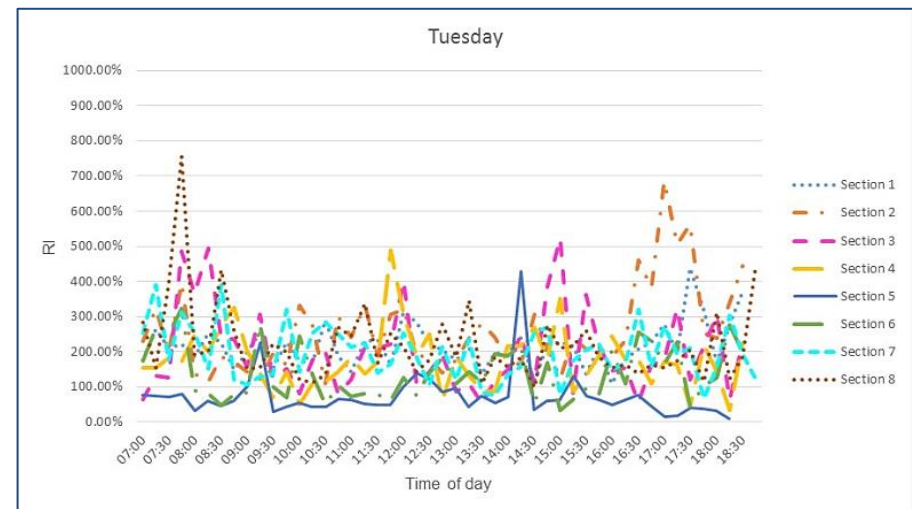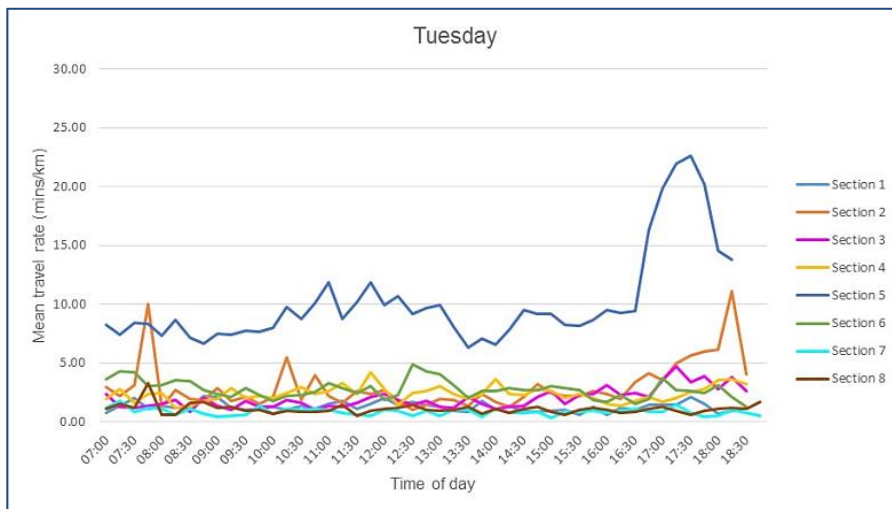
Figure 5.23: Freight mean travel rates and RIs against time of day on Tuesday (South Eastern direction)
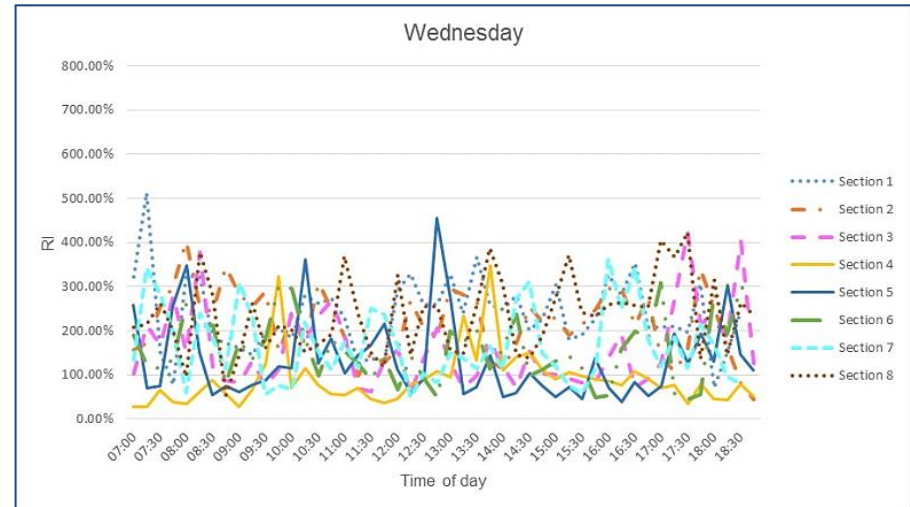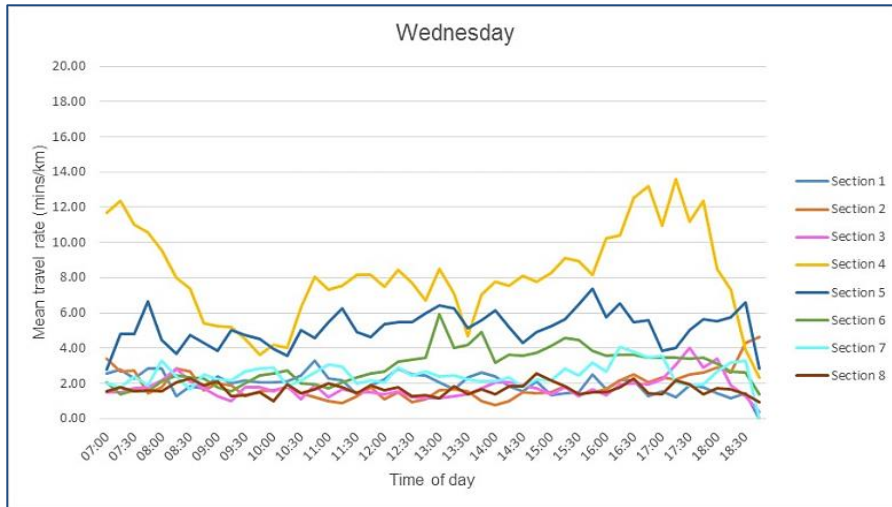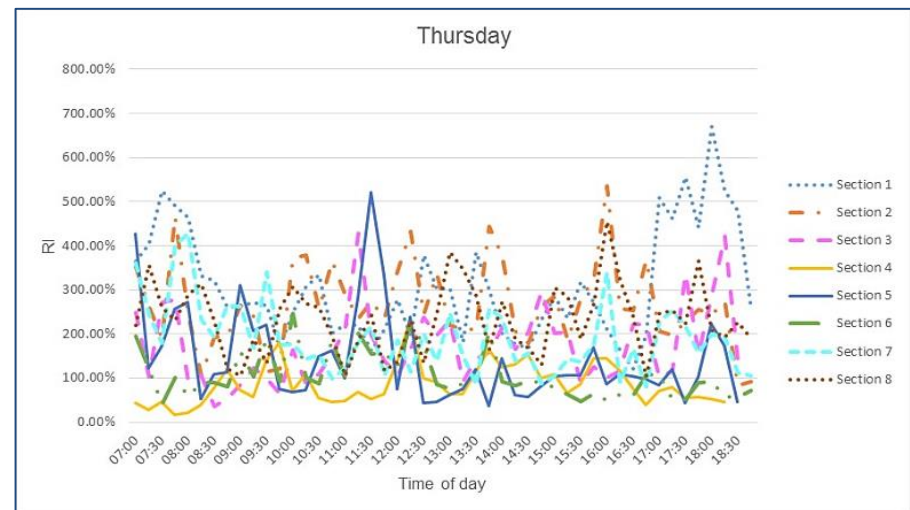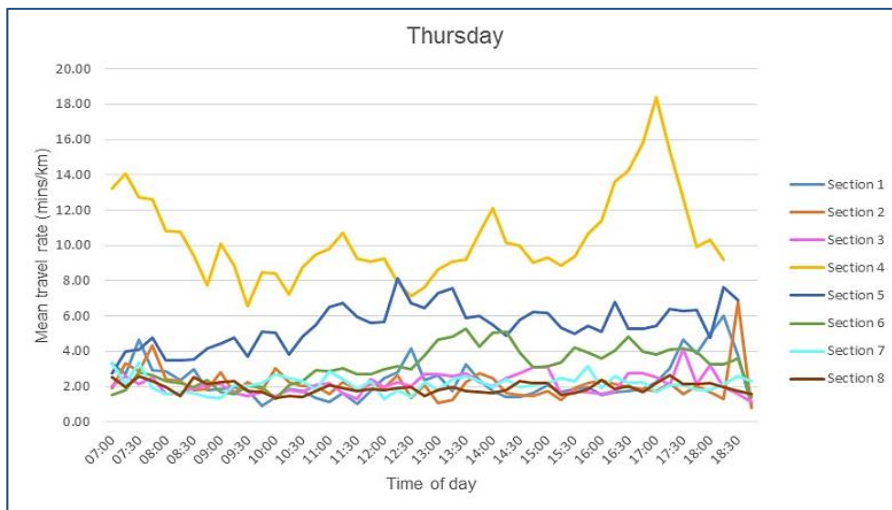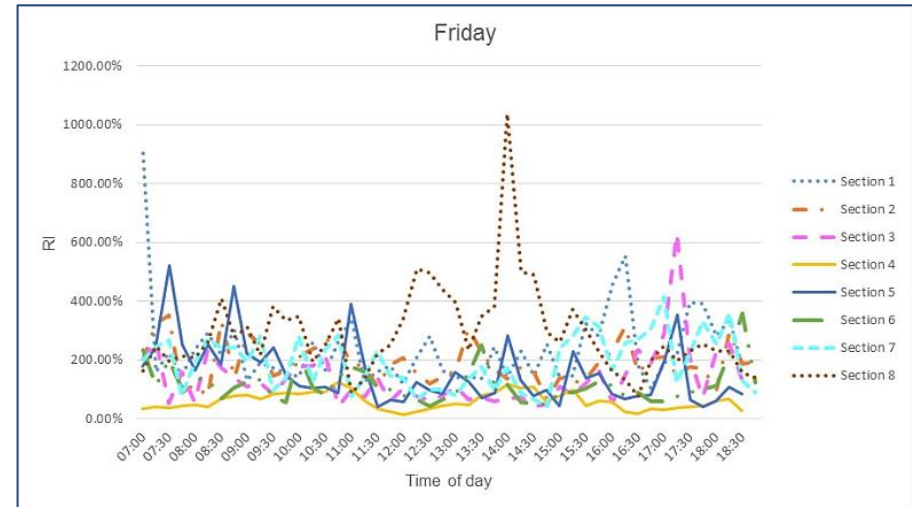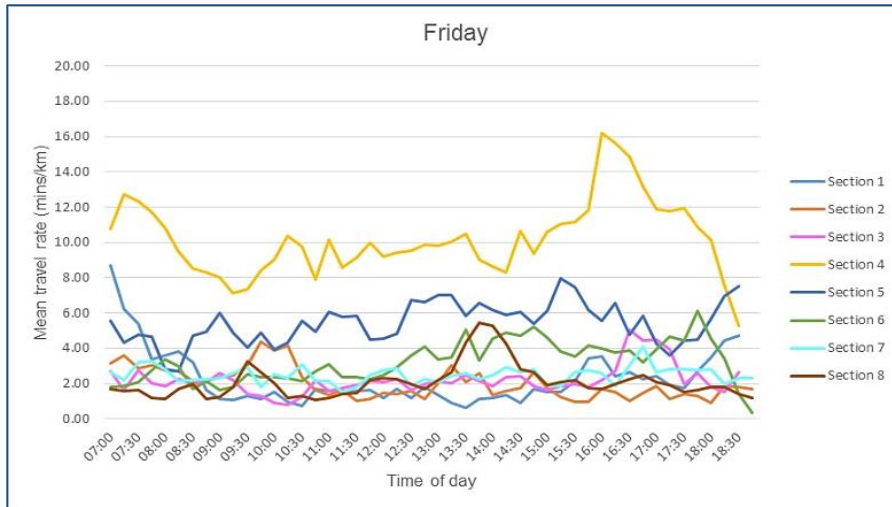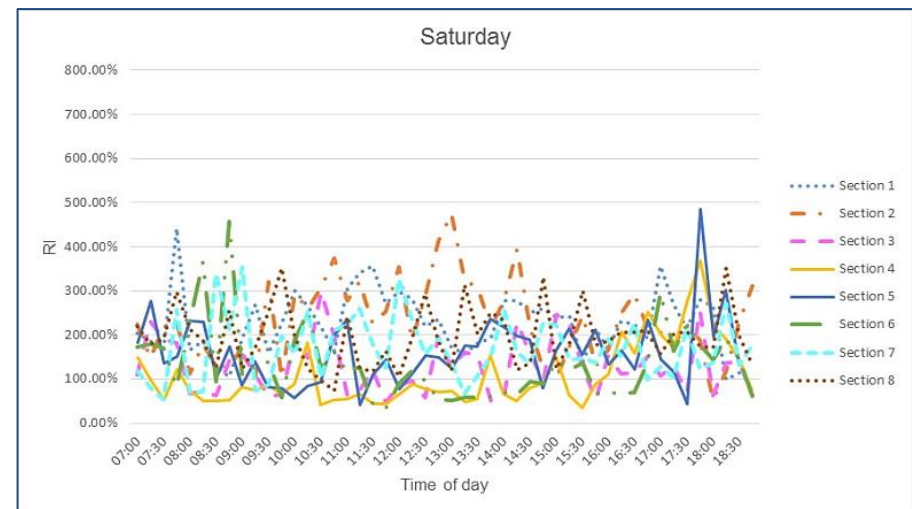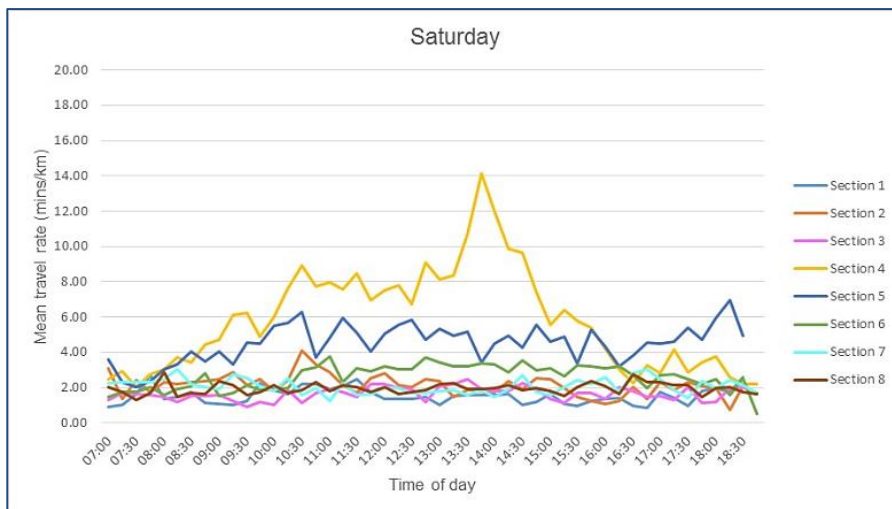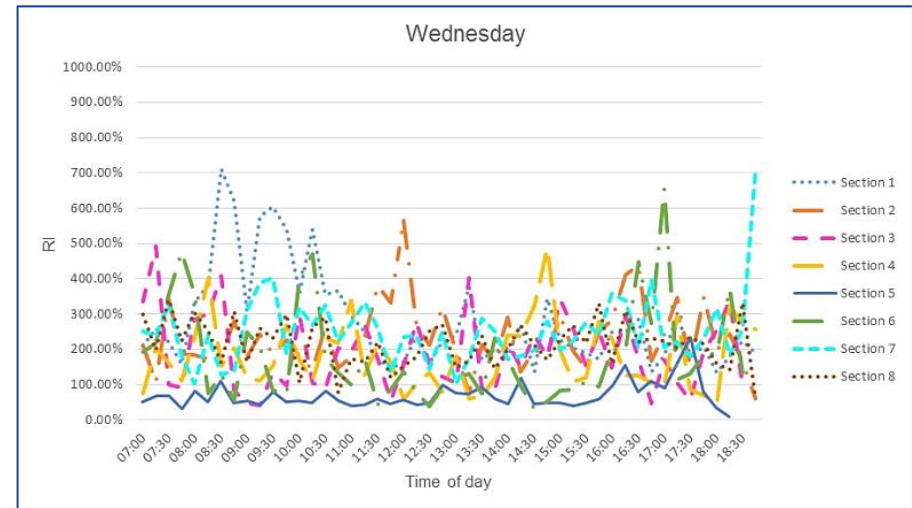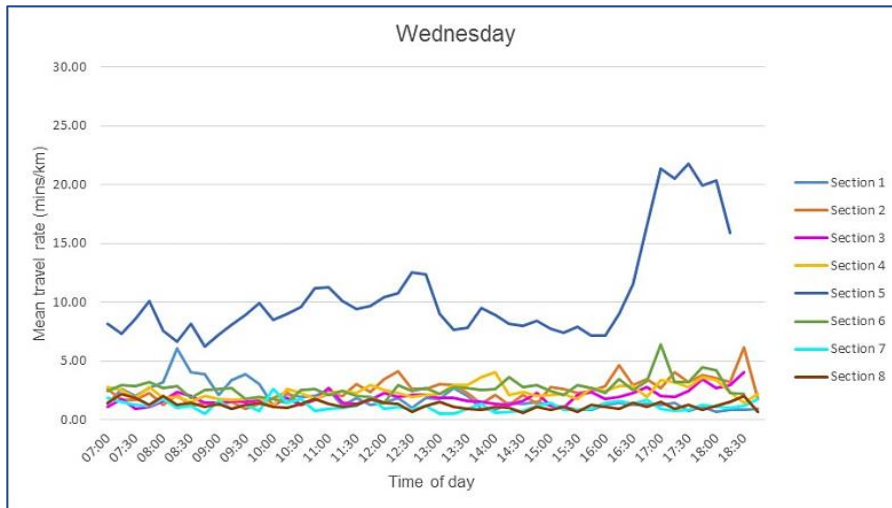
Figure 5.24: Freight mean travel rates and RIs against time of day on Wednesday (South Eastern direction)
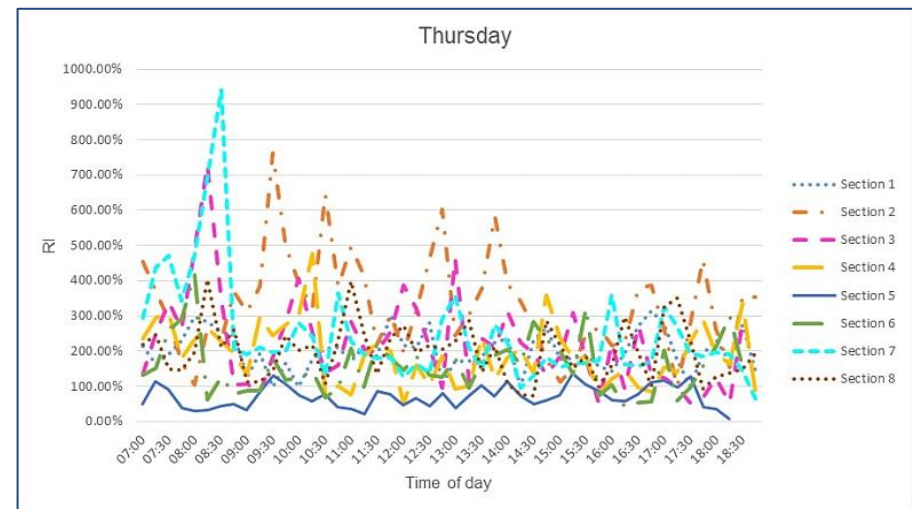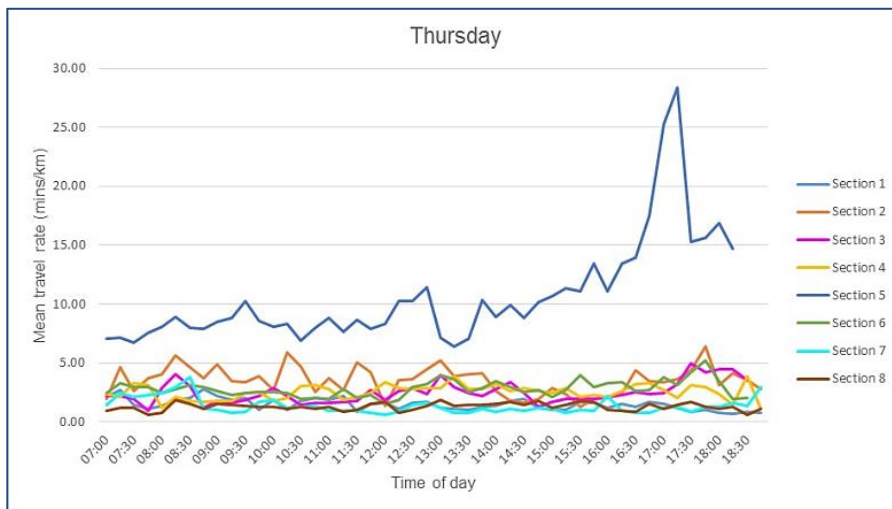
Figure 5.25: Freight mean travel rates and RIs against time of day on Thursday (South Eastern direction)
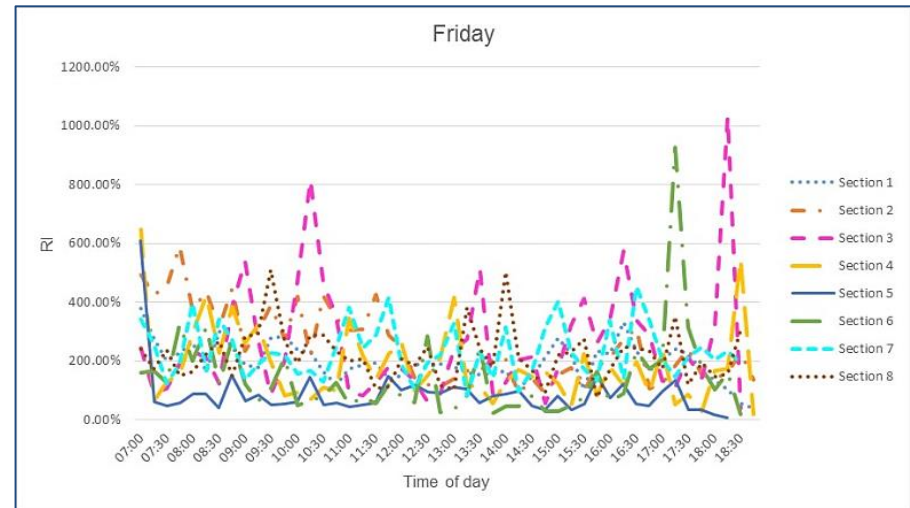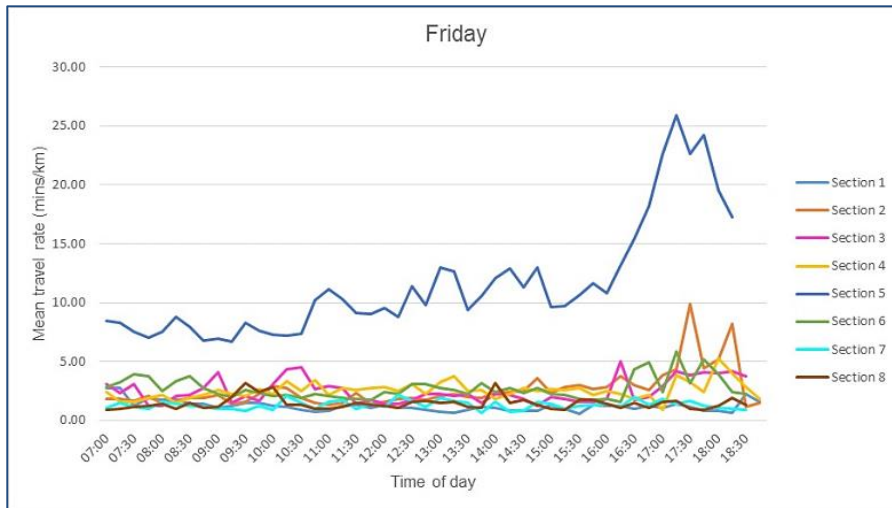
Figure 5.26: Freight mean travel rates and RIs against time of day on Friday (South Eastern direction)
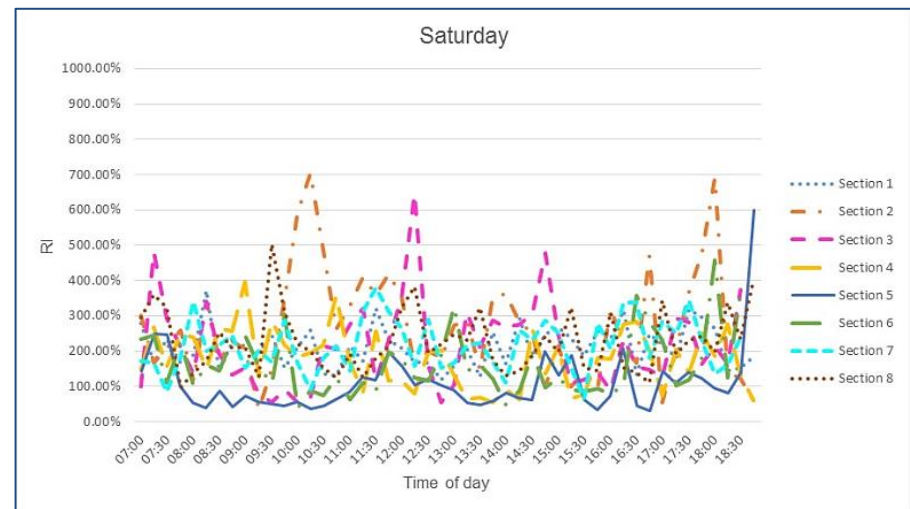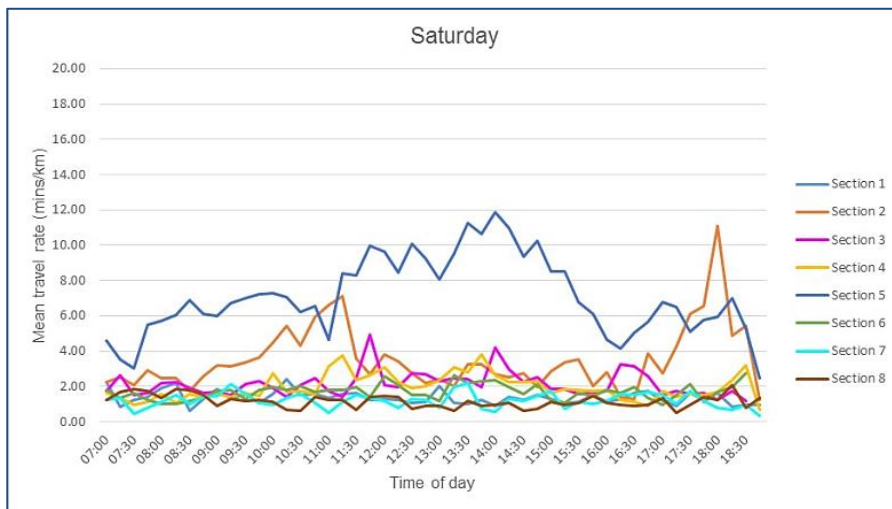
Figure 5.27: Freight mean travel rates and RIs against time of day on Saturday (South Eastern direction)
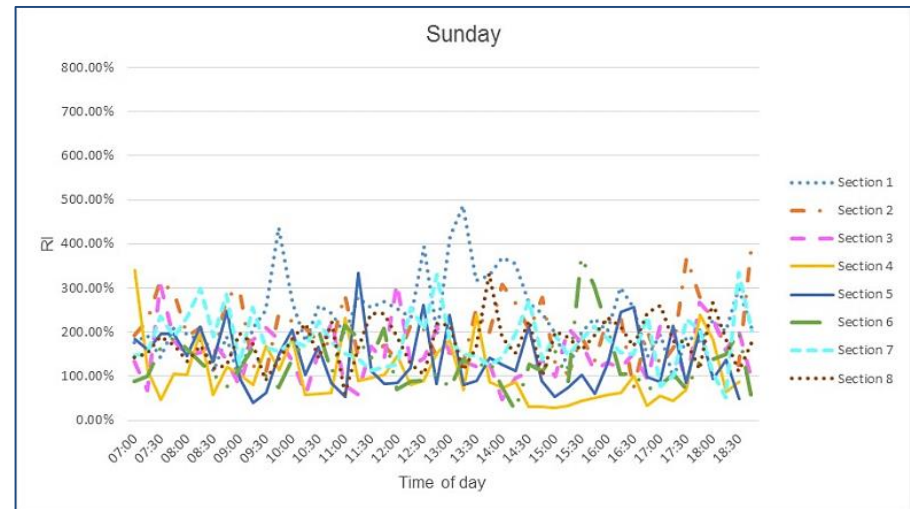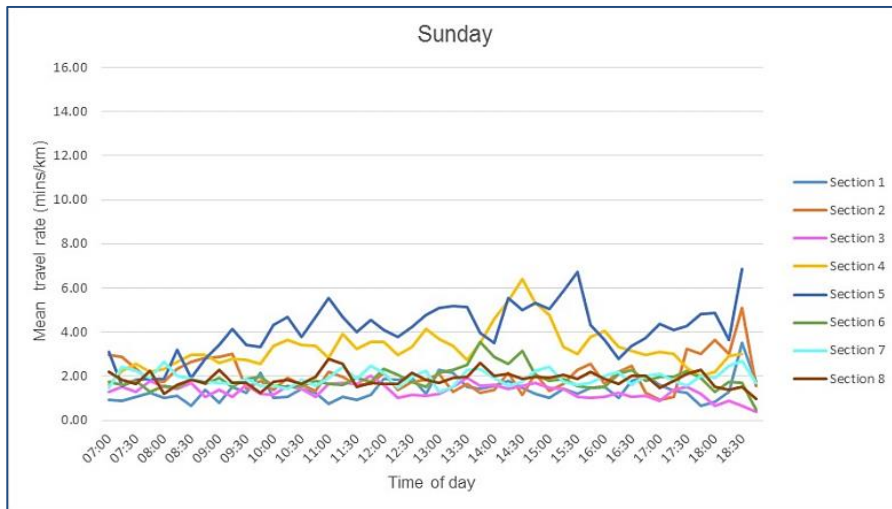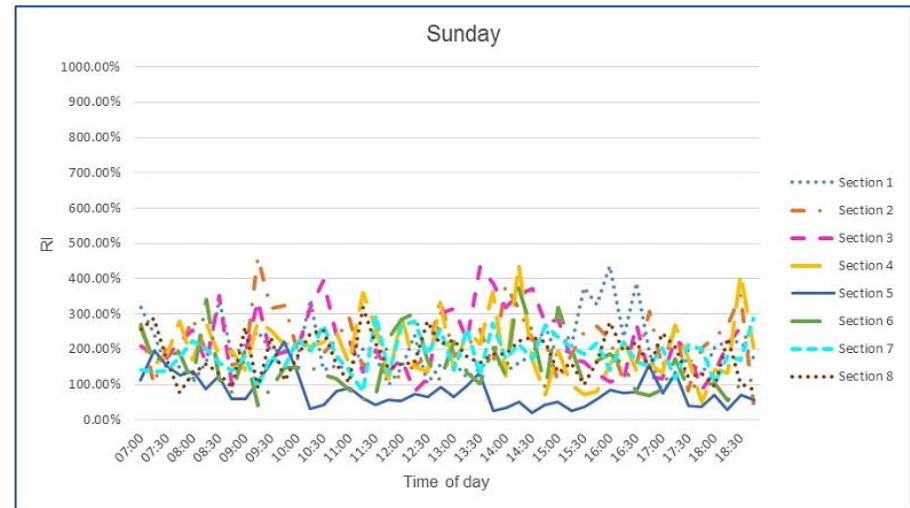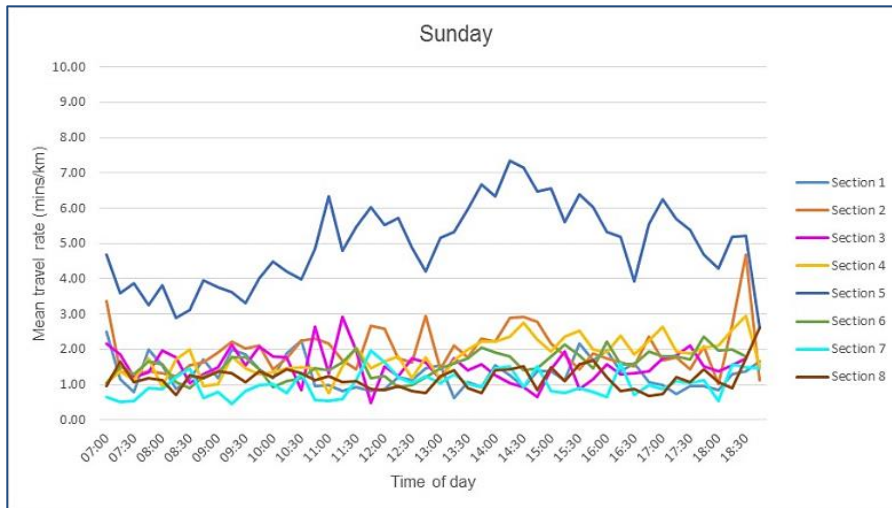
Figure 5.28: Freight mean travel rates and RIs against time of day on Sunday (South Eastern direction)

A summary of the trends in the South Eastern direction is as follows:

1. The slowest freight mean travel rates tend to occur on Section 5 (Museum Hill Interchange to Haile Selassie Roundabout) throughout the day and throughout the week. Section 2 (Enterprise Road Junction to Airport North Road Junction) also tends to have somewhat slow freight mean travel rates on some mornings and on most evenings. The freight mean travel rates on this section are even slower than those on Section 5 at 7:45 a.m. on Tuesday and at 6:00 p.m. on Saturday;

2. Clear freight mean travel rate peaks are seen mainly on Section 5. During weekdays, there is one peak period generally between 4:30 p.m. and 6:15 p.m. in the evening. On Saturday, a midday peak period occurs approximately from 11:15 a.m. to 3:15 p.m. On Sunday however, some general variation is evident in the freight mean travel rates through the day on the section. A travel peak can also be seen on Section 2 (Enterprise Road Junction to Airport North Road Junction) in the evening generally between 5:30 p.m. and 6:30 p.m. on several weekdays and on the weekends. Peak instances also occur on this section in the morning and in the midday on Tuesday and on the weekends. The rest of the sections generally exhibit little variations in the freight mean travel rates through the day throughout the week, apart from escalated variations on some of the sections on Saturday;

3. The freight mean travel rates on Section 5 generally extend to more than 22mins/km at their peaks on weekdays and to more than 12mins/km at the Saturday peak. On Sunday, the freight mean travel rate extends to more than 6mins/km at its slowest. On Section 2, freight mean travel rates extend to more than 11mins/km at their slowest peaks. Freight mean travel rates on the rest of the sections generally fall between 1min/km and 5mins/km. Lower values of freight mean travel rates are exhibited in the weekends compared to the weekdays on the sections though the values on Section 2 on Saturday tend to mirror those of the weekdays.

4. The RIs on Section 5 tend to be the smallest and most stable through the day throughout the week, falling below 100% on most occasions. However some large RI values are still seen on the section on Monday, Tuesday, Friday and Saturday, mostly in the afternoon and in the evening and being more than

400%. The RIs on the rest of the sections vary highly through the day on all days of the week and tend to be in the range of 100% – 400%. Some very large RIs are also frequently seen on Section 2 (Enterprise Road Junction to Airport North Road Junction), mainly in the morning and in the evening and being mostly above 500% and on Section 3 (Popo/Kapiti Roads Junction to Enterprise Road Junction), mainly in the morning and in the midday and being mostly above 500%. The other sections also record very large RI values on some days of the week mostly in the mornings and in the evenings. Generally, smaller RI values occur on Sunday compared to the rest of the week.

The above findings indicate the following:

1. Travel time reliability measurement is very useful to holistic understanding of congestion seeing as freight RI trends depict very different patterns and levels of congestion from freight mean travel rate trends along the segment;

2. With freight mean travel rates ranging generally between 1min/km and 5mins/km on most sections of the segment, this translates to general freight average speeds in the region of 20km/hr, suggesting excessive average delays on the segment and reinforcing the need for regular congestion improvements;

3. With freight RI values ranging generally between 100% and 400% and sometimes much larger, the sizes of freight buffers on the road segment are generally double to four times the sizes of freight expected travel times and are sometimes much bigger, suggesting excessive unexpected delays over and above expected delays. This then also suggests that as much, if not more, attention needs to be given to travel time reliability improvements as to improvements of other congestion parameters including V/C ratio, average travel time and average delay on the segment. There is also indication that travel time reliability tends to be lower where travel times are shorter and improvements that result in shorter average travel times without addressing travel time reliability could lead to more critical congestion in the form of lower travel time reliability;

4. Although Section 5 (Museum Hill Interchange to Haile Selassie Roundabout) is the most reliable of all the sections, it still suffers instances of very low travel time reliability and the effects of regular congestion on it are rather great and

much more than on the rest of the sections. On this basis, Section 5 stands out as suffering the greatest effects of congestion, suggesting that it should be prioritized for congestion alleviation efforts compared to the other sections. As stated previously, Section 5 is among the most travelled sections of the segment in terms of traffic volumes, rivalled only by Sections 1, 2 and 3, and can be expected to continue being highly travelled falling within the CBD, all the more reason why it should be prioritized;

5. Section 2 (Enterprise Road Junction to Airport North Road Junction) should also be prioritized for congestion alleviation efforts seeing that after Section 5, it suffers the next slowest freight mean travel rates and out of all the sections is characterized by the highest frequency of some of the largest RIs on the segment.

Overall, the two directions of travel show similarity in that:

1. Freight RI trends depict very different patterns and levels of congestion from freight mean travel rate trends along the segment and travel time reliability measurement is therefore very useful to holistic understanding of congestion;
2. The general freight average speeds on the segment are in the region of 20km/hr, with freight mean travel rates on most sections of the road segment falling generally between 1min/km and 5mins/km, suggesting excessive average delays and reinforcing the need for regular congestion improvements;
3. The sizes of freight buffers on the road segment are generally double to four times the sizes of freight expected travel times and are sometimes much bigger, with freight RI values ranging generally between 100% and 400% and sometimes much larger, suggesting excessive unexpected delays over and above expected delays. This then also suggests that as much, if not more, attention needs to be given to travel time reliability improvements as to improvements of other congestion parameters including V/C ratio, average travel time and average delay on the segment. There is also indication that travel time reliability tends to be lower where travel times are shorter and improvements that result in shorter average travel times without addressing travel time reliability could lead to more critical congestion in the form of lower travel time reliability;

4. Section 5 (Haile Selassie Roundabout to Museum Hill Interchange/Museum Hill Interchange to Haile Selassie Roundabout) stands out as suffering the greatest effects of congestion, meaning that it should be prioritized for congestion alleviation efforts on the road segment.

On the other hand, the main directional difference is as follows:

1. While Section 4 (Popo/Kapiti Roads Junction to Haile Selassie Roundabout) is the other section that should be prioritized for congestion alleviation in the North Western direction of travel, Section 2 (Enterprise Road Junction to Airport North Road Junction) stands out in this respect in the South Eastern direction of travel.

5.6 EXAMINATION OF INFLUENCE FACTORS OF THE FREIGHT TRAVEL TIME AND FREIGHT TRAVEL TIME RELIABILITY PERFORMANCE OF THE ROAD SEGMENT

Following the analysis of the freight travel time and freight travel time reliability performance of the road segment as above, the data on irregular congestion causing factors and previous studies of the road segment were examined and used together with knowledge gained about traffic conditions from the field study and otherwise to make judgments on performance influence factors other than inadequate physical road capacities relative to traffic volumes. The following observations were made:

1. Seeing as the patterns of freight travel time and freight travel time reliability on the road segment as a whole inclined towards commuter traffic patterns so that even the identified ideal hours for freight travel fell within the traditional off-peak commuter travel hours and vice versa, it can be said that the mainly commute road use of the segment exerts a major effect on freight travel, commuter congestion informing a large part of the extents of freight delays suffered. The HGVs data and field observations also indicated a majority of freight movements occurring generally between 10:00 a.m. and 3:00 p.m., freight

carriers obviously attempting to take advantage of reduced congestion in the off-peak commuter travel hours;

2. A visual comparison of the plots of freight mean travel rates and freight RIs as in Sections 5.5.1 and 5.5.2 above with the summaries of irregular congestion causing factors indicated that the largest freight RIs with sometimes corresponding worsened freight mean travel rates tended to be associated with the occurrence of one or more of the observed factors in the applicable time interval particularly on sections away from the CBD. However, there seemed to be little correlation between the patterns of occurrence of the observed irregular congestion causing factors and the trends of freight mean travel rates and freight RIs on the whole except that they tended to occur more frequently around the CBD where freight mean travel rates were more deteriorated. Of note is that traffic incidents accounted for over 70% of the factors observed along the road segment on most days of the week. The implication then is that traffic incidents (including accidents, vehicle breakdowns, debris in the travel lanes and events that occur on the shoulders, roadside and off-road); road works; extreme weather and special events are more likely the cause of the lowest freight travel time reliabilities on the outskirts of the CBD, traffic incidents in particular making a significant contribution, though these factors do not explain much of the reliability situation on the outskirts. Around the CBD on the other hand, the mentioned factors blend more normally into traffic conditions and likely contribute to the slower freight mean travel rates but do not necessarily explain the freight travel time reliability situation around the CBD;

3. In their study, GIBB Africa Ltd. & Associated Consultants of Ghana (2015, May) attributed existing bottlenecks in the road system between JKIA Turnoff and Likoni Road Junction majorly to abuse by both motorized and non-motorized traffic (NMT) including stopping of public service vehicles (PSVs) at undesignated locations without warning, haphazard crossing at various locations by high pedestrian volumes and attitudinal issues of the road users. They further attributed excessive delays to uncontrolled acceleration lanes at intersections. COWI A/S et al. (2012, October) also identified inappropriate driving behavior, illegal vehicle parking and stopping of PSVs at inappropriate locations as resulting in bottlenecks even at junctions that have satisfactory LOS along the road between Likoni Road Junction and James Gichuru Road

Junction. Hence it is possible that the unexplained freight travel time reliability on the segment is due to speed fluctuations from roadway abuse and uncontrolled traffic situations;

4. In light of 3 above, the lower freight travel time reliability associated with shorter freight travel time on the outskirts of the CBD compared to around the CBD is more likely a result of a lesser controlled traffic environment away from the CBD. This circumstance, coupled with the more moderate regular congestion outside the CBD creates greater opportunities for roadway abuse and including aggressive driving behavior which would result in greater speed fluctuations;

5. The road section within the CBD (Haile Selassie Roundabout to Museum Hill Interchange/Museum Hill Interchange to Haile Selassie Roundabout) is unique in that it does not follow the seeming trend of high reliability associated with a large size of regular congestion and vice versa. It still suffers some of the lowest freight travel time reliabilities on the segment. Also in light of 3 above, this could be attributed to the uncontrolled minor junctions along this section such as the junctions with Utalii Street and Harambee Avenue creating opportunities for such factors as aggressive driving behavior at these locations which would cause excessive speed fluctuations.

6. DISCUSSIONS

6.1 OVERVIEW

The study's hypotheses were that: 1) variations in travel time are quantifiable and explainable for establishment of travel time reliability; 2) freight travel time reliability measures for the Northern Corridor Road segment in Nairobi can be determined, with this information able to answer pertinent performance questions about the segment particularly in regard to unexpected delays; and 3) the freight travel time reliability information is useful for facilitating reliable movement on the segment by enabling comprehensive freight travel scheduling and improvements related to reliability influence factors.

6.2 FREIGHT PLANNING TIMES AND BUFFER TIMES, WITH FREIGHT MEAN TRAVEL TIMES

The segment freight planning times and buffer times, apart from telling respectively the total amounts of time and the extra amounts of time over the averages required to ensure on-time freight traversal of the segment 95% of the time, exhibited significant differences in trends over time on comparison with segment freight mean travel times. Previous travel time reliability studies have also shown differences in the time trends of planning time and buffer time against the time trends of mean travel time. Lyman & Bertini (2008) and Higatani et al. (2009) are cases in point. In the footsteps of these previous studies, this study therefore reiterates the importance of travel time reliability as an information tool to users, not only enlightening on the actual time consequences of unexpected travel conditions over and above average conditions but also serving to enable better travel time choices with careful consideration of both travel time and travel time reliability trends.

The already established feature of travel time reliability that is its variability over time was also clearly depicted in the patterns of freight planning time and freight buffer time obtained and the fact that the study established differences of these measures along with those of freight mean travel time over fifteen-minute intervals of the day for each day of the week including weekends means that freight carriers can have a

comprehensive picture of the experience on the segment. The weekend information is especially beneficial for them as they tend to conduct business extensively in the weekends compared to groups of travelers such as commuters. Lyman and Bertini (2008) and Higatani et al. (2009) showcased the differences in planning time, buffer time and mean travel time only across the hours of day and did not focus on the differences across the days of week. Their studies were however for demonstrating the characteristics of travel time reliability rather for than for offering information to users.

Hence from considering a combination of the values of freight mean travel time, freight planning time and freight buffer time and their respective and combined trends across time, the study was able to point out the segment ideal and unideal freight travel periods within the week, these allying to traditional commuter off-peak and peak travel hours respectively, and also that it is over four times more beneficial to transport freight during periods of high reliability than during periods of low reliability. This information is a useful guide as to how one might look at their choice of the time of travel. The charts of freight mean travel time, planning time and buffer time against time developed in the study could also be displayed such as on the website of the agency responsible for management of the road segment, which is KeNHA, with an optimization of the website to enable viewing on mobile devices. This would then provide a platform for freight carriers to easily access the complete segment freight travel time information for making their own wider ranging choices, so that even if their circumstances mean that they cannot fit their schedules within the ideal times, they are still able to act from a point of awareness of all possible implications of their choices.

Although there have been changes on the road segment following data collection such as completion of construction and opening to traffic of interchanges at Airport North Road Junction and Likoni Road Junction, opening to traffic of the Southern Bypass that tees off the road opposite Likoni Road and provision of footbridges at crossing points at Airport North Road, Enterprise Road and Popo/Kapiti Roads Junctions (*Map 6.1*), a spot check of predicted freight travel times against observed freight travel times along the section with improvements between JKIA Turnoff and Popo/Kapiti Roads Junction at random times during days between 25th April, 2016 and 29th April, 2016 showed that predicted freight travel times tallied well with observed freight travel

times[‡]. Out of fifty four checks, forty five or 83% showed no major deviation between predicted mean and median travel times and observed travel times while two longer observed travel times, being about three times longer, allied to the occurrence of an accident. Generally in cases of deviations, observed travel times were about one and a half times to three and a half times shorter or longer than predicted travel times, these comparing well with the buffers measured on the segment. The highest frequency of deviations anywhere was three shorter observed travel times out of nine cases between Popo/Kapiti Roads Junction and Enterprise Road Junction (South Eastern direction) and three longer observed travel times out of nine cases between Enterprise Road Junction and Popo/Kapiti Roads Junction (North Western direction), this frequency tending to suggest little rather than major effect of changes on these specific sections. It can be said therefore that the changes on the road segment so far are minimal and have not had much effect on travel times and travel time reliabilities. Hence the travel time information from the study is still well able to give users a picture of the experience on the segment. Further, even though it was observed during data collection for this spot check that much of heavy truck traffic now diverts to the Southern Bypass, the travel time information would still be useful for any choice that may be made to use the road segment rather than the Southern Bypass.

[‡] Observed travel times were measured directly by employing a probe vehicle to follow randomly selected heavy trucks within the traffic stream at the speed of the trucks and record the times of arrival at relevant data collection stations (chasing car probe vehicle technique).
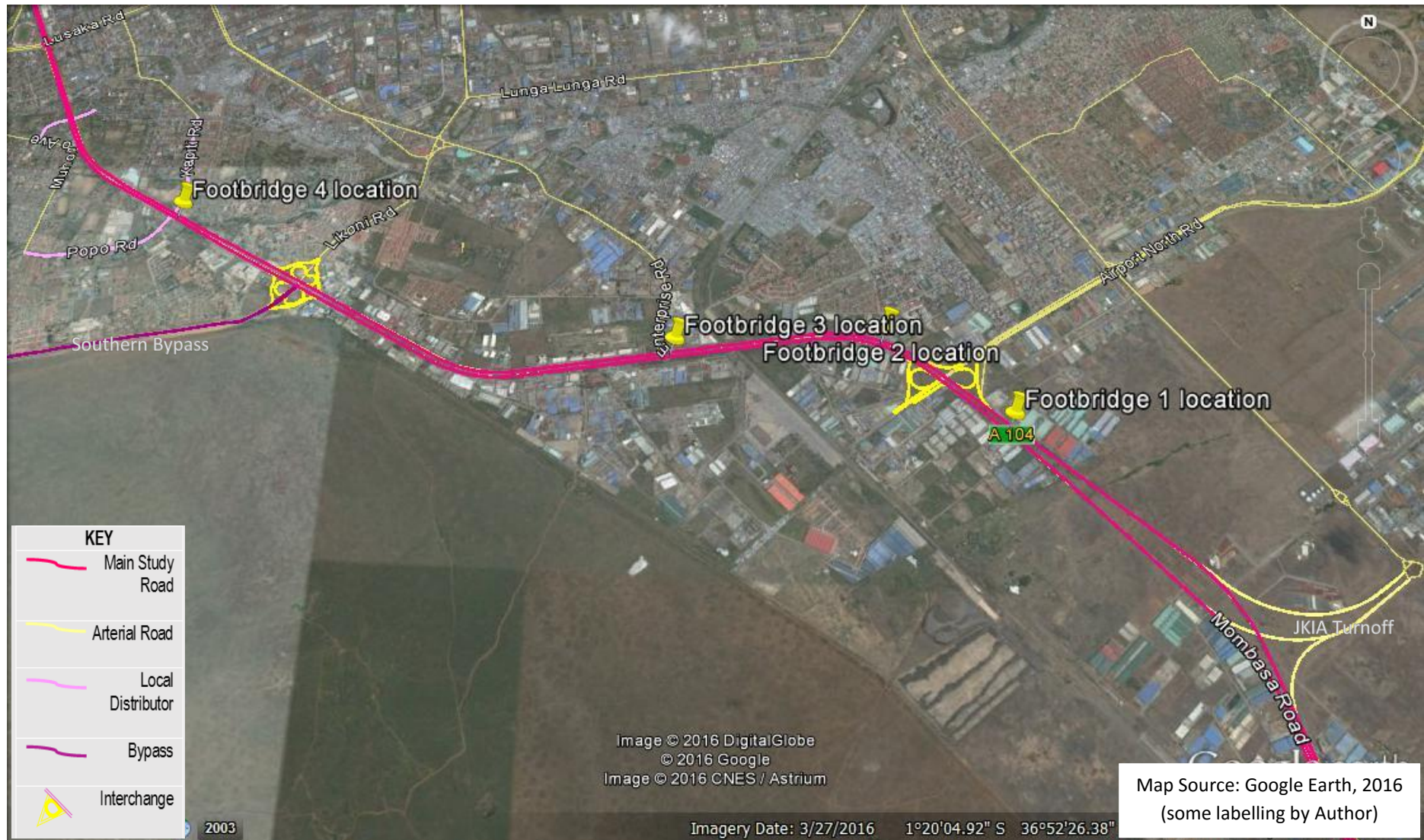
Map 6.1: Northern Corridor Road between JKIA Turnoff and Popo/Kapiti Roads Junction with changes

6.3 FREIGHT RELIABILITY INDICES (RIs), WITH FREIGHT MEAN TRAVEL RATES

Freight RIs on distinct sections of the road segment, apart from telling how much larger the buffers are than the expected travel times on the sections, exhibited much different patterns and levels of congestion on comparison with section freight mean travel rates over time. This is in line with previous travel time reliability studies which have well established differences in the patterns and levels of congestion as measured by travel time reliability measures versus by regular congestion measures. Mallet et al. (2006), Lyman and Bertini (2008), Higatani et al. (2009) and Chu (2011) all showcased these differences. This study therefore follows in the footsteps of the previous studies to reiterate the usefulness of travel time reliability to holistic understanding of congestion, not only enlightening on the actual extents of unexpected delays over and above average conditions but also serving to complement regular congestion measures in better interpretation of congestion.

The performance of the segment, with a measured general freight RI range of 100% – 400% and sometimes much larger values on its sections translating to section freight buffer sizes of generally double to four times the expected travel times and sometimes much bigger, is rather dismal. Although there is no standard agreed buffer threshold, the tone of previous literature has been that a buffer value double the expected travel time lies on the border of acceptable and unacceptable. A comparison with buffer measures on other major roads connecting to or traversing the main activity centres of principal cities around the world also shows that the road segment performs much below par. Lyman and Bertini (2008) measured latest BI values of about 20% – 90% on freeway routes providing direct connection to downtown Portland, Oregon in the US during the morning peak and about 50% – 140% during the evening peak, Higatani et al. (2009) measured BI values of about 60% – 120% during peak hours and below 40% during off-peaks hours on routes in the Hanshin Expressway Network connecting downtown Osaka City in Japan to suburban areas, Susilawati et al. (2010) measured latest BI values of about 30% – 80% on selected corridors providing direct connection to the Adelaide CBD in Australia and Chu (2011) measured RI values of about 70% – 150% on arterial road segments providing access to Kaohsiung Port in Kaohsiung City of Taiwan.

The findings of this study clearly add to those of COWI A/S et al. (2012, October); GIBB Africa Ltd. and Associated Consultants of Ghana (2015, May) and ESER Project & Engineering Co. Inc. and Botek Bosphorus Technical Consulting Co. (2015, June) in pointing out congestion improvement requirements for the road segment, having in the first instance highlighted the need to treat unexpected delays much as the previous studies highlighted the need to treat expected delays. The latter need is in fact reinforced in this study, with the finding that the general freight average speeds on the segment are in the region of 20km/hr. More importantly though is the indication in the patterns of freight RIs and freight mean travel rates obtained in the study that travel time reliability tends to be lower where travel times are shorter. This actually appears to be another feature of travel time reliability when compared with travel time, and has also been seen in the studies of Mallet et al. (2006), Higatani et al. (2009) and Chu (2011). It can be said that where travel times are short, being indicative of a good LOS, drivers take advantage of the available freedom to perform many manoeuvrability actions and on highly travelled roads especially, this is a thriving environment for the effects of irregular congestion causing factors. The previous studies of the road segment having considered improvements with the mind of shortening travel times, it would then be necessary to add the mind of dealing with factors of low travel time reliability to avoid an otherwise counter-productive result of the vision to relieve the road segment of congestion.

Considering further the section freight RI differences, which also served to reinforce the feature of travel time reliability that is its variability with route/sections of route, and the trends across time together with the section and time trends of freight mean travel rate, the study was able to prioritize the segment shortcomings for improvement. This approach relates to that of many travel time reliability studies including Lyman and Bertini (2008), Higatani et al. (2009) and Susilawati et al. (2010) which used travel time reliability measures along with regular congestion measures to point out the most critical shortcomings in the routes/systems/networks they studied. Although as has already been indicated the Northern Corridor Road segment in Nairobi requires improvements over its entire length, this information can be used as an indication of where maximum benefits would be achieved within the overall programme of improvements, establishing priority and informing subsequent appraisal studies.

6.4 FREIGHT TRAVEL TIME AND FREIGHT TRAVEL TIME RELIABILITY INFLUENCE FACTORS, WITH POSSIBLE IMPROVEMENTS

Exploring influence factors of the freight travel time and freight travel time reliability performance of the segment other than inadequate physical road capacities relative to traffic volumes, the mainly commute road use of the segment emerged as a principal factor, commuter congestion informing a large part of the extents of freight delays suffered. Generally, freight travelling in a high volume commuter setting can be expected to suffer critical delays as a result of having to contend with commuter congestion during morning, in some cases midday and evening rush periods in the work week and further congestion during weekend periods when customarily travel is undertaken for such activities as shopping and recreation, not to mention that conflicting operating characteristics of the two classes of traffic in such a setting also contribute to a fair share particularly of unexpected delays. With the expectation that the Northern Corridor Road segment in Nairobi will continue to serve high commuter traffic volumes into the long term, this makes a case for truck-only facilities that could much improve Northern Corridor freight travel time and freight travel time reliability through Nairobi while contributing to achieving better quality travel for the rest of the traffic on their dedicated sections in light of reduced interaction with freight traffic.

As has already been mentioned, it was noted by the time of completion of this study that much of the freight traffic that previously traversed the segment diverts to the newly operational Southern Bypass. In fact, there were already prior predictions that the Southern Bypass was a diversion option for up to 70% heavy truck and 50% medium truck traffic on the Northern Corridor Road associated with trips generated/attracted mostly between zones located on the stretch from Mombasa to Nairobi and the industrial zone and the ICD within Nairobi and zones located beyond the city towards the West (COWI A/S et al., 2012, October; GIBB Africa Ltd. & Associated Consultants of Ghana, 2015, May; ESER Project & Engineering Co. Inc. & Botek Bosphorus Technical Consulting Co., 2015, June). It is a deduction of this study that it could be beneficial to further explore the viability of dedicating the Southern Bypass as a truck bypass road for Northern Corridor freight traffic through Nairobi altogether or of the more moderate approach of establishing exclusive truck lanes along with other truck amenities such as truck lay-bys on the bypass with the mind that

a high degree of separation of freight traffic movements and other forms of traffic movements would achieve overall better management of travel time and travel time reliability on the Northern Corridor route in Nairobi.

Such a consideration may be supported by indications that the Southern Bypass leans towards serving the role of a Northern Corridor freight route more than any other role in the long-term. The first is that the bypass has also been projected to take just 10% of the total traffic from the main Northern Corridor Road in Nairobi (COWI A/S et al., 2012, October; GIBB Africa Ltd. & Associated Consultants of Ghana, 2015, May; ESER Project & Engineering Co. Inc. & Botek Bosphorus Technical Consulting Co., 2015, June), suggesting only a minimal expected use of it by forms of traffic other than Northern Corridor freight traffic.

The second indication is in city's historical development character and plans, particularly with regard to the general area crossed by the Southern Bypass. The vision of the *Nairobi Metropolitan Growth Strategy* of 1973 (Nairobi Urban Study Group, 1973) was that the then proposed Trans-Africa Highway connecting Kikuyu in the North to Mombasa Road in the South (which can be taken as congruent to the Southern Bypass) exists complementary to fairly self-sustaining developments in the Dagoretti, Kibera, Wilson Airport and Karen-Lang'ata areas, with industrial and commercial centres located close to the highway offering local employment, and these areas connected to the rest of the city by bus ways along roads including Naivasha, Ngong and Lang'ata (*Map 6.2*). The Trans-Africa Highway and the arterials leading to/from it would have offered good connectivity of the industries and commercial centres to other market locations while the need for commute from/to these areas would have been kept well in check and reasonably managed. So far however, the Wilson Airport remains in place and the rest of the subject areas have established as largely residential districts – save for the conservation zones within them – that are much dependent on the city core for jobs and other major functions, this a reflection of poor governance systems that have been unable to keep up with the city's development plans and other effective development management strategies in the face of limited resources and rapid urbanization (Ministry of Nairobi Metropolitan Development, 2008).
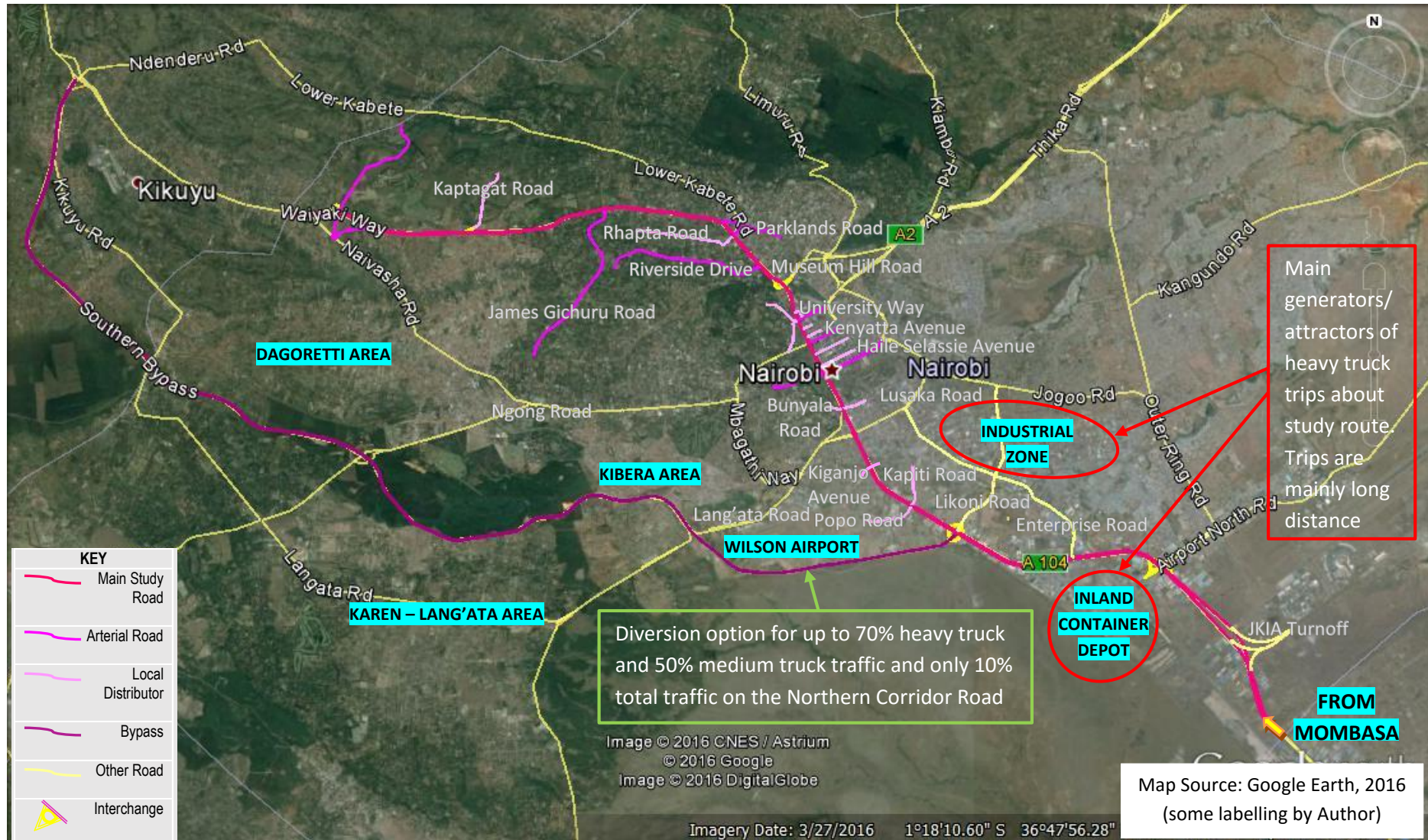
Map 6.2: Southern Bypass and its surroundings (some points that may justify truck facilities on the road are indicated)

The need for management of the commute between these residential districts is all the more critical now and the use of the Southern Bypass that emanates from them can at best be termed "minimal-occasional". It is unlikely too that the forms of these immediate surroundings of the Southern Bypass could in the near or long-term future change to conform to the original plan of accommodating developments with the capacity to encourage beneficial movement along the Southern Bypass while reducing dependence of these areas and possibly nearby upcoming areas such as Ngong and Ongata Rongai in the South West on the core of the city. Even if there was improved authority towards realizing the change, the costs of such land use alteration would already be too high, not to mention that resistance can be expected from the established communities in the areas. Hence, promotion of public transport along the arterial roads that lead up from the surroundings of the Southern Bypass to the city core with complementary transportation along feeder routes, which is still in tune with the 1973 city master plan and the transport vision for Nairobi Metropolis of the more recent *Nairobi Metro 2030* (Ministry of Nairobi Metropolitan Development, 2008), while applying strategies that cater more for Northern Corridor freight traffic movements along the Southern Bypass may be better for the needs of the concerned communities.

The profile of the Southern Bypass relative to the main generators/attractors of freight trips about the route (*Map 6.2*) would also be fitting for consideration of truck exclusive facilities, in line with research that has suggested that these provide a travel time and reliability benefit mainly for long distance truck trips with concentrated origin and destination locations about a route (Fischer, Ahanotu, & Waliszewski, 2002; Heffron & Hirschey, 2007; Transportation Research Board, 2010).

It is also a deduction of the study that another form of truck-only facilities that could be useful on the Northern Corridor Road segment in Nairobi is freight direct access ramps at key freight access locations along the road. Heffron and Hirschey (2007) indicated that freight direct access ramps connecting to/from freeway lanes could be warranted where there is a high volume of trucks needing to access a freight significant zone such as an industrial area. With the anticipation that the now under construction standard gauge railway (SGR) on the Northern Corridor will take on much of freight transport between Mombasa and the ICD, increased access truck traffic can be

expected from/to the ICD in addition to access truck traffic from/to the industrial zone (*Map 6.2*). On the other hand, improvement designs that have been proposed for the road segment envision that all access be undertaken from service roads, and specifically for access of the ICD and the industrial zone, this entails two-lane service roads in each direction of travel between Airport North Road Interchange and Likoni Road Interchange connected to Enterprise Road and a new ICD access road besides the existing ICD access road at-grade on a 2-level rotary interchange providing for overpass free flow along the segment at Enterprise Road Junction (GIBB Africa Ltd. & Associated Consultants of Ghana, 2015, May). To prevent major conflicts and hence very low reliabilities that would occur in the service areas as heavy trucks attempt to access the relevant freight zones in the midst of other access and local traffic resulting in unwarranted congestion on the main segment lanes, freight direct access ramps could be incorporated into the proposed Enterprise Road Interchange design for instead allowing trucks to pass directly from the left through lanes of the segment to Enterprise Road and the ICD access roads and vice versa. In the same breath, a freight direct access ramp could be incorporated into the proposed Likoni Road Interchange design for allowing trucks to pass directly from the left through lanes of the segment to the Southern Bypass at their main point of exiting the segment. It is estimated that the suggested additional provisions for freight traffic could be implemented without much effect on through traffic in light of the fact that the design of GIBB Africa Ltd. and Associated Consultants of Ghana (2015, May) also provides for additional through lane capacity to four lanes besides two more lanes for a bus rapid transit (BRT) system in each direction of travel between Airport North Road Interchange and Likoni Road Interchange.

The study further found evidence of association between the lowest freight travel time reliabilities and slowest freight travel times on the segment and the occurrence of one or more of irregular congestion causing factors including traffic incidents (accidents, vehicle breakdowns, debris in the travel lanes and events that occur on the shoulders, roadside and off-road); road works; extreme weather and special events, albeit by visual comparison. Traffic incidents were found to make a significant contribution to this association due to their much higher frequency compared to the other factors. The studies of Higatani et al. (2009) and Chu (2011) were more elaborate in the establishment of causal links between irregular congestion causing factors and travel

time and travel time reliability, modelling various relationships and quantifying distinctly the effects of the factors. The authors were thus able to tell exactly the delays attributable to specific factors in different time periods, factors that had the most serious effects and where improvements should be targeted, traffic incidents also emerging in their studies as having major influence on travel time reliability. Although such a quantitative approach was not the focus of this study of the Northern Corridor Road segment in Nairobi, the important place of irregular congestion causing factors and more so of traffic incidents in the context of delays on the segment was established. The need to put investment into minimizing and managing traffic incidents on the segment for addressing worst delay cases is clear.

The studies of COWI A/S et al. (2012, October), GIBB Africa Ltd. and Associated Consultants of Ghana (2015, May) and ESER Project & Engineering Co. Inc. and Botek Bosphorus Technical Consulting Co. (2015, June) proposed and designed strategies that could help address the above need, particularly with regard to reducing the chances of occurrence of traffic conflicts and thereby accidents. These include traffic separation strategies such as grade separation at all major junctions that would lessen interaction of through traffic along the segment with traffic on connecting arterial and other roads; acceleration and deceleration lanes, auxiliary lanes and storage turn lanes as per assessed needs that would lessen interaction of through traffic along the segment with merging/diverging traffic from/to other roads; alternatives to existing median turnarounds that would lessen interaction of through traffic with turnaround traffic along the segment; service roads that would lessen interaction of through traffic with local traffic along the segment; bus bays as per assessed needs that would allow stopping of vehicles such as PSVs along service roads with little interference to proceeding traffic and facilities for NMT such as crossing footbridges as per assessed needs that would minimize interaction of motorized traffic with NMT on the segment.

Also included are traffic signs and road markings along the segment for regulating traffic and guiding and alerting motorists. COWI A/S et al. (2012, October) further designed several interchanges along the segment with signal-controlled ramp junctions including interchanges at Popo – Kapiti Road, Kiganjo Avenue – Melili Road, Lang'ata Road – Lusaka Road and Bunyala Road in addition to retaining at grade

signal-controlled junctions at Haile Selassie Avenue, Kenyatta Avenue and University Way under an Uhuru viaduct with a mind of regulating traffic movements at the junctions. Coupled with these traffic control measures, GIBB Africa Ltd. and Associated Consultants of Ghana (2015, May) strongly voiced the opinion that KeNHA should collaborate with law enforcement and other relevant agencies towards ensuring that road users adhere to traffic regulations for smooth and safe use of the segment facilities.

In addition to these preventive measures, a deliberate effort is required for developing a comprehensive and well-coordinated traffic incident management programme to improve on detection, response to and clearance of traffic incidents so that normal traffic flow is restored as safely and as quickly as possible. The programme could in fact cover both the segment and the Southern Bypass for assuring good travel time and travel time reliability on the overall Northern Corridor route in Nairobi. KeNHA, as the agency responsible for management of the road segment, would best be in charge of planning and implementation of the programme, with well-defined and understood roles for other relevant agencies including law enforcement, rescue and emergency, towing and recovery and traffic information media. It would be necessary for the main agency to set up a traffic operations centre dedicated to monitoring operations on this transport system and equipped with appropriate surveillance and incident detection infrastructure and technologies. Especially important also, would be the setting up of and effective management of communication channels among detectors, responders and the public. Opportunities for partnership in surveillance, detection and information to users already exist with private information service providers who run traffic update web and mobile applications such as "ma3route" (ma3route Team, 2016) and "traffic UPDATE by AccessKenya" (Access Kenya Group, 2016), the latter linked to traffic cameras installed at strategic locations around Nairobi, including along the road segment, for relaying real-time visuals of traffic operations at the locations.

More interestingly, the study found that the irregular congestion causing factors that were the focus of field observations do not explain the entire reliability situation of the Northern Corridor Road segment in Nairobi. By relating the study findings to those of the previous studies of bottlenecks on the road segment, it was deduced that the unexplained freight travel time reliability on the segment could owe to speed

fluctuations caused particularly by roadway abuse and uncontrolled traffic situations. Roadway abuse is a key traffic feature on Kenyan roads and tends to have major problematic effects on operating conditions, especially where controls are absent or are not properly enforced as is usually the case. In fact, roadway abuse may provide a major explanation for why the Northern Corridor Road segment in Nairobi is far less reliable than comparable roads in principal cities elsewhere in the world. A study to closely relate roadway abuse effects to travel time reliability would be beneficial for gaining a clearer perspective. Even so, traffic control and enforcement against roadway abuse must be taken as integral to delay countering efforts on the segment, with good improvement measures already proposed as per earlier discussions.

Nonetheless, an additional means of traffic control that has proved successful is the use of ramp meters to manage entry of vehicles from interchange and service ramps into the main traffic flow on freeways (*Figure 6.1*). With proper simulation of traffic conditions on a main freeway line and on its on-ramps in order to design well-responsive meters and to determine appropriate control approaches, ramp meters serve to eliminate random disruptions of flow of the main traffic by traffic from the ramps and associated conflicts, resulting in a number of benefits including good travel time reliability and even effective ramp queue management. These are even more beneficial if they are designed to operate depending on prevailing traffic conditions (Federal Highway Administration, 2015).

An evaluation of ramp meters in the Twin Cities metropolitan area of Minnesota, US estimated that freeway travel times were twice as unpredictable without ramp meters as with ramp meters and that peak period accidents were 26% higher without ramp meters than with ramp meters. Overall, a benefit/cost ratio of 15 to 1 of the ramp metering system of the metropolitan area was assessed (Cambridge Systematics Inc., SRF Consulting Group Inc., & N.K. Friedrichs Consulting Inc., 2001). Hence it is deduced that even greater travel time reliability benefit could be derived from incorporation of ramp meters at strategic locations along the Northern Corridor Road Segment in Nairobi with system-wide control.

Source: Parsons Brinckerhoff (as cited in FHWA, 2015)
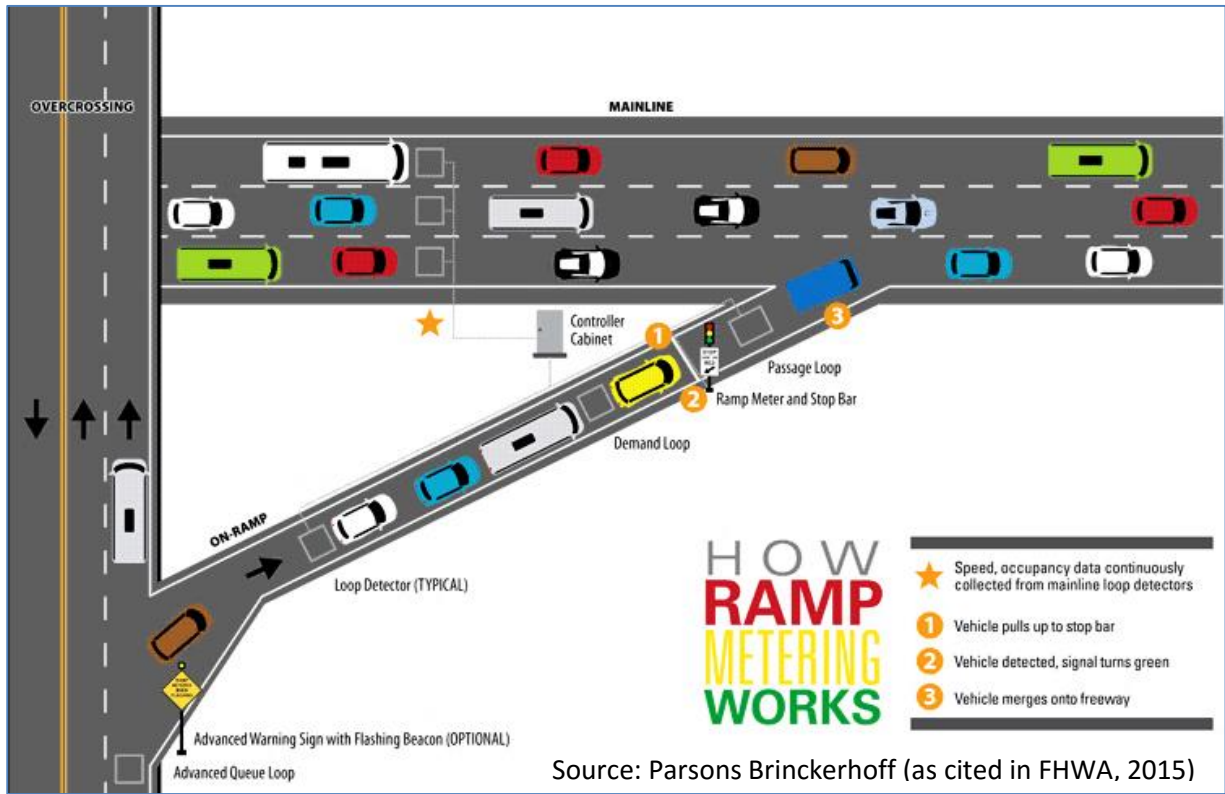
Figure 6.1: Example of ramp metering configuration and how it operates

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

This study determined that the concept of travel time reliability measurement as described in existing research provides various definitions of travel time reliability, associated measurement indices and measurement techniques for quantifying and explaining variations in travel time to establish travel time reliability. The travel time reliability measures of planning time and buffer time were identified along with the travel time measure of mean travel time as suited for producing the study's trip scheduling information. Further also to these three measures, the travel time reliability measure of reliability index (RI) along with the travel time measure of mean travel rate were identified as suited for producing the study's performance evaluation information.

Applying a modelling approach to measurement, the study derived, for the entire Northern Corridor Road segment in Nairobi, freight mean travel times, freight planning times and freight buffer times across fifteen-minute intervals of the day for each day of the week in each direction of travel and in the same breath, for sections along the segment, freight mean travel rates and freight RIs.

Considering the trends of the above information, the following were determined: 1) the ideal freight travel periods within the week on the segment ally to off-peak commuter travel hours and vice-versa; 2) it is over four time more beneficial to transport freight on the segment during periods of high reliability than during periods of low reliability; 3) the segment performs dismally, with section freight buffer sizes of generally double to four times the expected travel times compared to an acceptable threshold of double the expected travel time and to better performing more or less similar function roads around the world; 4) the findings of the study add to those of previous congestion studies of the road segment, first with pointing out the need to treat unexpected delays much as the previous studies pointed out the need to treat expected delays and more importantly with indicating the necessity to consider improvements for dealing with low reliability in addition to those for shortening travel times, which was the focus of the previous studies, lest there occurs a counterproductive result of the goal to relieve the road segment of congestion; and 5) the road sections Haile Selassie Roundabout –

Museum Hill Interchange (both directions), Popo/Kapiti Roads Junction – Haile Selassie Roundabout (North Western direction) and Enterprise Road Junction – Airport North Road Interchange (South Eastern direction) stand out for priority improvements along the road segment.

A display of the trends of freight mean travel time, freight planning time and freight buffer time from the study on the website of the agency responsible for management of the road segment, which is KeNHA, with an optimization of the website to enable viewing on mobile devices was indicated as a platform for freight carriers to easily obtain this information for their planning purposes. The information was also proved still useful in spite of changes that have occurred along the road segment.

The influence factors of the freight travel time and freight travel time reliability performance of the segment and improvement needs thereby were determined as follows: 1) the mainly commute road use of the segment, making a case for truck-only facilities; 2) traffic incidents, justifying the need to put investment into minimizing and managing these; and 3) roadway abuse coupled with inadequate traffic control, calling for improved traffic control and enforcement as integral remedial measures.

It was therefore deduced that the following could be beneficial for addressing the above needs: 1) an exploration of the viability of dedicating the Southern Bypass as a truck bypass road for Northern Corridor freight traffic through Nairobi, considering the current and expected use of it by the said freight traffic compared to other forms of traffic, or of the more moderate approach of establishing exclusive truck lanes along with other truck amenities such as truck lay-bys on the bypass; 2) an incorporation of freight direct access ramps into already proposed Enterprise Road and Likoni Road Interchanges designs; 3) in addition to already proposed and designed strategies of traffic separation; traffic control and enforcement that would prevent accidents, a deliberate effort for developing a comprehensive and well-coordinated traffic incident management programme covering the segment and the Southern Bypass and spearheaded by KeNHA; 4) an incorporation of ramp meters at strategic locations along the segment with system-wide control as an additional means of traffic control.

7.2 RECOMMENDATIONS

Following the conclusions drawn from the study, the following were recommended:

7.2.1 Provision of freight travel time information

Travel time information web pages displaying the charts of freight mean travel time, planning time and buffer time against time from the study were created (*Figure 7.1*) and it is recommended that these be adopted by KeNHA with suitable modifications on their website. It is also recommended that the website be optimized for viewing on mobile devices to give users fingertip access to the information. The time alerts displays should guide users on the ideal and unideal trip cases for each day of the week.

7.2.2 Exploration of truck-only facilities

It is recommended that an exploration of the viability of dedicating the Southern Bypass as a truck bypass road for Northern Corridor freight traffic through Nairobi or of the more moderate approach of establishing exclusive truck lanes along with other truck amenities such as truck lay-bys on the bypass be carried out.

It is also recommended that consideration be given to modifying proposed Enterprise Road and Likoni Road Interchanges designs for including access ramps to be used by trucks only for direct access (*Map 7.1*).

7.2.3 Development of traffic incident management programme

It is recommended that a comprehensive and well-coordinated traffic incident management programme covering the road segment and the Southern Bypass be developed, run by KeNHA and with well-defined and understood roles for other relevant agencies. The main agency should take advantage of opportunities that exist for partnership in the programme with private information service providers who already run traffic update web and mobile applications, including the ma3route team and the Access Kenya Group.
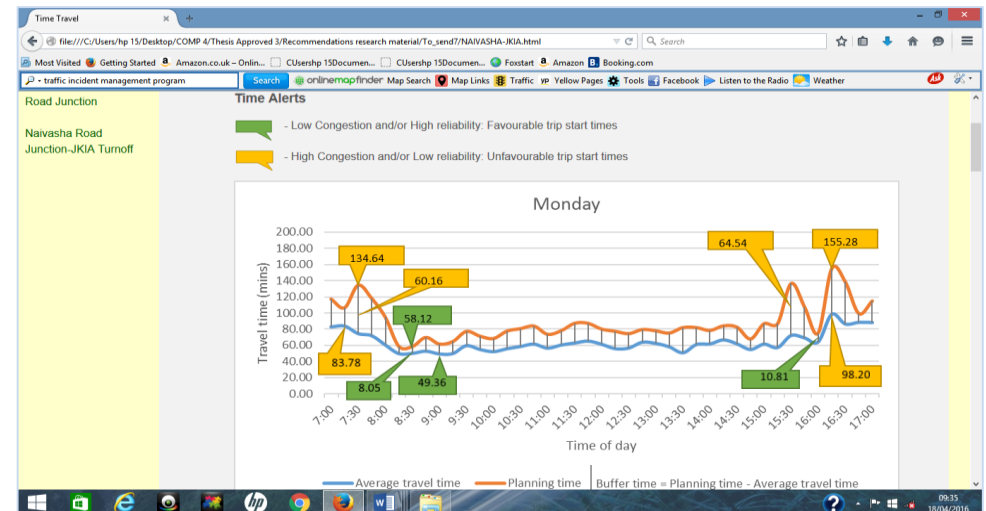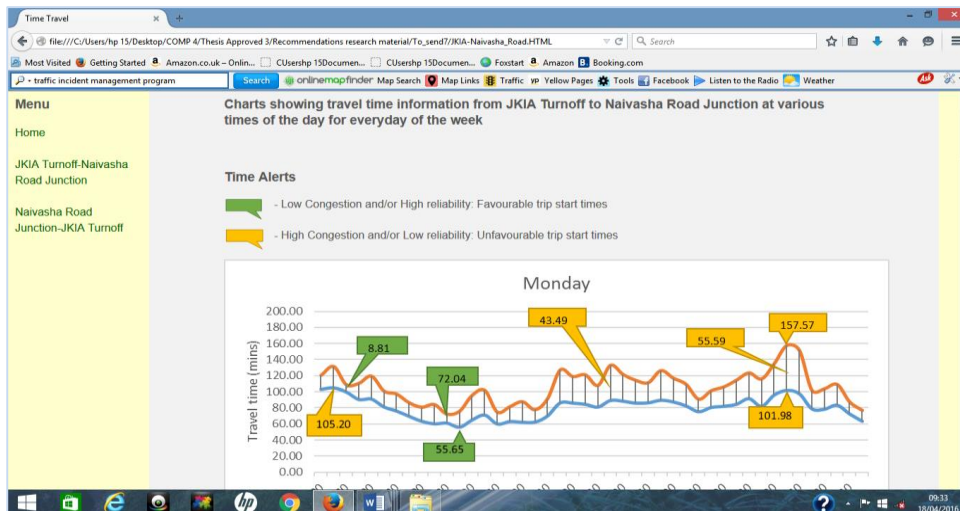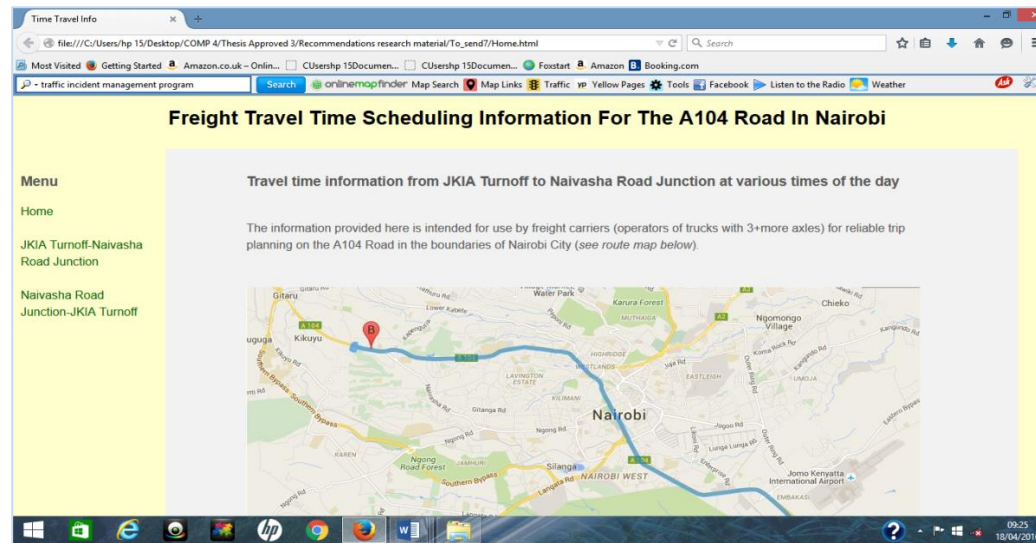
Figure 7.1: Parts of home page of freight travel time information of the Northern Corridor Road segment in Nairobi (top) and time charts display pages of North Western direction (bottom left) and South Eastern direction (bottom right) linked to the home page

Map 7.1: Proposed Enterprise Road and Likoni Road Interchanges with recommended modifications

Text labels within the map:

INDUSTRIAL ZONE

Larger size rotary required to accommodate recommended ramps and service roads connections

Service roads connections

Recommended direct connection of left through lanes of segment to ramp. Service road should underpass this connection.

Existing ICD access road proposed to connect to rotary

Recommended direct access ramps connecting left through lanes of viaduct above to rotary below.

Proposed new ICD access road

Service roads connections

INLAND CONTAINER DEPOT

Map Source: Google Earth, 2016; Image Overlays Source: GIBB Africa Ltd. & Associated Consultants of Ghana (2015)

KEY
Main Study Road
Arterial Road
Southern Bypass
Interchange

Image © 2016 CNES / Astrium
Image © 2016 DigitalGlobe
© 2016 Google
Imagery Date: 3/27/2016   1°19'43.36" S   36°52'05.10" E elev 1642 m

7.2.4 Exploration of ramp metering system; maintenance of traffic control devices

It is recommended that consideration be given to incorporating a ramp metering system on the road segment, covering provision of the ramp metering infrastructure with sufficiently designed ramp meters at strategic locations along the segment to operate depending on prevailing traffic conditions.

It is further recommended that due attention be given to maintaining continuous operation and function of all traffic control devices used on the segment for maximum benefit.

7.2.5 Way forward

Having demonstrated the usefulness of travel time reliability as an information and a congestion diagnostic tool, it is recommended that it be adopted in more studies for provision of travel time information and among the primary performance evaluation tools in future studies of the Northern Corridor Road segment in Nairobi and of other road sections of the corridor as well as other road systems in Kenya.

Provision of travel time information should in fact be adopted by relevant transportation providers as a practice on the above transport systems, in a sustained effort to engage users in more effective use of them. On the other hand, one of the areas that the future performance studies could improve on is the examination of relationships between individual travel time variability factors and travel time reliability, taking into account roadway abuse as one of the variability factors if the results may give strength to enforcement of traffic regulations as a means of promoting good travel time reliability.

To enable easier and more efficient management of the large amounts of travel time and other data required for the recommended studies, advancement of ITS incorporating infrastructure for continuous collection, storage, collation and analysis of data is recommended. A system such as PORTAL that is used in Portland, Oregon in the US could be adopted. This could also easily enable provision of real-time traveler

information through a user interface in the system to give users experience even as circumstances change. Other emerging data collection technologies such as use of drones could also be explored.

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APPENDICES

APPENDIX A

LICENSE PLATE RECORDING FIELD SHEET

LOCATION: …………………………………………… DIRECTION OF TRAVEL: ……………………………………………………..

GENERAL WEATHER: ………………………………………

DAY OF WEEK: …………………………………… DATE: ……………………………………… OBSERVER NAME: ……………………………………………………..

7:00	7:15	7:30	7:45	8:00	8:15	8:30	8:45	9:00	9:15	9:30	9:45	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45	12:00	12:15	12:30	12:45

APPENDIX A

LICENSE PLATE RECORDING FIELD SHEET																							
LOCATION: .... DIRECTION OF TRAVEL:																							
GENERAL WEATHER:																							
DAY OF WEEK: .... DATE: .... OBSERVER NAME:																							
13:00	13:15	13:30	13:45	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45

APPENDIX B

	IRREGULAR CONGESTION CAUSING FACTORS OCCURRENCE LOG			

LOCATION: ……................. **DIRECTION OF TRAVEL:** ………………….. **DATE:** ....

DAY OF WEEK: …………........ **OBSERVER NAME:** ………………….......

IRREGULAR CONGESTION CAUSING FACTOR CODES:

ACCIDENT: A *VEHICLE BRAEKDOWN: B* *DEBRIS ON TRAVEL LANE: D* *SHOULDER/ROADSIDE EVENT: S* *OFFROAD EVENT: O*

TRAFFIC CONTROL MALFUNCTION: M *ROADWORKS: R* *SPECIAL EVENT: E* *EXTREME WEATHER: W*

TIME (hrs)	IRREGULAR CONGESTION CAUSING FACTOR (Code)	PERCEIVED DURATION (mins) – Time from first observation to perceived traffic recovery after clearance	COMMENTS
07:00			
07:15			
07:30			
07:45			
08:00			
08:15			
08:30			
08:45			
09:00			
09:15			
09:30			
09:45			
10:00			
10:15			
10:30			
10:45			
11:00			
11:15			
11:30			
11:45			
12:00			
12:15			
12:30			
12:45			

IRREGULAR CONGESTION CAUSING FACTORS OCCURRENCE LOG

LOCATION: ……..................... DIRECTION OF TRAVEL: …………………... DATE: ....

DAY OF WEEK: …………........ OBSERVER NAME: ………………….......

IRREGULAR CONGESTION CAUSING FACTOR CODES:

ACCIDENT: A	*VEHICLE BRAEKDOWN: B*	*DEBRIS ON TRAVEL LANE: D*	*SHOULDER/ROADSIDE EVENT: S*	*OFFROAD EVENT: O*
TRAFFIC CONTROL MALFUNCTION: M	*ROADWORKS: R*	*SPECIAL EVENT: E*	*EXTREME WEATHER: W*	

TIME (hrs)	IRREGULAR CONGESTION CAUSING FACTOR (Code)	PERCEIVED DURATION (mins) – Time from first observation to perceived traffic recovery after clearance	COMMENTS
13:00			
13:15			
13:30			
13:45			
14:00			
14:15			
14:30			
14:45			
15:00			
15:15			
15:30			
15:45			
16:00			
16:15			
16:30			
16:45			
17:00			
17:15			
17:30			
17:45			
18:00			
18:15			
18:30			
18:45			

APPENDIX C

<table>
<tr><th colspan="4">Example Sample (4:00 - 4:15 p.m. on Monday for Section 1, NW direction)</th><th></th><th colspan="4">Calculation Log</th></tr>
<tr><td>Vehicle Code</td><td>JKIA Turnoff</td><td>Airport North Rd Jn.</td><td></td><td></td><td>Log-normal</td><td>Normal</td><td>Std. normal</td><td></td></tr>
<tr><td></td><td colspan="2">MONDAY</td><td></td><td></td><td>$Time = x$</td><td>$y = \ln(x)$</td><td>$y' = y - \mu_y$</td><td></td></tr>
<tr><td></td><td>Arrival Time</td><td>Arrival Time</td><td>Travel Time (mins)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1</td><td>16:16</td><td>16:25</td><td>0:09</td><td></td><td>9</td><td>2.20</td><td>0.91</td><td></td></tr>
<tr><td>2</td><td>16:17</td><td>16:26</td><td>0:09</td><td></td><td>9</td><td>2.20</td><td>0.91</td><td></td></tr>
<tr><td>3</td><td>16:19</td><td>16:26</td><td>0:07</td><td></td><td>7</td><td>1.95</td><td>0.66</td><td></td></tr>
<tr><td>4</td><td>16:20</td><td>16:21</td><td>0:01</td><td></td><td>1</td><td>0.00</td><td>-1.28</td><td></td></tr>
<tr><td>5</td><td>16:22</td><td>16:24</td><td>0:02</td><td></td><td>2</td><td>0.69</td><td>-0.59</td><td></td></tr>
<tr><td>6</td><td>16:23</td><td>16:25</td><td>0:02</td><td></td><td>2</td><td>0.69</td><td>-0.59</td><td></td></tr>
<tr><td>7</td><td>16:25</td><td>16:31</td><td>0:06</td><td></td><td>6</td><td>1.79</td><td>0.51</td><td></td></tr>
<tr><td>8</td><td>16:27</td><td>16:34</td><td>0:07</td><td></td><td>7</td><td>1.95</td><td>0.66</td><td></td></tr>
<tr><td>9</td><td>16:24</td><td>16:38</td><td>0:14</td><td></td><td>14</td><td>2.64</td><td>1.36</td><td></td></tr>
<tr><td>10</td><td>16:15</td><td>16:16</td><td>0:01</td><td></td><td>1</td><td>0.00</td><td>-1.28</td><td></td></tr>
<tr><td>11</td><td>16:20</td><td>16:21</td><td>0:01</td><td></td><td>1</td><td>0.00</td><td>-1.28</td><td></td></tr>
<tr><td>12</td><td>16:26</td><td>16:27</td><td>0:01</td><td></td><td>1</td><td>0.00</td><td>-1.28</td><td></td></tr>
<tr><td>13</td><td>16:16</td><td>16:20</td><td>0:04</td><td></td><td>4</td><td>1.39</td><td>0.10</td><td></td></tr>
<tr><td>14</td><td>16:17</td><td>16:21</td><td>0:04</td><td></td><td>4</td><td>1.39</td><td>0.10</td><td></td></tr>
<tr><td>15</td><td>16:19</td><td>16:22</td><td>0:03</td><td></td><td>3</td><td>1.10</td><td>-0.18</td><td></td></tr>
<tr><td>16</td><td>16:20</td><td>16:23</td><td>0:03</td><td></td><td>3</td><td>1.10</td><td>-0.18</td><td></td></tr>
<tr><td>17</td><td>16:21</td><td>16:25</td><td>0:04</td><td></td><td>4</td><td>1.39</td><td>0.10</td><td></td></tr>
<tr><td>18</td><td>16:22</td><td>16:28</td><td>0:06</td><td></td><td>6</td><td>1.79</td><td>0.51</td><td></td></tr>
<tr><td>19</td><td>16:23</td><td>16:29</td><td>0:06</td><td></td><td>6</td><td>1.79</td><td>0.51</td><td></td></tr>
<tr><td>20</td><td>16:27</td><td>16:32</td><td>0:05</td><td></td><td>5</td><td>1.61</td><td>0.33</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$Mean\ (\mu_y)$</td><td>1.28</td><td>0.00</td><td>$Mean\ (\mu'_y)$</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$Std.Dev.(\sigma_y)$</td><td>0.82</td><td>0.82</td><td>$Std.Dev.(\sigma'_y)$</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$Mean\ Time\ (\mu_x) =$</td><td></td><td>5.03</td><td>(Eqn. 3.3)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$z_\alpha\ for\ 50^{th}\ percentile =$</td><td></td><td>0</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$z_\alpha\ for\ 95^{th}\ percentile =$</td><td></td><td>1.645</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$Median\ time\ (x_{0.50}) =$</td><td></td><td>3.61</td><td>(Eqn. 3.11)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$95^{th}\ percentile\ time/$ $Planning\ time\ (x_{0.95}) =$</td><td></td><td>13.80</td><td>(Eqns. 2.5 and 3.11)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$Buffer\ time =$</td><td></td><td>8.77</td><td>(Eqn. 2.6)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$Mean\ travel\ rate =$</td><td></td><td>1.94</td><td>$\frac{Mean\ (\mu_x)}{section\ length}$</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>$RI\ (\%) =$</td><td></td><td>282.82%</td><td>(Eqn. 2.10)</td></tr>
</table>