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A GIS Approach to Measuring Public Transport Travel Delay on Higher Order Roads in the City of Cape Town

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Abstract:

On a daily basis, hundreds of thousands of people in the City of Cape Town rely on road-based public transport as a means of commuting. A major factor that influences the passengers' experience is the travel time to reach a desired destination. Due to various physical and operational factors, some sections of the road network experience high congestion and travel time delays during the morning and afternoon peak periods. Quantifying these delays, and the number of road-based public transport passengers exposed to the delay along a specific road section during a peak period allows informed decision-making and prioritisation. GIS and spatial data analysis are powerful tools to determine where and when such delays occur. Various spatial data sets exist that were jointly analysed to quantify the delay and the passenger volumes exposed to the delay on the city's public transport network.

Keywords: public transport, congestion, travel delay, probe data, bottlenecks

1 Introduction

The City of Cape Town experiences very high levels of traffic congestion in South Africa, and according to TomTom's congestion index, the city is ranked as having the second highest levels of congestion in the country after East London and currently ranks at 179 in the world (TomTom, 2021). As the population of the city grows, this situation gets amplified each year as the number of road users also increases. Long queues frequently form on higher-order roads due to downstream bottlenecks (City of Cape Town, 2019). These bottlenecks occur where road-based demand exceeds the capacity of the infrastructure, leading to all lanes being utilised at full capacity. Such a situation causes the operational speed to drastically reduce, leading to an increase in travel times (City of Cape Town, 2019).

Given the significant number of public transport users in the city (City of Cape Town, 2019), it is crucial to understand how and to what extent longer travel times affect the duration of public transport trips. It is important to note that the purpose of the study was not to develop a new method for measuring congestion but rather to utilise an existing method of assessing congestion in the city and correlate it with the number of passengers affected by these delays. The novelty of this approach, therefore, lies in determining the number of road-based public transport users spatially during morning and afternoon peak hours, and then analysing passenger volumes along with travel delays to rank public transport bottlenecks. While standardised data formats such as General Transit Feed Specification (GTFS) exist and are utilised by some public transport operators in South Africa, these formats do not provide real-time information on the actual number of passengers per vehicle (Google Transit, 2023). Hence, alternative sources of passenger data needed to be considered. A Geographic Information System (GIS) is an ideal tool for addressing these inquiries due to the availability of essential spatial datasets, as well as the ability to segment the road network and peak hours spatially and temporally.

2 Background

2.1 Public Transport In The City of Cape Town

Cape Town, similar to many other urban centres in South Africa, is experiencing rapid population growth, with an increasing demand for travel (City of Cape Town, 2019). Most residents rely on public transport to gain access to economic, social, educational, medical, recreational, and other activities. In 2017, more than 70% of people in the lowest income group were reliant on public transport and more than 50% in the low-medium income group (City of Cape Town, 2019). Public transport is an absolute necessity for a significant part of the population.

However, the transport system is challenged by the fact that the majority of public transport trips are undertaken by Road Based Public Transport (approximately 70% for work trips) *i.e.*, using minibus taxis (MBT, 46%) and buses (23%) (City of Cape Town, 2019). Rail is estimated at 28% but the overall quality, reliability, and availability of rail

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services are deteriorating, and commuters rely more and more on MBTs and buses (City of Cape Town, 2019).

These challenges reduce access and mobility of residents and impact the economic and social advancement of its residents A key measurement of poor performance of the transport network is traffic congestion, especially along major public transport routes during the morning and afternoon peak hours. Identifying these key routes and quantifying the negative impacts of congestion on public transport users is important to assist in prioritising and mitigating these issues.

2.2 The Use Of Probe Data For Measuring Travel Delays And Congestion

Probe data refers to the positional and temporal data that is collected from a global positioning system (GPS) enabled onboard device that tracks a vehicle's location over time, typically for anti-theft purposes. Multiple studies have been conducted to establish the reliability of probe data for accurately capturing congestion trends (Lattimer & Glotzbach, 2012, Jia, et al., 2013, Coifman & Seoungbum, 2013, Kim, et al., 2011). However, the most common forms of congestion detection methods are radar detection and loop detection. The downside to these methods is that they are not as geographically scalable and readily available as probe-based speed measurements (Adu-Gyamfi, et al., 2015). Lattimer & Glotzbach (2012) illustrated that on average there is an 8 – 9 km/h difference between probe speed data and ground truth (measured by radar/loops). In a study conducted by Jia, et. al. (2013) on a rural low-volume road, it was found that the mean absolute error between probe speed data and ground truth was roughly 6%.

Latency also plays a role in probe speed accuracy, as has been found by Coifman & Seoungbum, (2013) and Kim, et al., (2011). They discovered that time-lags could sometimes be as high as 10 minutes, shifting the phase of the speed curve and reducing the temporal accuracy of reported probe speeds. However, correcting for such latency could increase the accuracy of the probe speeds to an absolute error of approximately 2.5 km/h compared to ground truth.

It has also been shown by Adu-Gyamfi, et al., (2015) that there exists a positive correlation between the accuracy of congestion trends from probe data and the length of time over which data is collected. The longer the data collection period, the higher the accuracy of the congestion trend. The accuracy also differs for different road classes. The accuracy is roughly 74% and 63% on freeways and non-freeways for short-term measurements (events with a duration of 15 to 30 minutes), and this increases to 95% and 68% on freeways and non-freeways for medium-term measurements (events with a duration of one to three hours)

Long-term congestion patterns (recurring on a weekly and monthly scale) are the trends that this study focussed on and was found to be accurate for detecting general trends over time. Although a median error of 6km/h was observed, phase relationships were perfectly synchronized for both probe data and ground truth measurements with a correlation coefficient of 0.93 (Adu-Gyamfi, et al., 2015).

3 Purpose and Objectives

The purpose of this study was to identify the bottlenecks on the road network that are most heavily affected by congestion-induced delays and have the highest number of impacted public transport passengers.

The main objectives were to utilise available spatial information to:

1. Quantify and verify travel delays on the road network using real-time speed information obtained from probe data.
2. Determine and validate the actual number of public transport passengers on the road network using onboard survey data and other traffic count information.
3. Calculate the total passenger delay experienced at each bottleneck and rank them in order of priority, from highest to lowest.

4 Data Source and Data Collection

This section provides an overview of the data sources that were used in the execution of this study. Table 1 lists the data sources. Note that the analysis was based on pre-COVID-19 conditions, therefore only data sources up to February 2020 were included in the analysis.

Section	Data Source	Description	Time Period
4.1	Screenline counts and cordon counts	Classified daily traffic counts and respective passenger occupancies across the City	2016 - 2017
4.2	Intersection Counts	Intersection traffic counts across the City	2015 - 2020
4.3	Bus Onboard Surveys	Surveyed all bus routes across the day over a 6-month period. Information on the number of trips per route, as well as boarding and alighting passenger information per route.	2016 - 2017
4.4	MBT Onboard Surveys	Onboard surveys of all routes, but only a sample of vehicles along each route. No info on how many trips per route. Boarding and alighting information	2018

		on each passenger along each route.	
4.5	In-Vehicle Probe Data	Annonamised private vehicle tracking information provided by Tracker	February 2020

Table 1: List of Data Sources

4.1 Screenline And Cordon Counts

Multi-modal cordon count survey data from 2017/2018 were extracted from the City's available database to understand the extent of public transport vehicles and passengers entering and leaving specific areas. The available information per count location included vehicle volumes per mode, occupants in both public and private transport vehicles (by service provider), and pedestrian volumes crossing the cordon or screenline. The vehicles were classified and recorded by mode, travel direction, and occupancy in 15-minute intervals (from 05:30 to 19:00).

Screenline surveys were also undertaken on pre-defined locations on certain road corridors to determine traffic flows across screenlines in the City. The survey information and method of recording were the same as for the cordon counts. Passenger volumes and the distribution per 15-minute interval for the morning and afternoon peak periods were extracted from these screenline and cordon counts. Distributions were graphed and analysed at a suburb level, combining both MBT and bus passenger volumes.

4.2 Intersection Traffic Counts

Innovative Transport Solutions has access to a database of historical traffic counts at many intersections across the city. Information from these intersection counts was used to confirm public transport and general traffic volumes along the specific public transport routes. The database of intersection counts included traffic volumes for each approach, and also turning movements for at least the two peak periods of the day, but sometimes for longer periods up to eight hours. Respective count information was extracted for the last five years (up to February 2020). The shorter-duration traffic counts were extrapolated to the full study peak periods using extrapolation factors determined from longer-term counts at nearby intersections.

4.3 Bus Onboard Surveys

A comprehensive survey of all bus routes was undertaken in 2016/2017. The survey was completed over a period of 6 months. Every trip along all bus routes was surveyed with details on the passenger load and off-loading at every bus stop. Surveyors recorded information for all routes on a GPS-enabled device and all trips were monitored at least once, with the reverse directions constituting separate trips.

For the purposes of this study, average passenger volumes per peak period per route were extracted from these surveys to quantify the number of bus passengers per road section (the sum of all passengers of all routes travelling along the same road section). This was done per the direction of travel to ensure both peak- and off-peak passenger movements are captured and accurately mapped.

4.4 Minibus Taxi Onboard Surveys

A city-wide on-board minibus taxi (MBT) survey was undertaken in 2017/2018 to understand network coverage, route profiles and passenger information of Cape Town's MBT services. For each MBT route, data was collected for a minimum of three MBT trips in the morning peak (05:30 – 09:30) as well as in the afternoon peak (15:30 – 18:00) and a minimum of two MBT trips in the off-peak period (11:00 – 15:00). These routes are typically fixed between an origin and destination, with some route variations occurring on lower order roads.

Since the dataset included only three surveyed trips per MBT route per peak period it is not possible to determine the total ridership (demand) on MBTs as was possible to do with the bus data. Therefore, the total MBT passengers per route had to be estimated. This was done using the number of bus vehicles along the route as a proxy for the number of MBT vehicles along the same road section, provided that MBTs were surveyed along the specific road section. The details of this methodology are described in Section 5.

4.5 In-Vehicle Probe Data

One of the main objectives of this study was to identify locations where public transport vehicles are exposed to congestion and the extent of this congestion. For this reason, in-vehicle probe data was used to identify and quantify congested road sections along the major public transport routes. The information was provided by Tracker South Africa. Tracker is a vehicle tracking company which offers personal vehicle tracking and comprehensive fleet management to customers throughout Southern Africa. The sample size for February 2020 across the study area was 54 582 unique vehicles and 244 336 231 unique positional coordinates, each recorded with a speed, date/time, and direction. Note that this was a pre-COVID-19 period and was specifically selected as such. The onboard technology allows reporting of the location of each vehicle to an accuracy of at least five metres, but generally more accurately. The temporal resolution of the data was generally less than one minute per consecutive data point per vehicle. The data was stored in a relational database management system (Google Bigquery) and could be spatially queried using structured query language (SQL).

5 Methodology and Analysis

The methodology for calculating passenger delay using the spatial data sources referred to in Section 4 can be outlined as follows:

1. Define a road network and covert it to a spatial database
2. Calculate average speeds and travel delays on the road network using probe data
3. Calculate the number of public transport passengers on the road network
4. Calculate the total passenger delay per road section
5. Rank bottlenecks from highest to lowest passenger delay

5.1 Definition Of The Road Network

Congestion may occur on small spatial scales, and it was therefore decided to use 100 metres as the maximum length for road sections. OpenStreetMap centrelines were used as the base network and were split up into sections with lengths of a maximum of 100 metres.

The directionality of the road links was necessary when calculating the average speeds and average number of passengers per direction. Each link was therefore assigned an average bearing attribute (degrees clockwise from north). In the cases where there was only one centreline representing both directions in the base network, these links were duplicated and their directionality reversed, to represent traffic moving in the opposite direction. Only Class 1, 2, 3 and 4 road sections were included since these routes typically accommodate public transport. These links were then uploaded as a spatial database in Google Bigquery.

5.2 Average Speeds And Travel Delay On Road Links

In order to calculate the average speed on each 100-metre link, a spatial SQL query was used that evaluated probe data points within 20 metres from each link. An average speed was calculated for each 15-minute interval in the morning (5:00 – 10:00) and afternoon (15:00 – 19:00) peak hours. Only data points for typical weekdays (Tuesdays, Wednesdays and Thursdays) were considered, and the bearing (travel direction) of the probe data points had to match the bearing of the underlying route section to maintain directional integrity. The coverage of probe sample data and representativity thereof were investigated to ensure the correct application of the data.

The definition for congested speeds corresponds to a level of service E, as per the Highway Capacity Manual (Anon., 2016). Level of service is a measure of congestion and is ranked from A to F, where A is free flow conditions and F is the most congested. Level of service E indicates that the amount of traffic is high, and the average speed is dropped to 20 - 30 per cent of free flow conditions, indicating the driver's comfort, patience and convenience as poor.

Based on this definition of congestion, a road link was considered congested if the average speed on the link fell below the following thresholds:

- Principal Arterials/Freeways (Class 1): < 30 km/h
- Major Arterials (Class 2): < 25 km/h
- Minor Arterials (Class 3): < 20 km/h
- Collector streets (Class 4): < 20 km/h

In order to calculate the delay, the free-flow speed of each link had to be known. This was calculated by taking the average of all 15-minute intervals where the speed limit is above the congested speed threshold. Once the free-flow speed was calculated per 100-metre link, the delay per 15-minute interval was calculated by taking the difference in free-flow speed and congested speed (formula 1). The section length was then divided by this speed differential to get the delay in minutes for each road section per 15-minute interval (formula 2).

1) $\Delta V_{7:15-7:30} = V_{free-flow} - V_{avg.\ 7:15-7:30\ (when\ below\ congestion\ threshold)}$

2) $Delay_{7:15-7:30} = \frac{Section\ Length}{\Delta V_{7:15-7:30}}$

5.3 Number Of Public Transport Passengers On The Road Network

The calculation of the number of public transport passengers was broken down into three steps:

- Calculation of the number of bus passengers
- Calculation of the number of MBT passengers
- Scaling the total number of public transport passengers to 15-minute intervals

5.3.1 Number Of Bus Passengers For The Entire Peak Period

In order to understand the passenger demand on each link, it was necessary to pre-process the bus onboard survey data. For each bus route surveyed, a spatial tracks file was available in shapefile format. From the survey, the average number of passengers on each route was calculated across the entire peak period (the data is not accurate to the nearest 15-minute interval). This was then joined to the route shapefile. Due to the route shapefile having been created from a GPS tracks file, the directionality of travel was available for each route. In order to get a direction match with the underlying base network, each bus route was broken up into sections with a maximum length of 100 metres and was assigned an average bearing attribute.

Since duplication of a route occurs by splitting it up into 100-metre sections, a single unique bus route section was joined to the underlying base network section only once. This removed the potential double-counting of passengers per duplicated route. The bus link was spatially intersected only if the bearing of the 100-metre bus route was similar to the bearing of the 100-metre base network section. Once all bus route sections were spatially intersected with the underlying base network sections, the average passengers

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per route were summed to get the total number of bus passengers from all routes per 100-metre base network section for the entire peak period. The breakdown of bus passenger volumes per 15-minute interval was still unknown at this stage.

5.3.2 Number Of MBT Passengers For The Entire Peak Period

Since the total population of MBT passengers was unknown, bus passengers were used as a proxy for MBT passengers. Buses and MBTs typically share the same routes due to the fact that they mostly serve the same major origin-destination pairs, and this was verified using the onboard survey data. To use bus passengers as a proxy, intersection traffic counts (see Section 4.2) across the City were analysed. At each count location, the number of buses and MBTs were known for a given peak period. This could be used to calculate a ratio of bus-to-MBT passengers, using 41 as the average bus occupancy and 14 as the average MBT occupancy in the peak period, as derived from the onboard survey data.

Due to discrete count locations across the city, zonal boundaries were defined that covered the road network extent and an average bus-to-MBT passenger ratio was calculated per zone. This ratio was then carried over to all 100-metre links contained in the zone and applied to the bus passenger count in order to derive MBT passengers on the same link. The result was the total number of MBT passengers from all routes per 100-metre base network section for the entire peak period. The breakdown of MBT passenger volumes per 15-minute interval was still unknown at this stage.

5.3.3 Total Public Transport Passengers Per 15-minute Interval

Since the number of bus and MBT passengers had been calculated per link for the entire peak period, it was necessary to scale the total count to a corresponding demand profile per 15-minute interval. These profiles were obtained from the cordon and screenline counts that were available city-wide. A distance matrix was calculated from each link's centroid to the five nearest cordon/screenline locations. The five nearest demand profiles were then averaged and assigned to the link as a percentage distribution of passengers per 15 minutes, for bus and MBT passengers respectively.

These profiles made it possible to respectively redistribute the total bus and MBT passengers per peak period to an estimated passenger count per 15-minute interval on each 100-metre link. This ensured that the temporal granularity for both the delay information, as well as the passenger information was the same and therefore comparable.

5.4 Total Passenger Delay On The Network

With the delay and passenger count known on each 100-metre link for each 15-minute interval of the peak periods, it was possible to calculate the passenger delay for the whole peak period by multiplying the delay with the passenger count for each 15-minute interval, and then adding all the passenger delay for all 15-minute intervals in the given peak period. The calculation can be seen in formulas 3 and 4.

3) $$Delay_{total\ AM} = \sum_{n=1}^{20} Delay \times Total\ Passenger\ Count$$

4) $$Delay_{total\ PM} = \sum_{n=1}^{16} Delay \times Total\ Passenger\ Count$$

where n represents the product of the delay and passenger count for each 15-minute interval (5:00, 5:15, …, 9:45 for the morning, and 15:00, 15:15, …, 18:45 for the afternoon). The total passenger minutes lost were then calculated for each 100-metre base network section per direction and peak period.

The next step involved visually examining the outcome on a map to identify and group sections of the network that were impacted by that same bottleneck. These bottlenecks typically occur at busy intersections or freeway segments where traffic merges. To determine the total passenger minutes lost caused by each bottleneck, the passenger minutes lost for all 100-meter links associated with the same bottleneck were added together. Finally, the bottlenecks were ranked based on the extent of passenger delay, from the highest to the lowest.

6 Results

All the results obtained in the study were mapped using ArcGIS Online. This platform allowed end users to interactively engage with the data and zoom/pan to locations of interest for closer inspection. Although both peak periods were analysed, only the results for the AM peak period are shown in this paper.

In Figure 1, the minutes lost per passenger per direction per 100-metre link for the morning period are shown. This figure illustrates the magnitude of delay due to congestion. Workshops were held with city officials that had a good understanding of traffic flow across the City, and they confirmed that the areas highlighted in the study correlated well with known congested links during peak periods.

In Figure 2, the total number of public transport passengers during the morning peak period is shown. These passenger volumes were calculated following the methodology outlined in Section 5.3. To ensure accuracy, the derived passenger volumes were compared with ground truth data, including cordon, screenline, and intersection count data. This comparison was used to confirm that the passenger volumes obtained through spatial analysis accurately reflected realistic passenger volumes across the entire public transport network.

Using the data shown in Figure 1 and Figure 2, the total passenger minutes lost could be calculated for each link as described in Section 5.4. The result is shown in Figure 3. Certain 100-metre links were then grouped together if they were caused by the same bottleneck, and the passenger minutes lost for all these individual links were summed to get the total passenger minutes lost for the entire bottleneck. This result can be seen in Figure 4, where the top 40 bottlenecks are represented by the sections of the road that they impact.

For the purposes of this paper, these bottlenecks were mapped as lines with graduated thickness without indicating the actual priority as determined in the study.

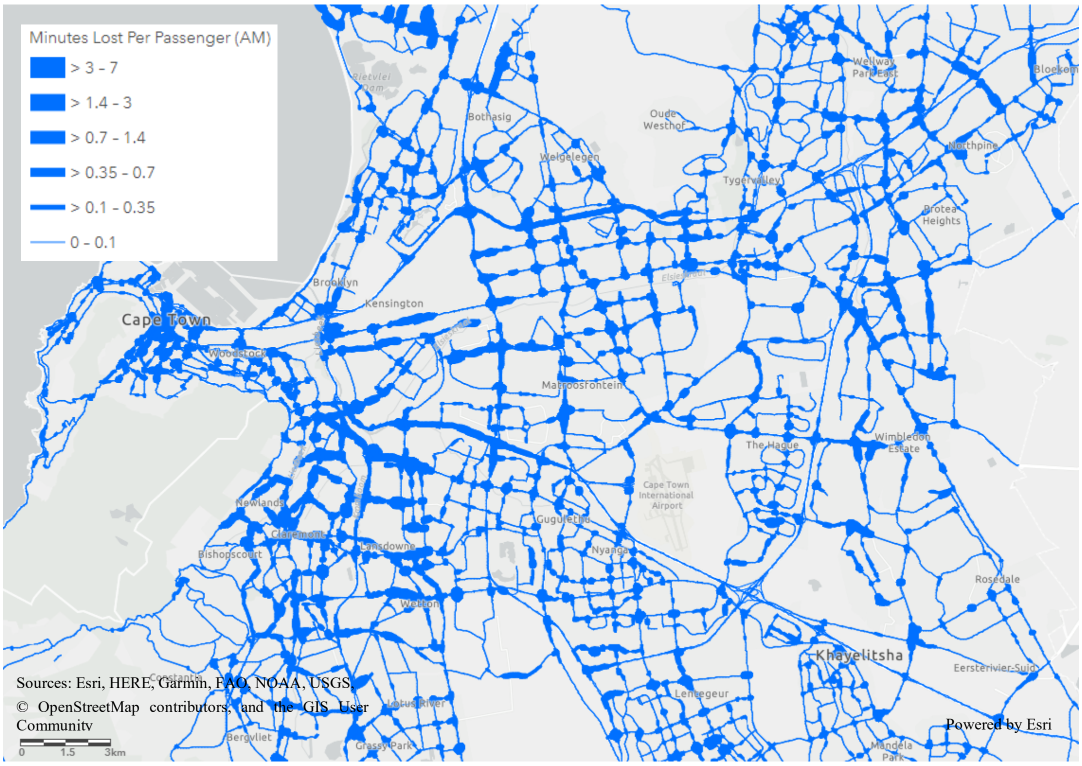

Figure 1: Total minutes lost per passenger per 100-metre link per direction (5-hour Morning Peak Period)

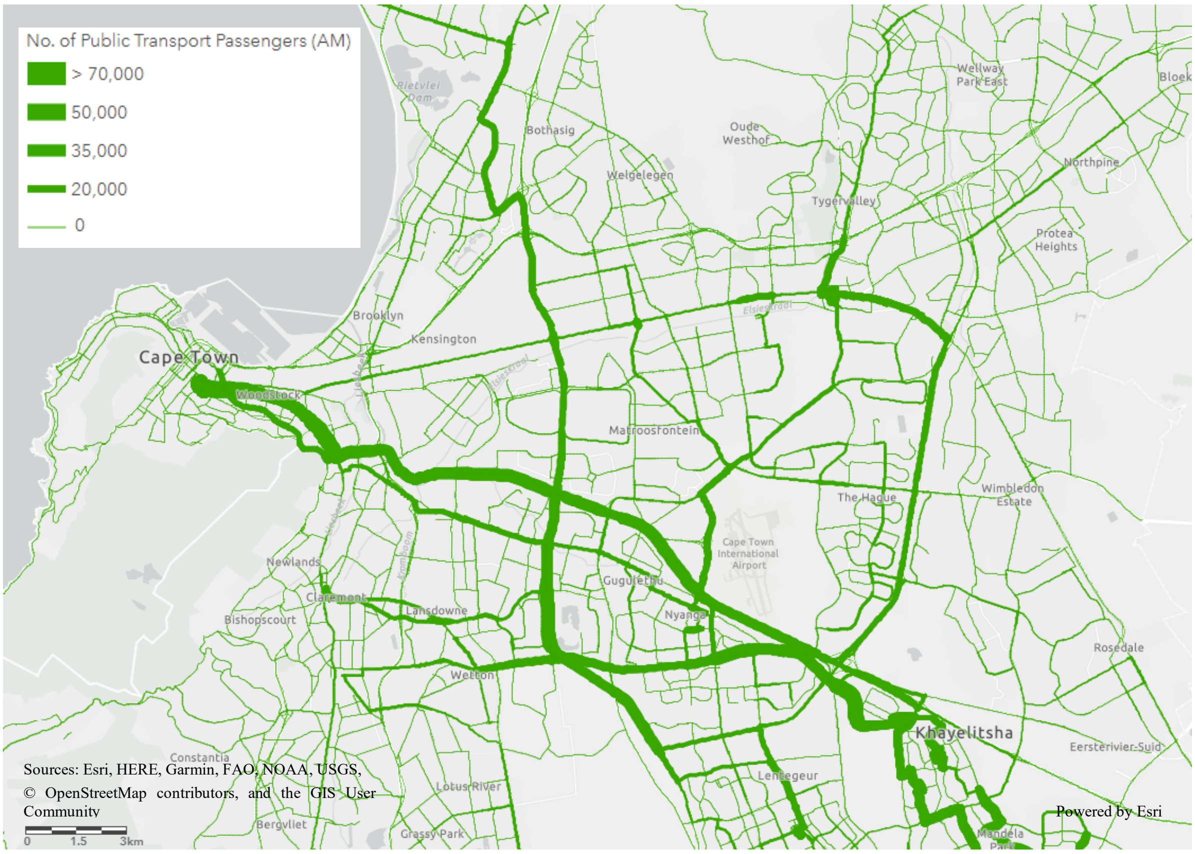

Figure 2: Total public transport passengers per 100-metre link per direction (5-hour Morning Peak Period)

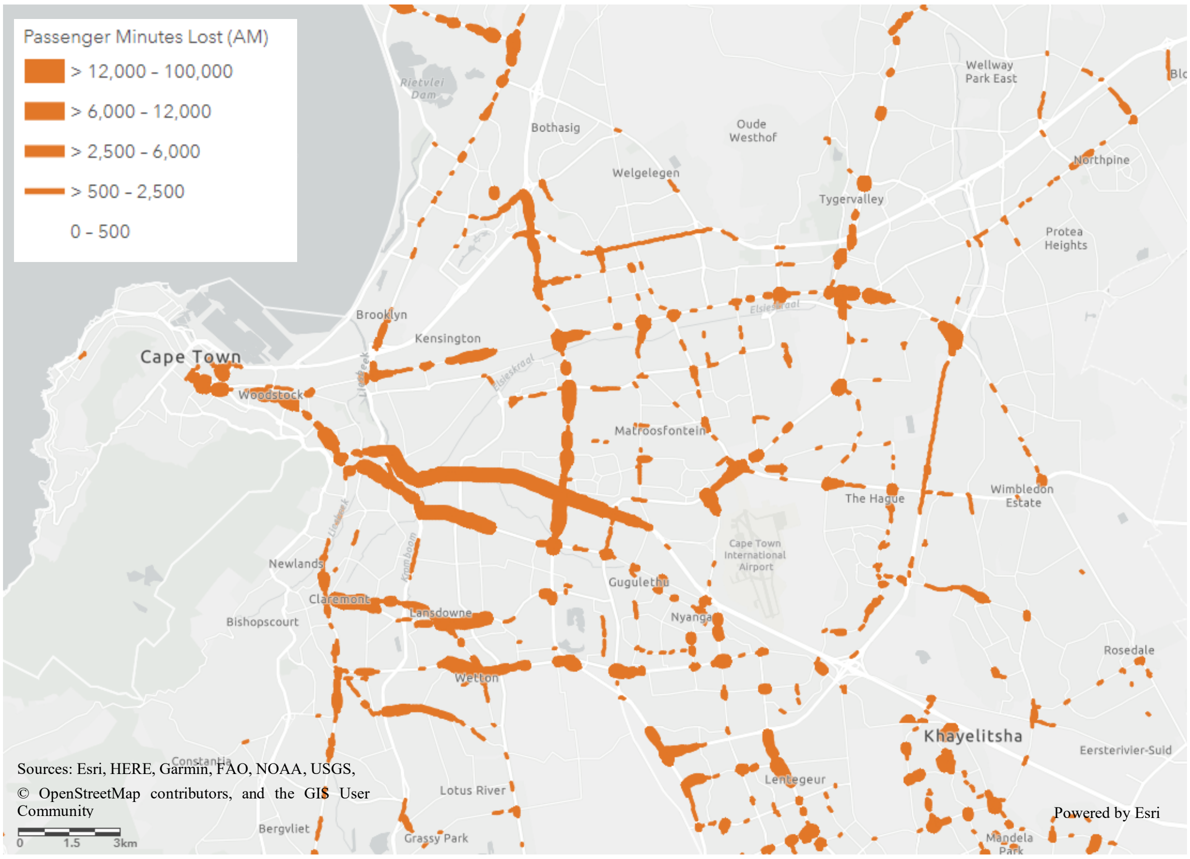

Figure 3: Total passenger minutes lost per 100-metre link per direction (5-hour Morning Peak Period)

Figure 4: Top 40 road-based public transport bottlenecks ranked by total passenger minutes lost

7 Summary and Conclusion

The growth and development as well as the influx of people to Cape Town have exceeded the rate at which transport infrastructure and systems have been provided in order to cope with the resulting travel demand. This, coupled with the decline of the passenger rail service over the last few years has resulted in a sharp increase in the road-based travel demand, further impacting negatively on the congestion levels to which both public and private transport are exposed. The congestion in Cape Town is well known and the impact it has on commuters, especially public transport users, is noteworthy.

Spatial analytical methods were successfully used to quantify traffic congestion and delay and calculate and estimate the total number of public transport passengers based on available survey data and count information. Although standards such as GTFS are used by some formal public transport operators, no standardised method of recording the total number of road-based public transport passengers in real-time currently exists, especially for MBT passengers. Therefore it was necessary to conduct bus and MBT onboard surveys and spatially analyse the passenger volumes.

The mere size of the probe database (244 336 231 records) necessitated the use of a relational database environment since such large data volumes cannot be effectively processed or analysed in local GIS desktop software from files such as shapefiles or CSV files. Thus, in order to draw congestion trends from available probe data, all the relevant data sets were converted to spatial databases, which could then be analysed and compared using spatial SQL queries in Google BigQuery.

The study identified and prioritised 40 locations which were clearly causing delays to most road-based public transport users. In many instances, the delays were also experienced by general traffic and any upgrades aimed at improving public transport movements would also improve the operations of general traffic.

Firstly, based on the unique analytical approach followed in this study it was possible to identify and evaluate priority locations on an equal footing and on a city-wide scale. Secondly, the impact of these locations could be quantified systematically. This allowed a fair comparison among the locations and an assessment of actual impacts. Thirdly, it allowed prioritisation of these locations based on the total adverse impacts of the locations. The methodology can be easily reapplied to identify and prioritise more locations for other cities in the future, given that the necessary onboard surveys are conducted to quantify passenger volumes on the road network.

8 List of Acronyms

COVID-19	Corona Virus Disease 2019
CSV	Comma Separated Value
GIS	Geographic Information System
GPS	Global Positioning System
GTFS	General Transit Feed Specification
MBT	Minibus Taxi
SQL	Structured Query Language

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