Optimizing Bus Routes in Nicosia

Haris Gavranović[*] Tijana Stojančević[†] Milena Kresoja[‡]
Marcos Charalambides[§] Peep Miidla[¶] Georgia Lynott[‖]
Amy Mallinson[**] Ioannis Kyriakides[††]

July 31, 2017

Team participants
Haris Gavranović, International University of Sarajevo, Bosnia, haris.gavranovic@gmail.com
Tijana Stojančević, University of Novi Sad, Serbia, tijana.stojancevic@uns.ac.rs
Milena Kresoja, University of Novi Sad, Serbia, milena.kresoja@dmi.uns.ac.rs
Marcos Charalambides, Sharpnote, Cyprus, marcos.charalambides@gmail.com
Peep Miidla, University of Tartu, Estonia, peep.miidla@ut.ee
Georgia Lynott, University of Manchester, UK, georgia.lynott@postgrad.manchester.ac.uk
Amy Mallinson, University of Manchester, UK, amy.mallinson@postgrad.manchester.ac.uk
Ioannis Kyriakides, University of Nicosia, Cyprus, kyriakides.i@unic.ac.cy

The problem was presented by
Andreas Athanasiades, General Manager at OSEL (Transportation Organization of Nicosia District), Cyprus

at the **125th European Study Group with Industry (ESGI125)**
(1st Study Group with Industry in Cyprus, www.esgi-cy.org)

Abstract

In this report the conclusions by the team of experts that took the "Transportation Organization of the Nicosia District (OSEL)" challenge are provided. The challenge was to identify ways to improve efficiency of the bus network and increase the utilization of the network by the public. A thorough analysis

[*] International University of Sarajevo, Bosnia, haris.gavranovic@gmail.com
[†] University of Novi Sad, Serbia, tijana.stojancevic@uns.ac.rs
[‡] University of Novi Sad, Serbia, milena.kresoja@dmi.uns.ac.rs
[§] Sharpnote, Cyprus, marcos.charalambides@gmail.com
[¶] University of Tartu, Estonia, peep.miidla@ut.ee
[‖] University of Manchester, UK, georgia.lynott@postgrad.manchester.ac.uk
[**] University of Manchester, UK, amy.mallinson@postgrad.manchester.ac.uk
[††] University of Nicosia, Cyprus, kyriakides.i@unic.ac.cy (Corresponding author)

of the various factors that affect bus route planning is provided. Moreover, a demonstration of a simplified route planning problem is described in order to motivate further work on this topic. Recommendations are provided to the company on the way to move forward towards solving the problem of creating a bus network with increased efficiency and grater appeal to the public. Specific recommendations include the collection of a larger amounts of data that can be used to generate models used in simulation analysis. Data include demographic data on bus usage and bus usage preferences by the public. In addition, data is required on bus travel times, walking distance to the nearest bus stop by the commuter, and traffic data.

Keywords: Bus route planning, constrained optimization

1 Introduction

Nicosia, the capital of the Republic of Cyprus, is the only divided capital in Europe. This, combined with the narrow streets towards the centre of the city, a lack of data and a lack of popularity of public transport, makes it very difficult to create and run a successful bus network. The Transportation Organization of the Nicosia District (OSEL) hopes that if the bus network were more efficient it would be more appealing to the public by covering more population while reducing commute time.

There have been many academic papers published on the transit route network design problem due to its relevancy. According to [1] the problem is usually approached by using practical guidelines and ad hoc procedures, analytical optimization models or meta-heuristic methods. If the most basic approach is used and the transport route network is designed using ad hoc procedures and practical guidelines then there is no guarantee that the resulting network is not far from optimal. Equally analytical optimization models are only suitable for idealized situations. This is because the problem is NP hard, combinatorially complex and can be non-linear. On the other hand meta-heuristic approaches are able to find locally optimal solutions.

According to both [1] and [2] the heuristic approaches used to tackle the transit route design network problem vary according to the specific nature of the case at hand as most transit route design problems involve maximising or minimising some form of cost function that encapsulates the specific constraints, requirements and wishes of the case at hand. Common algorithms/methodologies include the genetic algorithm, local search, simulated annealing, random search, the nearest first search method and the tabu search method. This means that most approaches are highly dependent on the problem solvers local knowledge and intuition. Common problems that occur involve over simplification and incorrect assumptions. However when a meta-heuristic model works well the real life benefits can be great. For example [3] tells the story of a small town in the North of England with a population of 103,000 which recorded an estimated loss of 35,000 in 1965-6. Here the current bus network had essentially remained the same for the last thirty years but the main industrial and residential locations had changed. In fact most of the service frequencies were based on the ferry services which were carrying less than half the number of people than thirty years previously. It was estimated by the authors of [3] that their new bus network could make annual savings of about 36,500.

In this work we propose a general framework for improving both the efficiency of public transport and its appeal to the commuters. The framework includes an optimization problem with constraints that takes into account bus network resources, distribution of population to be served and user preferences. The formulation of the framework has yielded the need for acquiring more data from the bus network such as accurate bus travel times, distances between bus stops etc, and public needs to be served such as population distribution and demographics and commuter preferences. In addition, an optimization methods is applied based on available population distribution data to produce bus routes alternative to the ones currently used. The method applied has the goal to maximize people transfer rate in order to both satisfy serving more people and reducing travel times.

2 Framework

2.1 Cost Function

In this section we propose an approach for solving network design problem in public transportation in Nicosia. The problem of interest can be formulated as an optimization problem with constraints. We give general framework for developing an objective function. The objective function that we propose allow incorporating various operators, user components, resources and the impacts of transportation on the users.

The proposed objective corresponds to the users overall cost and it includes two main parts: walking cost and utility bus cost. Walking cost is associated to the walking time of a single person to the bus stop. In its straightforward version, the utility bus cost corresponds to the traveling time on the bus. Both costs are associate to the single persons. However, they can be aggregated by neighborhood or by part of the neighborhood. Therefore, we minimize the following objective function

$$u = \sum_{i \in N} \omega_{walk}^{i} t_{walk}^{i} + \sum_{i \in N} \omega_{bus}^{i} t_{bus}^{i}, \tag{1}$$

where:

- N - number of passengers
- $\omega_{walk}^{i}, \omega_{bus}^{i}$ - coefficients that represent passenger cost associated to walking and bus utility respectively
- $t_{walk}^{i}, t_{bus}^{i}$ - travel time associated to walking and bus utility respectively.

This approach can be further extended by minimizing the following objective function

$$z = c \sum_{k,j \in M} f_P(k,j), \qquad (2)$$

where

- $f_P(k,j)$- passengers' cost function
- c - coefficient that represent passenger cost
- M - number of OD pairs k, j (OD is abbreviation for origin destination matrix).

The passengers' cost function $f_P(k,j)$ in (2) can be formed to reflect users' cost that include walking time and bus tun time like in (1). In addition, it can include waiting time and transfer time. Therefore, the general form of the function is

$$\sum_{k,j \in M} f_P(k,j) = \sum_{r \in R} \sum_{k,j \in M} [d_{kj}(t^{kj}_{walk} + t^{kj}_{wait} + t^{kj}_{bus} + t^{kj}_{transfer})], \qquad (3)$$

where

- R - set of all routes
- d_{kj}- demand from stop k to j
- $t^{kj}_{walk}, t^{kj}_{wait}, t^{kj}_{bus}, t^{kj}_{transfer}$ - walking, waiting, bus and transfer time that each passenger experiences.

In order to make both objective functions, (1) and (2), more realistic and sensitive to the needs of the stakeholders (decision makers and users), we can develop objective functions further. It can be done by incorporating measures of a service quality.

A suitable way to quantify quality measures is to interview local people (current passengers, potential passengers, etc). We will present two survey approaches from the literature that can be good starting point. For instance, measures can be classified into three main groups as shown in Table 1.

The most important issue in analyzing quality measures of public transportation is to estimate weights of passengers perceived quality. Figure 1 shows results obtained from one study in Helsinki. The authors examined the importance of service quality attributes for public transport. It can be concluded that perceived total quality of public transportation is results of combined effect of objective and subjective factors in individual travel experiences accumulated over longer period of time. The objective factors are for example travel time, travel cost, etc. As shown on Figure 1, route network and travel time have the most important influence on passengers. This fact verifies our proposal for the objective functions. The lowest weight was assigned to interaction between passengers.

We also provide a global literature review of different approaches. It is given in Figure 2.

Table 1: Service quality measures [4]

Non-use reasons	Use reasons	Service quality attribute
Long wait at bus stops;	Inexpensive service;	Frequency;
Overcrowded buses;	Quick service;	Number of bus stops;
Low frequency;	Car nonavailability;	Cleanliness of interior, seats, etc.;
Slowness of vehicles;	Lower risk of road accidents;	Comfort on bus;
Service unreliability;	Difficulty of car parking;	Security against crimes on bus;
Need for transfers;	Practicality (less tiring trip);	Availability of shelter at stops;
Difficulty of carrying loads;	No driving license;	Availability of benches at stops;
High fare;		Availability of seats on bus;
Poor accessibility to bus stops;		Information on services;

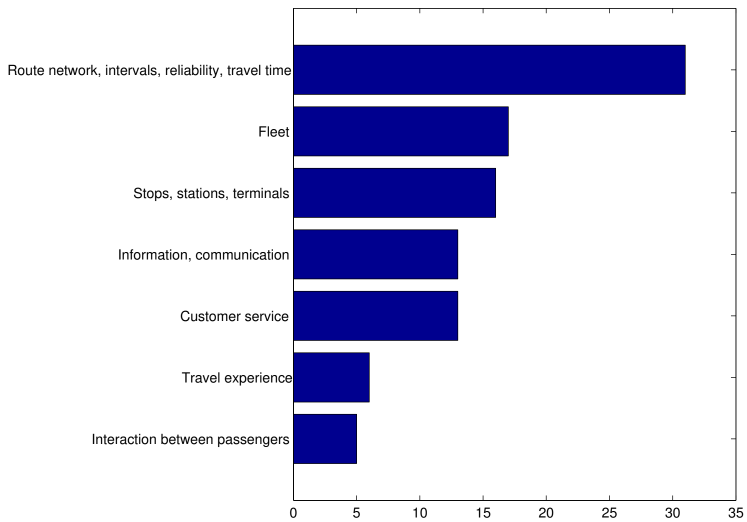

Figure 1: Weightings of perceived total quality of public transport by quality theme (%) [5]

First Author	Year	Problem	Me.	Objectives	Constraints	Application	Specificity
Patz	1925	TNDP	H	Number of empty seats	Bus capacity, Demand	Small example	Optimal on specific example
Lampkin et al.	1967	TNDFSP	H	Number of direct passengers, Total travel time	Fleet size	Ex: G.-B.	Skeleton method
Salzborn	1972/80	TNFSP	M	Fleet size, Passengers waiting time	Passengers arrival rate	-	Feeder service
Silman et al.	1974	TNDFSP	H	Fleet size, Journey time, Overcrowding	Budget	Ex: Haifa	Skeleton method
Rapp et al.	1976	TNSP	H	Transfer optimization	-	Ex: Basel	Interactive graphics system
Sonntag	1977	TNDP	H	Average travel time, Number of transfers	Restricted set of possible lines	Ex: Dusseldorf	Railway
Mandl	1979	TNDP	H	Routes directness, Travel time	Constant frequency, Service coverage	Example	Urban
Bel et al.	1979	TNDFSP	H	Passengers total travel time	Budget	2 ex (France)	Replanning problem
Hasselstrom	1979/81	TNDFSP	M	Number of transfers, Number of passengers	Budget	Software	Variable demand
Scheele	1980	TNFSP	M	Passengers travel time	Capacity, Fleet size	-	-
Furth et al.	1982	TNFSP	M	Number of passengers, Waiting time	Fleet size, Maximum headway, Budget	Example	-
Han et al.	1982	TNFSP	H	Minimizing the maximum "occupancy level" at the maximum load point for each route	Fleet size, Capacity for each route	-	Trip assignment to overlapping routes
Koutsopoulos et al.	1985	TNSP	M	Waiting time, Operator costs, Vehicle crowding	Fleet size, Capacity per route	Simple ex.	-
Ceder et al.	1986	TNDFSP	H	Excess travel time, Transfer and Waiting time, Vehicle costs	Minimum frequency, Fleet size, Route length	Theoretical	Public transit process model
Klemt et al.	1987	TNTP	H	Transfer synchronization	-	Example	QSAP modelling
Van Nes et al.	1988	TNDFSP	M	Fulfil the demand, Number of direct trips	Fleet size	Example	-
Pape et al.	1992	TNDP	H	Number of lines, Number of direct passengers	Service coverage	Ex: Dusseldorf	Concept of corelines
Bookbinder et al.	1992	TNTP	O	Waiting time	Routes network, Fixed headways	Theoretical	Random travel times
Xiong et al.	1993	TNDP	E	Total travel time, Cost	-	Benchmark	Network improvement
Shih et al.	1994/98	TNDFSP	O	Travel time, Satisfied demand, Fleet size	-	Example	Trip assignment model for timed transfer terminals
Constantin et al.	1995	TNFSP	M	Users total expected travel and waiting time	Fleet size	Examples (3)	Urban
Daduna et al.	1995(a)	TNTP	NS	Transfer time	Lines, Frequencies	Examples	-
Baaj et al.	1995	TNDFSP	O	Number of direct trips, Waiting time, Transfer time	Headway, Fleet size, Capacity	Ex: Austin	Skeleton method
Chakroborty et al.	1995/97/98	TNTP	E	Passengers total waiting time	Fleet size, Maximum headway, Stopping time bounds, Maximum transfer time	Simple example	Several cases are studied
Bussiek	1998	TNDFSP	M	Number of direct passengers, Operator costs	Level of service, quality, Number of resources	Examples	Railway, Periodic schedules
Carrese et al.	1998	TNDFSP	H	Users waiting time and excess time compared to minimum path, Operator costs	Demand satisfaction, Routes length, Number of transfers, Total travel time, Fleet size	Ex: Rome	Urban
Pattnaik et al.	1998	TNDFSP	E	Operator costs, Passengers travel time	Headway, Load factor	Example	Urban
Dhingra et al.	1999	TNDSP	E	In-vehicle travel time, Number of buses and standees, Demand satisfaction, Walking time	No transfers, Headway bounds, Maximum load factor, Fleet size, Routes length limits	Simple	Feeder service
Lee et al.	2000	TNDFSP	H	Users travel time	Network, Fixed total demand	-	Variable trip demand
Chowdhury et al.	2001	TNFSP	H	Transfer coordination	Fleet size, Capacity	Example	Intermodality
Chakroborty et al.	2001	TNTP	E	Transfer coordination (waiting time), Fleet size	Total fleet size, Stopping time, Headways, Transfer time	Theoretical	Fleet size considerations
De Palma et al.	2001	TNTP	M	Riders' total schedule delay costs	Desired boarding times	Theoretical	Single transit line
Ceder et al.	2001	TNSP	H	Number of simultaneous arrivals	Headway bounds	Examples	Simultaneous arrivals
Chakroborty et al.	2002	TNDP	E	In-vehicle time, Unsatisfied demand, Number of direct, 1-transfer, 2-transfer passengers	Road network	Benchmark	-

Figure 2: Transit Network Design And Scheduling:a Global Review, Guihaire&Hao, godina

Independent Inputs **Data to have**	**Planning Activity**	**Output**
Route performance indicators Demand data Supply data	**Network design**	Route changes New routes
Subsidy available Buses available Service policies Current patronage	**Frequencies setting**	Service frequencies
Demand by time of day Times for first and last trips Running times	**Timetable development**	Trip departure times Trip arrival times

2.2 Origin-Destination Matrix

As seen in formulation of the objective function (2), a special issue is an origin-destination (OD) matrix. By definition, OD matrix describes the flow of people. In other words, it consists of travel flows from each origin to each destination in the considered network. The most used way to estimate elements of OD matrix is to conduct surveys. Surveys can be conduct on board, when questionnaires are distributed to passengers. The questionnaires consist of questions regarding origin and destination information. Using the responses, the elements of the matrix are estimated.

3 A Simplified Optimization Approach

In addition to creating a high-level framework which would give the company a basis for further investigation, we attempted to produce a much simplified version of the network optimization problem which demonstrates some of the key features of the solution method. The problem was formulated as a network optimization problem, with a set of nodes based on current bus stop locations that were weighted according to the surrounding population density. We ignored questions of frequency and focused solely on the optimal placement of a route between a given origin and destination. A simplified cost function was then formulated based on maximizing the flow rate of population along a route. We then chose to implement a tree-based search algorithm in order to optimize the selection of nodes for a single bus route.

3.1 Choosing and weighting nodes

The company provided us with a list of the geographical locations of the current bus stops, which we chose to use as the nodes for our network. In addition, we were able to obtain the population distribution for the city by post code area. The nodes were assigned a weight according to the surrounding population: we first matched each bus stop to its corresponding post code area, and then distributed the population in that area equally amongst all the bus stops (i.e. nodes) in that area. The result was a set of 800 nodes, denoted N, located at the current bus stops, each given a weighting w_i. It was then possible to define the people transfer rate for a pair of nodes N_i, N_j, as

$$\rho_{ij} = \frac{w_i}{t_{ij}},$$

where t_{ij} denotes the travel time (by bus) for a user between the node N_i and N_j. An additional assumption is that the distance between bus stops was taken to be the Euclidean distance and a constant average bus travel velocity including stops was considered. In a future implementation both population per node and travel distance and time can be improved by using data on these quantities.

3.2 The objective function

Since the company's concern was with improving service to customers, we chose to ignore operator costs in the first instance, and lacking detailed knowledge about the demand of the user base, we sought to simplify the problem by assuming demand for trips from a node to be directly proportional to the number of citizens living in the vicinity of that node. Thus, we wanted to find routes that would maximize service by passing through densely-populated areas, whilst minimizing the total travel time for customers to their destination. We therefore sought to maximize the sum of the "people transfer rate", ρ_{ij}, between each pair of nodes in a route route, based on the population distribution at each node and the travel time between the nodes, so the value of the mth bus route, r_m can be quantified as

$$\max_m R_m = \sum_{i=1}^{N-1} \rho_{i,i+1}.$$

where N is the total number of bus stops in path m.

3.3 Finding optimal routes

We chose to implement a decision tree based approach, with pruning to reduce computational complexity, which finds an optimal route between a given start and terminal point. There are limitations to this method— it still requires the manual selection of origin and terminus points for each route, and the routes are calculated sequentially rather than being considered as a whole — but we required a method which could be easily implemented.

We illustrate the tree algorithm with an example, as shown in Fig. 3.

The algorithm proceeds as follows:

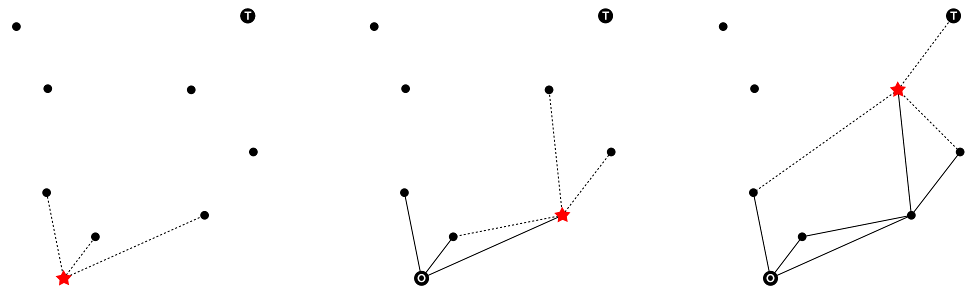

Figure 3: Tracing the progression of the algorithm one node at a time - for the current node (starred) the 3 nearest nodes are identified and added to a new possible path.

1. Starting at the origin node, identify the 3 nearest neighboring nodes.
2. Each of the nearest nodes is added to a new path, which is stored in a set of possible paths $\mathcal{P}$.
3. For each path in $\mathcal{P}$, identify the 3 nodes nearest to the end node that are not already contained in the path. Create 3 new paths by adding each node to the current path.
4. For each of the new paths:
   (a) If the new path exceeds the maximum path length p_max, remove ('prune') this path from $\mathcal{P}$.
   (b) If the new path now includes the terminal node, add this path to the set of solution paths $\mathcal{S}$.
   (c) If the new path does not exceed p_max and does not include the terminal node, add this to the set of possible paths $\mathcal{P}$ and continue with step 3 until all paths in P have been pruned or added to $\mathcal{S}$.
5. The cost function is evaluated for each solution path in $\mathcal{S}$ and the best paths are selected and presented to the user.

The pruning technique is illustrated in Fig. 4. This mechanism, combined with the restriction that a path cannot revisit a node, will decrease the computational cost of the algorithm somewhat, but the number of paths to be explored in a network will still grow exponentially as more nodes are added. This is typical of network optimization problems, and makes finding a globally optimal solution impossible in most cases. Our approach could be improved in future by employing a meta-heuristic algorithm, such as the tabu search, which can help prevent back-tracking and revisiting nodes by use of a memory function.

3.4 Results for optimal route selection using the simplified approach

Next the results of the optimal route selection using a simplified approach are outlined. As mentioned in Section 3.3 the method will iterate over paths originating at

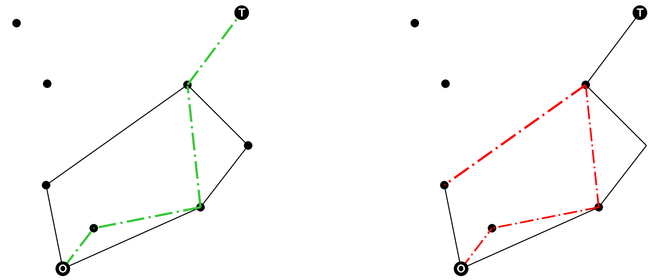

Figure 4: An example of pruning in the algorithm - the network on the left shows a solution path in green, which joins the origin to the terminal node without exceeding the maximum distance. On the right, the path in red has exceeded the maximum distance and is eliminated (pruned) from the set of possible paths.

a pre-specified stop until they terminate at the final destination (central station). Paths that either drift away from the central station are pruned and a set of possible paths that terminate at the central station are marked as valid and remain for consideration. Valid paths are sorted based on maximum transfer rate. Transfer rates and and other useful information on the paths such as total distance and estimated travel times are provided to a human user. A human user, which is considered to be an experienced operator is then able to provide their additional expertise in order to select one of the best routes that satisfies any other additional criteria or preferences. A set of origin and destination stops was taken to be the current route ’100’. The improvement in transfer rate per people currently reported is three-fold. Considering that a number of approximations were taken to obtain this improvement the study group considers this improvement as a motivation for further investigation of this problem. In order to visualize the process and the original versus the final chosen path the location of all bus stops is plotted along with the current path, iterations of the decision tree-based method, and final path for Route ’100’ are plotted. In Figure 5 the current route ’100’ is plotted. In Figures 6, 7, 8, 9, 10, 11, 12, 13, and 14 the best path is shown for each iteration of the algorithm. The best path is the one with maximum transfer rate and is selected among other high transfer rate paths which are saved in the algorithm memory and continue to evolve. Therefore, paths shown at each iteration differ as the best path in each iteration is selected among the pool of best paths. Finally, two paths that produced large people transfer rates are provided in Figures 15 and 16.

4 Conclusion and Recommendations

During the week we have outlined the various factors that should be taken into account by the company when designing efficient bus routes. We have found the design of a bus network to be a complex process which we have formulated as an optimization problem with constraints. We have identified that, in order to be able to achieve a solution to the problem, more information needs to be provided to an optimization algorithm due to the many dependencies that exist when designing bus routes. A demonstration of a solution to a simplified version of the optimization

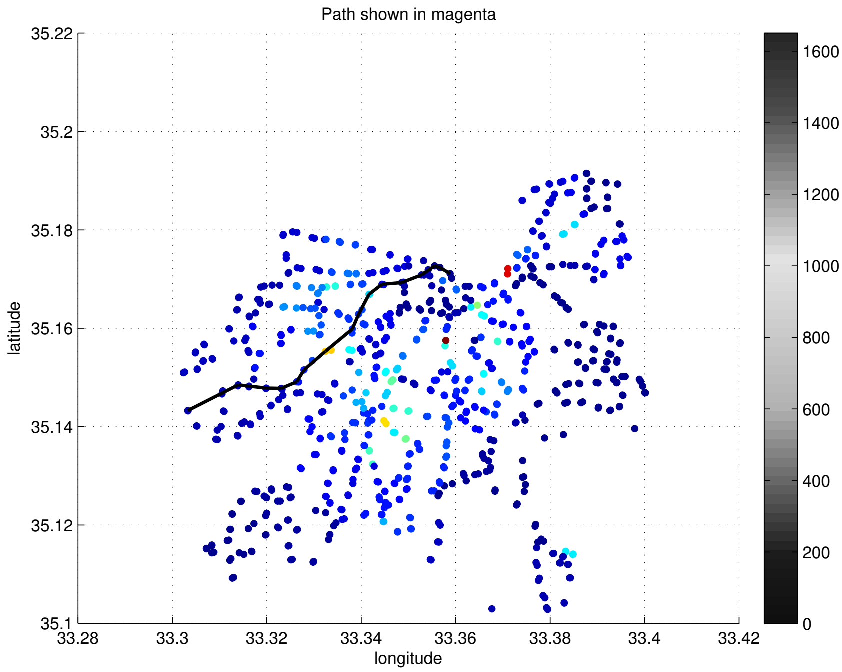

Figure 5: Current Path (Route 100).

problem was created to motivate the further development of a software solution and the collection of more data from the existing bus network. We propose that the company consults experts in mathematics, engineering, and computer science to plan a project of data collection, formulation of the optimization problem, and software implementation in order to create a dynamic method of assigning bus routes based on the various factors identified in this report. Finally, the specific data collection recommendations are provided below.

Data collection recommendations

A recurring issue which came up was the lack of data that was fine enough to build sufficiently accurate models. Collecting appropriate data should, therefore, be a priority for the company going forward.

We propose gathering information at the neighbourhood level that includes demographics (age, gender, etc.) as well as where people choose to travel to around the city. This data can then be used to build an accurate origin-destination matrix. The Cyprus Statistical Service has some recent data on population breakdown and demographics by administrative areas as well as some data from a 2009 survey on people's movement preferences. Nonetheless, conducting a new, up-to-date, dedicated survey to collect finer information would be ideal.

In addition to constructing an origin-destination matrix, it is also necessary to have an accurate distance metric. The principal measurements required are bus travel times and walking times; ideally, sufficient data should be gathered so that these can be determined between any pair of points in Nicosia. A good first approximation would be to use the Google Maps API which would allow the company to query approximations to walking times and driving times between any pair of

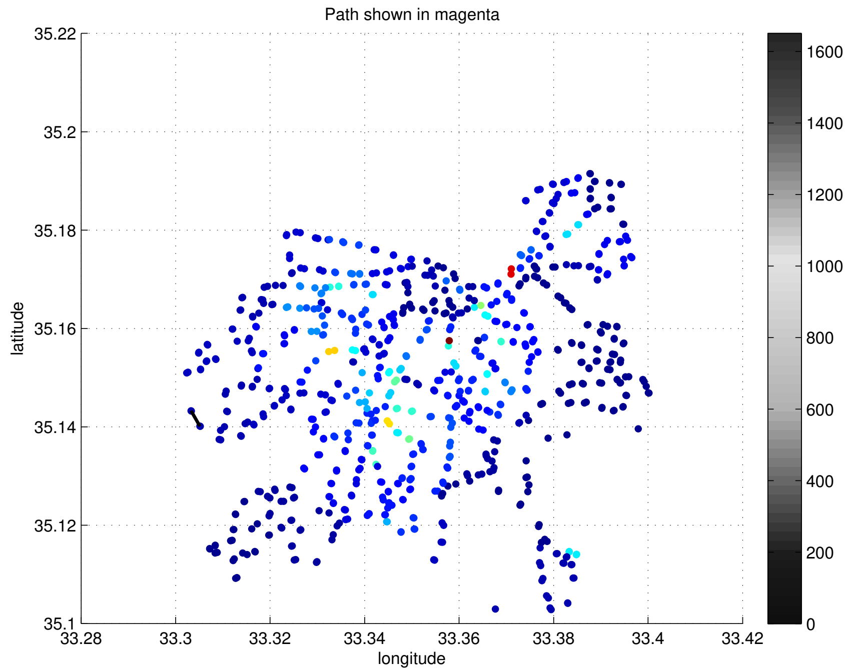

Figure 6: Path Identification Process.

points.

Finally, it would be invaluable to have information on how traffic varies and evolves during the typical week. The new GPS tracking system which is currently being implemented by the company may be able to address the need for detailed traffic data to a high degree. A better solution could be to collaborate with one of the traffic data service providers (for example, www.traffic4cyprus.org.cy) to obtain this data.

Acknowledgements

The Organising Committee of ESGI125 would like to thank the Mathematics for Industry Network (MI-NET, www.mi-network.org), COST Action TD1409 for generous funding and support with the logistics of this first Study Group with Industry in Cyprus. Many thanks also to the Cyprus University of Technology that provided venue, organisational and funding support, as well as to all our other sponsors and supporters, and particularly KPMG Cyprus (major sponsor).

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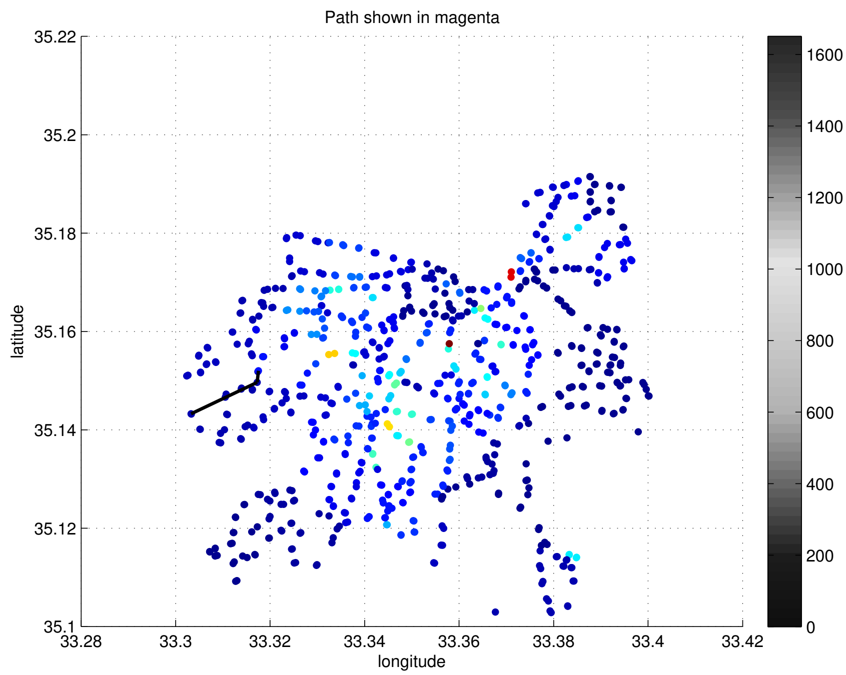

Figure 7: Path Identification Process.

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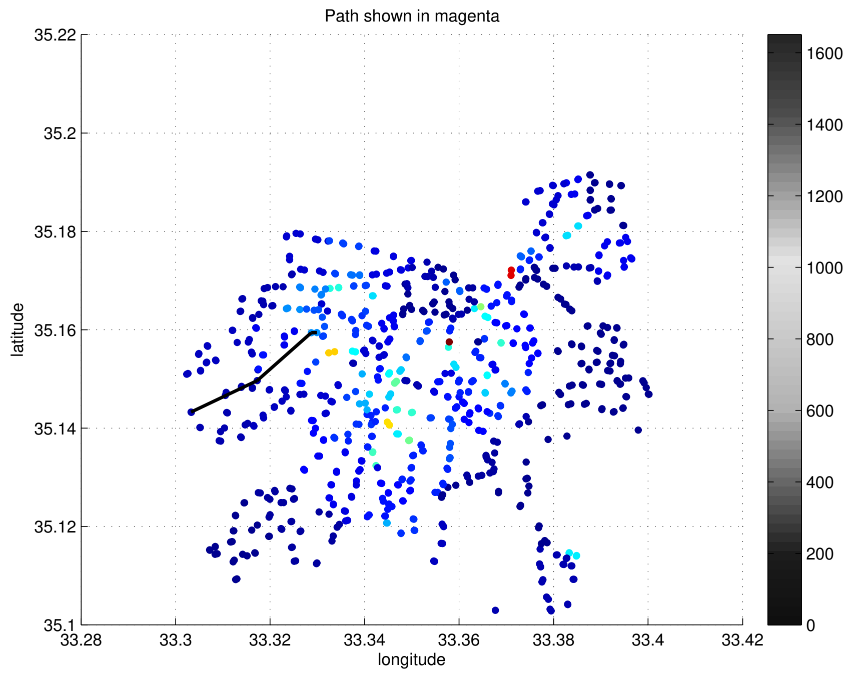

Figure 8: Path Identification Process.

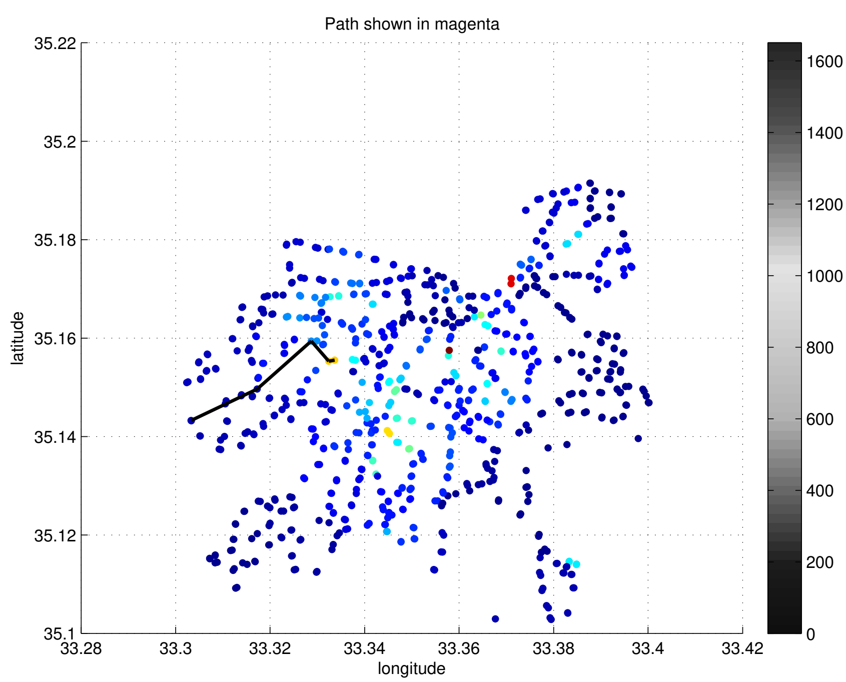

Figure 9: Path Identification Process.

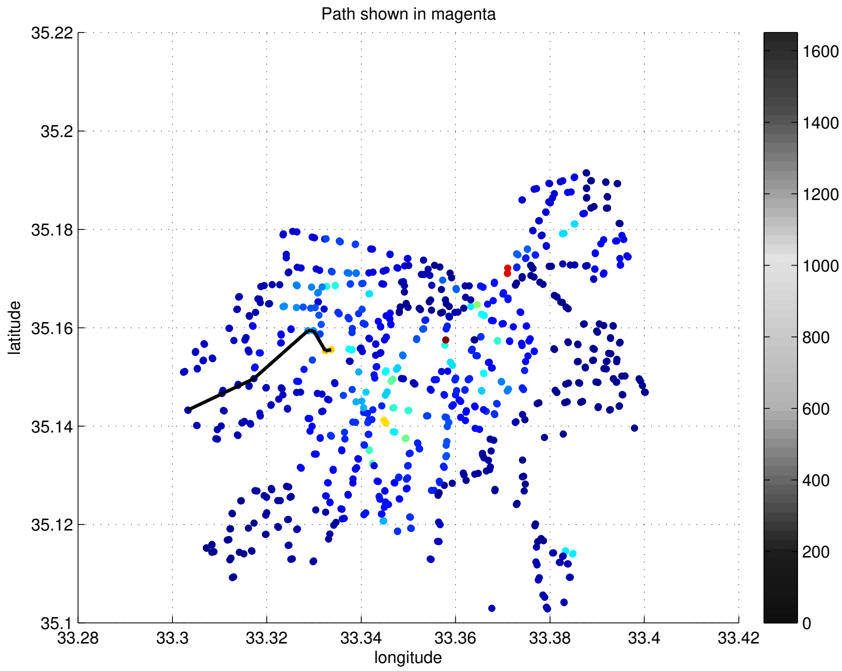

Figure 10: Path Identification Process.

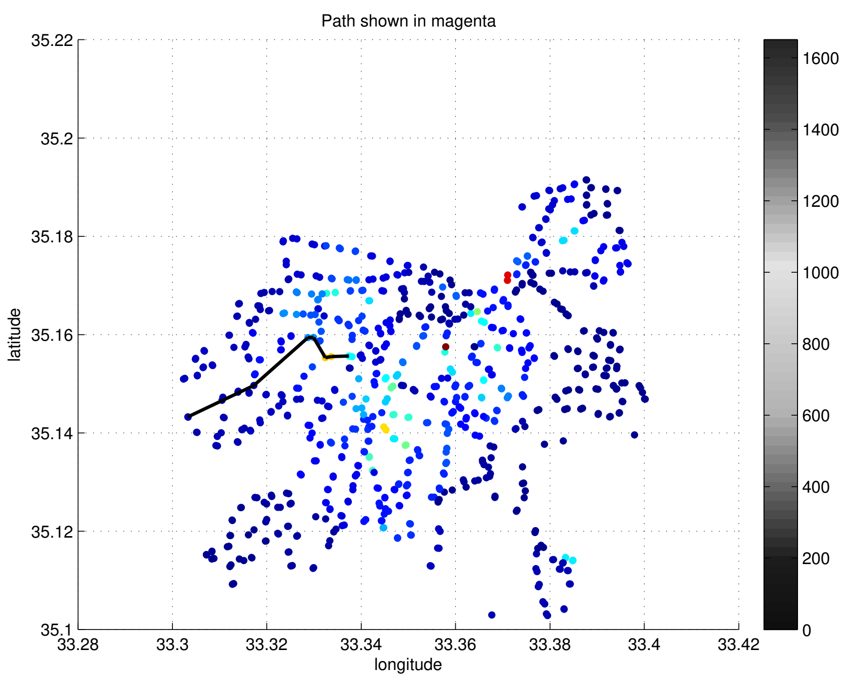

Figure 11: Path Identification Process.

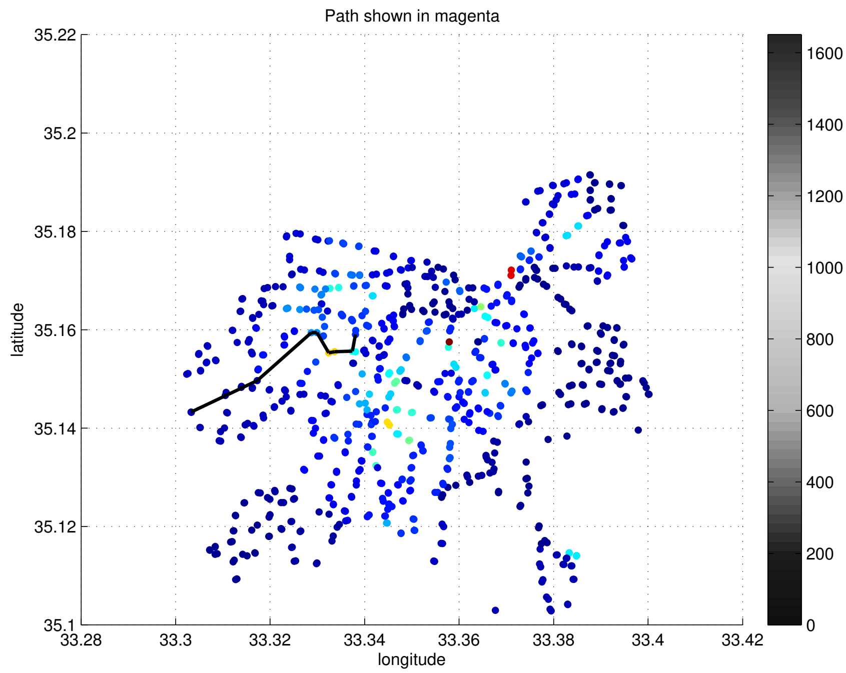

Figure 12: Path Identification Process.

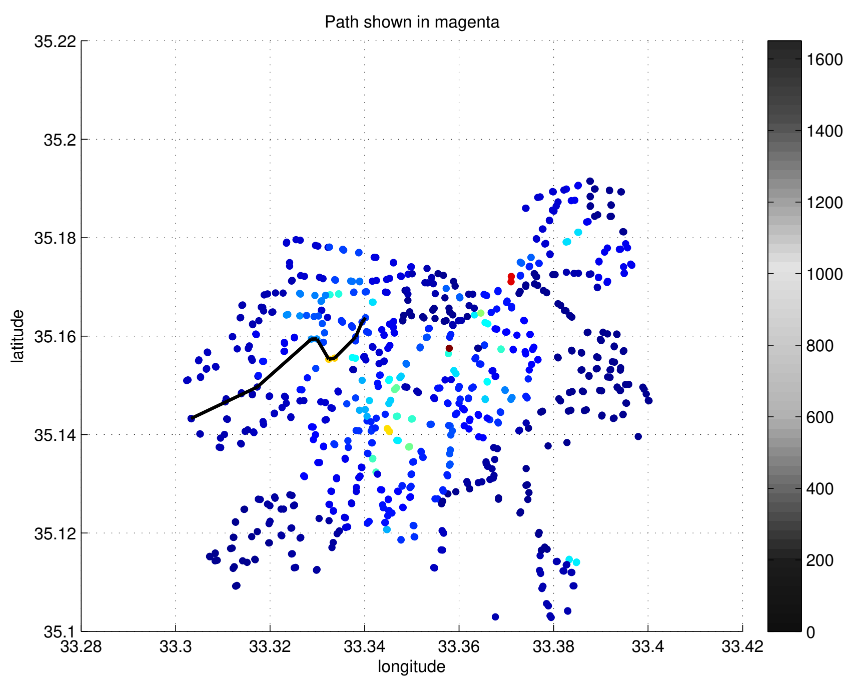

Figure 13: Path Identification Process.

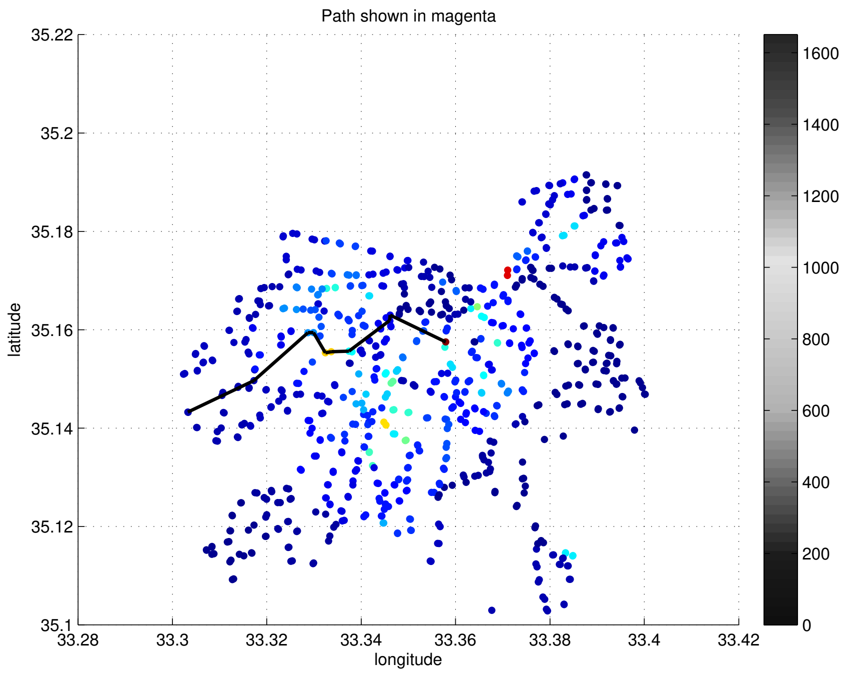

Figure 14: Path Identification Process.

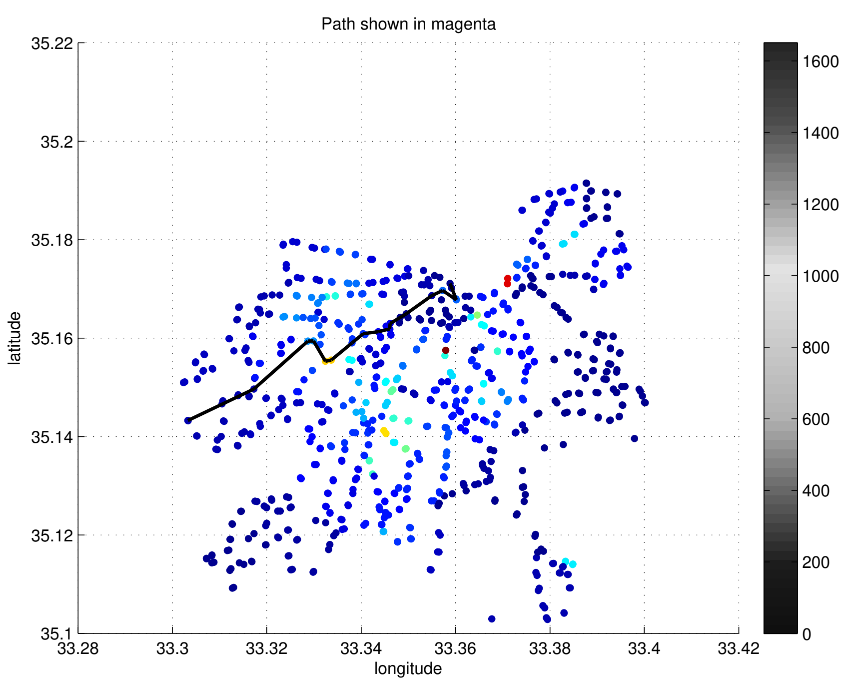

Figure 15: Path Completion Option 1.

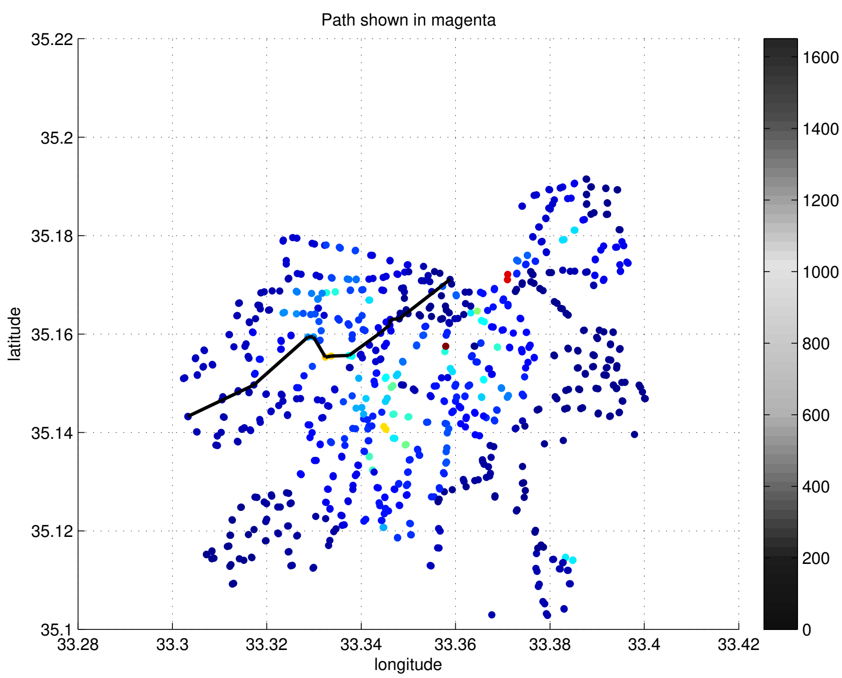

Figure 16: Path Completion Option 2.