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Dynamic User Assignment & Bus Routing for On-Demand Park and Ride Systems

KIOS Research & Innovation Center of Excellence/ Intelligent Transportation Systems: Undergraduate Research Opportunities Program (UROP)

Grigoris Ioannis Manitaras
Assoc. Prof. Stelios Timotheou, Christos Makridis

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1.0: Introduction

This research project aims to bring together two fields in the broader transportation systems region: Route Reservation Schemes and On-Demand Bus Route Generation. Its aim is to explore optimal resource allocation of a bus fleet in a city utilising route reservations.

In Park-and-Ride (PNR) systems, commuters park in a designated starting point and use public transportation to continue their journey, usually into a city [1]. These systems encourage traffic volume to remain outside the city center, thus reducing congestion and parking necessities within the city, all while hopefully saving the bus user time and money. The city we will be exploring is Nicosia, the capital of Cyprus which has a PNR system that has removed from the streets approximately 80,000 cars in 2023 (350-400 cars daily) [2].

Route Reservation Schemes prevent congestion by jointly combining route guidance and demand management by the means of delayed departures [3]. A reservation describes trajectories in both space and time, such that each time slot has an upper limit of reservations and each road cannot exceed its critical density. A reservation request involves an Origin-Destination (OD) pair and a desired departure time. A Route Reservation Controller (RRC) software can get this data as input and return a response including the assigned path and an assigned departure time that may differ from the one requested.

The way these two fields are joined is by generating dynamic bus routes based on demand data and reserve them using a RRC before car, or 'background' traffic can reserve their journeys in the network. In our case a scalable system to realize route reservations in real and simulated networks is used [4].

2.0: Methodology

2.1: Problem Description

In computer science and traffic simulation, a road network can be described as a dual graph, where each lane of a road is a node and connections between nodes represent junctions. Using OpenStreetMaps and additional software we can create a dual graph of a real city without the need of recreation. For this project the main road 'arteries' of the city of Nicosia are preserved and all smaller roads and neighbourhoods discarded. Knowing that the average distance a human can traverse in a 10minute window is 800 meters on average, the network is split into 800m x 800m cells, each containing two bus stops, usually on a single road, facing each other.

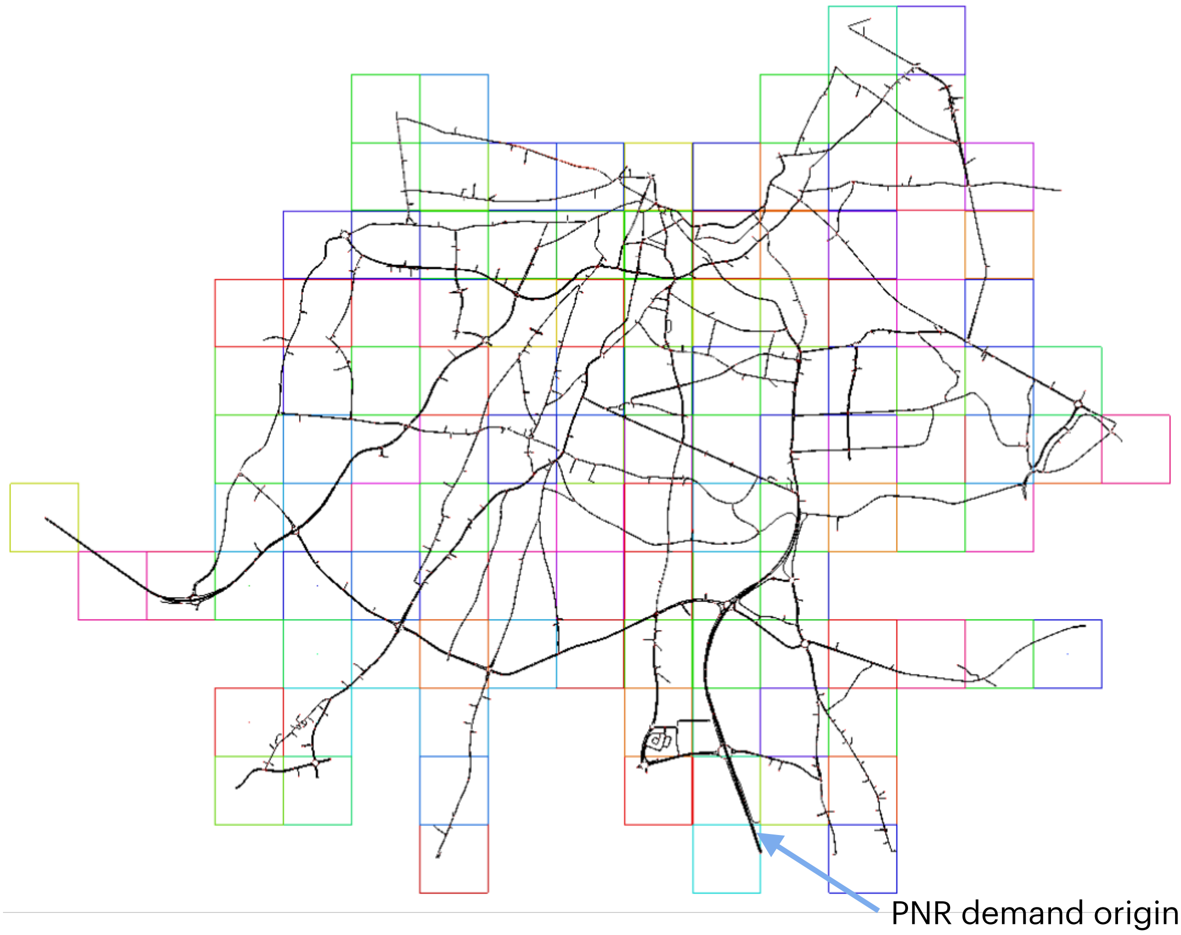


Fig. 1: The road network split into cell regions.

This network is populated as follows:

- 'Background' traffic: we assume a set of random OD pairs in the span of an hour. A flow of 10,000 vehicles/hour is targeted.
- 'PNR' traffic: trips that are coming into the city (single-source) with random destinations. Their origin, the motorway next to GSP Stadium is marked in figure 1. We expect approximately 8,800 vehicles to enter Nicosia in the span of an hour.

The PNR traffic can be analysed to generate demands per cell, per 10 minutes as we would like serve passengers in 10-minute intervals. This is done by examining which cell the road/edge marked as a trip's destination falls under. A heat-map of this data for the first interval follows:

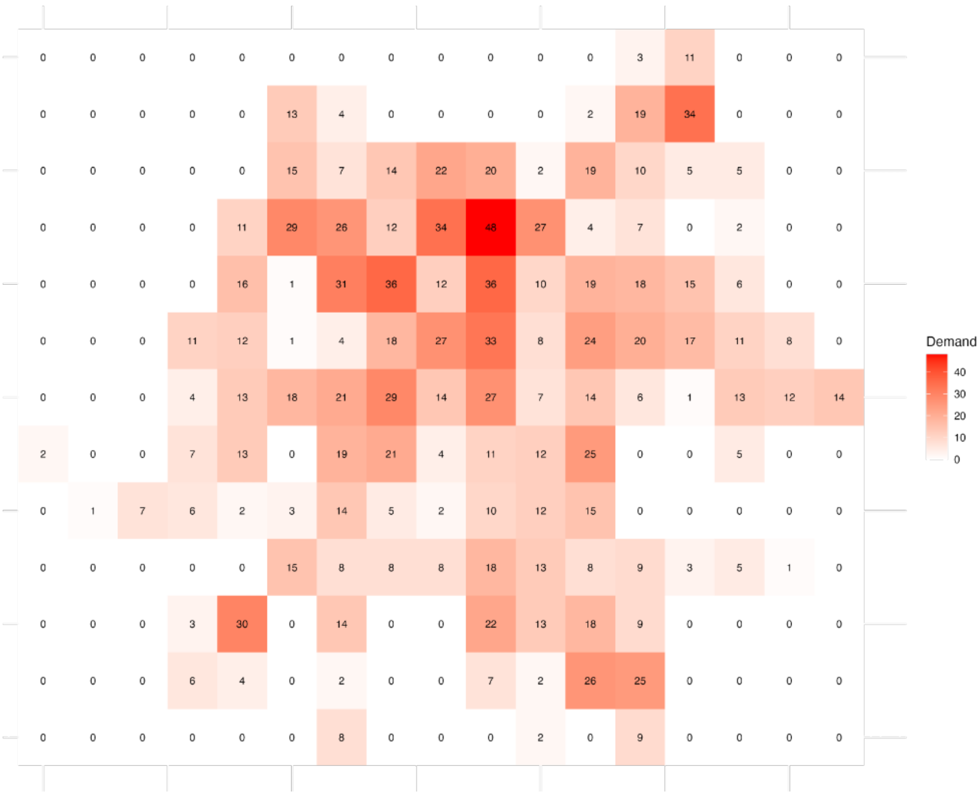


Fig. 2: The demand distribution of the first 10 minutes in the network.

Our PNR resources involve an imaginary infinite supply of 80-seat buses which can be used to generate any routes we might want. There are three scenarios under which we categorise our traffic:

1. Buses & Cars with Reservations (BCR): Background demand is assigned to car trips, using a reservation scheme. The additional PNR

demand is assigned in buses per time interval. Buses have priority in the reservation scheme.

2. Cars only, with Reservations (CR): Background and the additional PNR demand are both assigned to car trips, using reservations.

3. Cars only, Uncontrolled (CU): Background and the additional PNR demand are both assigned to car trips, without using reservations.

2.2: The BCR Algorithm

In scenario 1, the additional PNR demand (as shown in Fig. 1) needs to be assigned to a number of buses in an optimal manner. To do this we utilise the technique of clustering. Two clustering 'rounds' take place: firstly, a K-Means probabilistic super-clustering of the demand into 5 clusters [5]. Secondly, a mathematical optimization sub-clustering of each super-cluster [6]. Once these are done we finally perform routing within the sub-clusters to generate the path each bus is to take. An example clustering result of the first interval can be seen in Figure 3, where each colour represents a different bus.

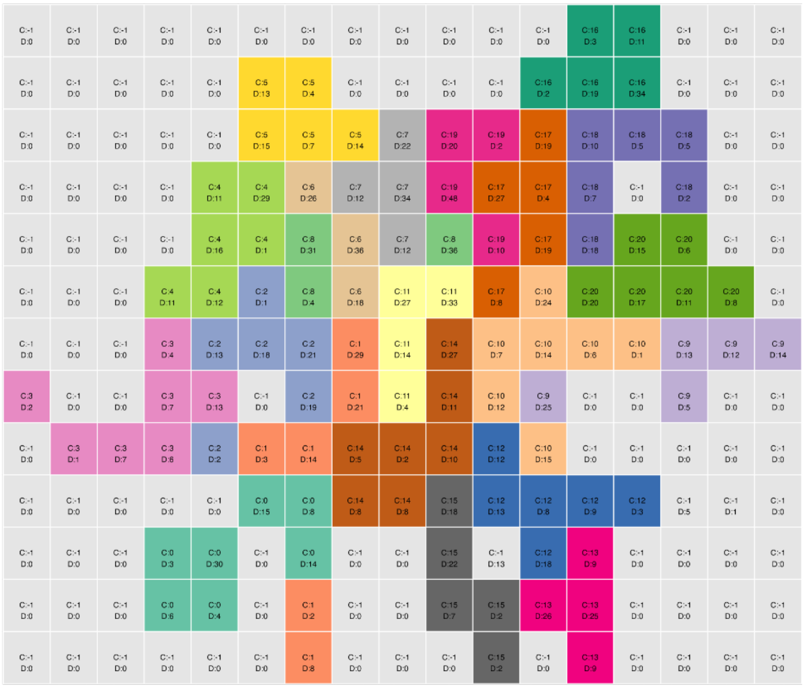


Fig. 3: The cluster formation of the first 10 minutes in the network (C=cluster ID, D=total cell demand)

The K-Means algorithm used here randomly generates centroids for the 5 super-clusters and assigns cells near each centroid to the same cluster. It then iteratively rebalances the clusters, ensuring optimal groups.

The mathematical optimization sub-clustering works by solving the following minimization formulation, where:

$$
\begin{aligned}
&minimize && \sum_k \sum_{i,j} d_{ij} y_{ijk} && (1)\\
&s.t. && \sum_i x_{ik} \le c_k && (2)\\
& && \sum_k x_{ik} \ge f_i && (3)\\
& && z_{ik} \le x_{ik} && (4)\\
& && x_{ik} \le M z_{ik} && (5)\\
& && y_{ijk} \le z_{ik} && (6)\\
& && y_{ijk} \le z_{jk} && (7)\\
& && y_{ijk} \ge z_{ik} + z_{jk} - 1 && (8)\\
& && y_{ijk} \ge 0 && (9)\\
&where && z_{ik}, y_{ijk} \in \{0,1\} &&\\
& && M \gg f_i \forall i &&
\end{aligned}
$$

- d_{ij}: Distance between cells i and j.
- y_{ijk}: (Binary variable) whether cells i and j belong to bus for sub-cluster k.
- x_{ik}: Number of passengers with destination i, assigned to bus for sub-cluster k.
- c_k: Capacity of bus for sub-cluster k.
- f_i: Demand of cell i.
- z_{ik}: (Binary variable) Describes the integer variable x_{ik}.
- M: A helping constant, much greater than any demand value.

Eq. 1 minimizes the distance between the cells of each sub-cluster k.
Eq. 2 ensures that the capacity of bus for sub-cluster k is not exceeded.
Eq. 3 ensures that all demand is assigned to buses.
Eq. 4-5 ensure that $z_{ik} = \begin{cases} 1 & if\ x_{ik} > 0 \\ 0 & \text{otherwise} \end{cases}$

Eq. 6-9 ensure that $y_{ijk} = \begin{cases} 1 & if\ z_{ik} > 0 \wedge z_{jk} > 0 \\ 0 & \text{otherwise} \end{cases}$

2.3: Routing Within Clusters

Once we know which clusters and therefore bus stop pairs we must traverse, we finally need to form a path in the network level that each bus will follow. This essentially is an implementation of the Travelling Salesman Problem (TSP) as we must find the best path possible going through each cell and then returning to the starting position of the PNR system [8].

For each sub-cluster k we find a route by following these steps:

A. Reach k by by finding the the cell $i \in k$ that is closer to the source cell s (GSP Stadium in our case). We then find the shortest path to either of the two bus stops within cell i.

B. Connect all cells within k by finding the cell $j \in k$ that is closer to the current cell i. Next we find the shortest path to either of the two bus stops within cell j. Finally we assign the current cell i to j and repeat until all cells have been visited.

C. To return to GSP Stadium from i we find the shortest path to either of the two stops within cell s.

2.4: Technology Stack

The above algorithms were added on top of an existing Route Reservation Controller (RRC) and written in Java. The RRC uses an InfluxDB instance running in a Docker container as its backend and also communicates with Eclipse SUMO through the Traci API, which can simulate a road network and vehicle trips/traffic

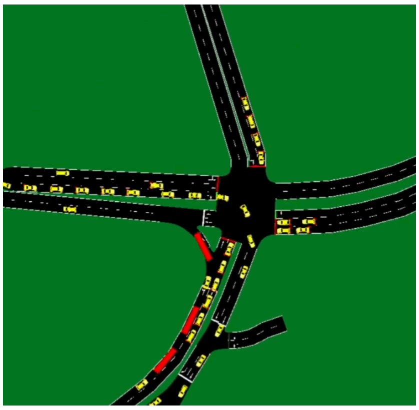


Fig. 4: Simulating traffic using Eclipse SUMO

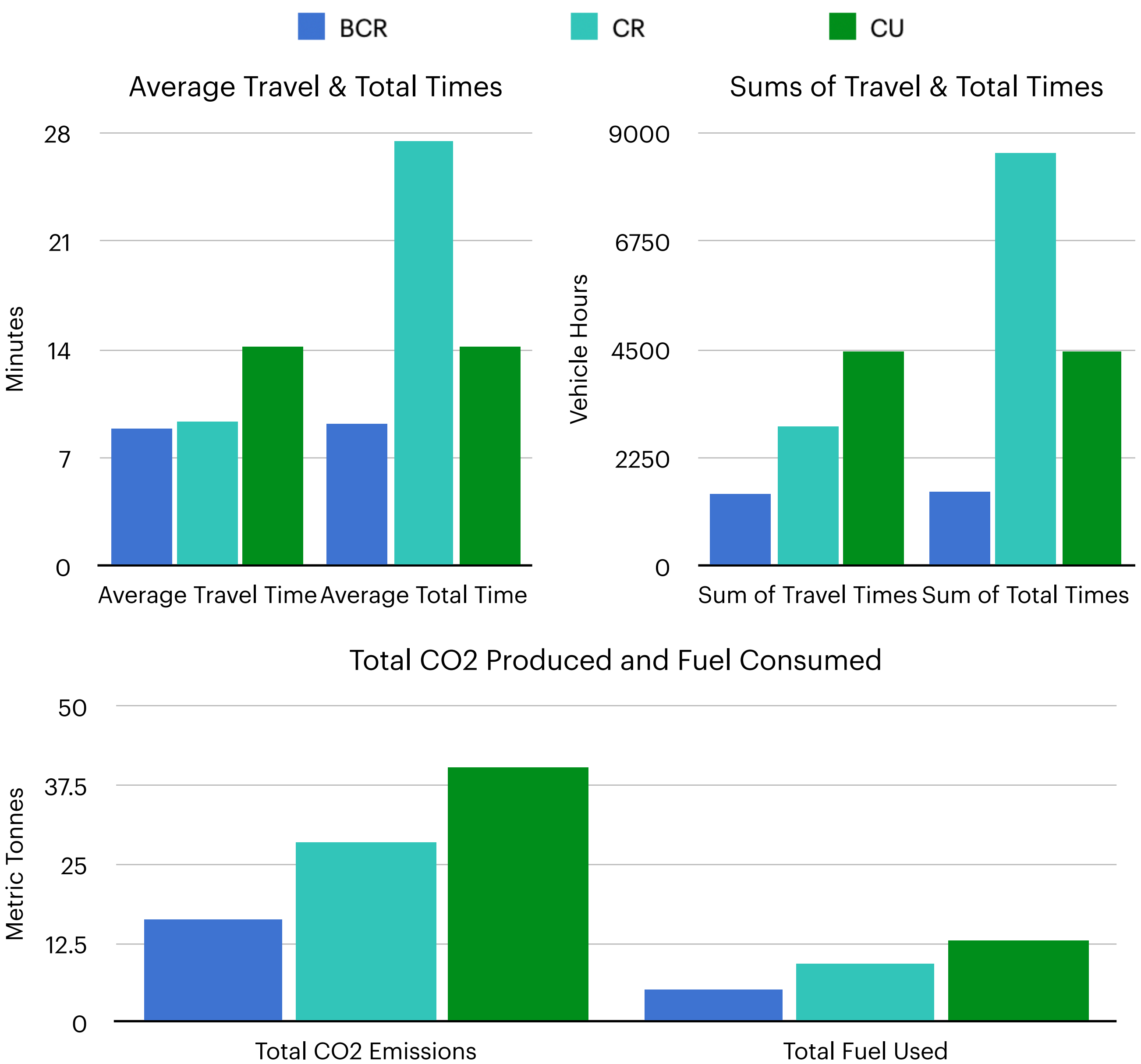
[7]. GitHub was used for version control and R to produce visualisations and summary statistics of measurements.

3.0: Results

The following metrics were recorded while simulating the total ~18,000 trips in our road network under the three scenarios mentioned in 2.1:

- Travel time (Arrival time – Departure time).
- Total time (Arrival time – Desired departure time (using reservations)).
- CO_2 emissions.
- Fuel consumption.

The following bar charts are plotted for these metrics:



Although the trends between scenarios in the data above are expected, one might be confused with the increased average and sum total times for the CR scenario. However this is also expected, since the RRC will issue departure time delays due to the increased number of vehicles in the network (18800 compared to 10017 when assigning PNR demand to buses in the BCR scenario).

4.0 Conclusion & Future Work

In this KIOS CoE UROP project we demonstrate an on-demand PNR service. We prepare a realistic road network using the main arteries of the city of Nicosia, generate background and PNR trip demand and evaluate and compare its traffic performance under a reservation scheme.

The project has faced some limitations. Firstly, we experienced a lack of real-world OD data forcing us to resort to randomly generated demands. Next, A single starting source and PNR system approach may limit this project's application to different public transportation services. Furthermore, limited access to computational power resulted in creating and simulating a network that is lacking detail (smaller roads and neighbourhoods). Finally, due to sake of logarithmic time complexity and scaling the necessity of firstly issuing super-clusters using a probabilistic K-means algorithm results in sub-optimal solutions. Ideally, we'd mathematically optimize the entire network.

Future works may include testing with more realistic demands, incorporating human bus commuters in our simulation so we are able to measure their final walking time to their destination after being dropped off for more realistic results and optimizing the super-clustering approach. Finally, a better approach for solving the TSP could be implemented, since currently we are forming the bus routes using a closest neighbour approach.

Overall, this project has provided me with invaluable experience in independent research proposal/execution and many new skills in my field.

5.0 References/Bibliography

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