SYNOPSIS

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Degree for which submitted: **Ph.D.** Department: **Civil Engineering**

Thesis title: **Extraction of Urban Mobility Patterns and Their Use in Transit Route Network Design for Large Cities**

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Month and year of thesis submission: **March 2026**

Public transportation is an integral part of a city's transportation system. The design of a public transportation system comprises several aspects, such as the design of a transit route set, the allocation of frequency on the transit routes, the preparation of transit vehicle schedules along different transit routes, the assignment of transit vehicles to various transit routes, and the assignment of crews to various transit vehicles. Ideally, all these aspects should be addressed simultaneously to obtain a well-designed transit system. However, due to the complexity of the overall transit system design process, its various aspects are solved sequentially, starting from the design of the transit route set. The design of transit route sets alone is a difficult combinatorial problem.

The transit route sets are designed based on their ability to spatially agglomerate the trips. The more trips the routes serve, the better they can be said to perform. However, the origins and destinations of the trip maker may not lie exactly along the route to be designed. Therefore, the design of the transit route is based on the assumption that its users are willing to shift their origins and/or destinations by some distance to be served by the transit system. The origin-destination (OD) matrix representation of travel demand is widely used in transportation planning and engineering, including the design of transit routes. When used for route set determination, the OD matrices have several limitations. These limitations include an arbitrary shift in trip endpoints (due to predefined zones without any regard to whether trip makers will indeed shift their origins and destinations

to their zone centroids), loss of information on pairing of trip endpoints, and loss of information on intra-zonal trips. Note that all existing methods of designing a transit route set are based on the OD matrix and, consequently, they all suffer from these limitations. In addition to the limitations of the OD matrix, the difficulty of generating route skeletons for route set design, and the repeated use of the trip assignment procedure to improve them, render the existing method of designing transit route sets ineffective for large cities[1].

In practice, a reasonable transit route set is designed for a city based on planners' experience, knowledge, and understanding of the city's mobility patterns[2]. Consequently, one is never sure what all the qualitative criteria would have contributed to the development of the route set. There is a need for a road-based transit route set design method that, given travel demand and road network data, can develop a set of transit routes for large cities that satisfy most of the travel demand directly (i.e., with few transfers) and also cover a large part of the city. These observations motivate the work proposed in this thesis. This work aims to develop a mathematical framework for designing an efficient set of road-based transit routes for large cities (with large road networks comprising tens of thousands of nodes and links) from travel demand data. The proposed framework is based on a novel agglomeration method that differs from the traditionally used OD matrix, in which trip endpoints are the basic unit of agglomeration. The proposed agglomeration method treats trips as the basic entities and allows specifying by how much trips may change their direction and location in order to align with other trips. Such a distance specification can also be interpreted as the maximum access/egress distance that trip makers are willing to cover in order to use transit routes.

The proposed method of designing the transit route set comprises three steps and an optional post-processing step. The first step is the novel trip-based agglomeration (TBA) method that treats a trip as a line segment rather than as two endpoints during agglomeration. Such a representation of a trip preserves information on trip endpoint pairing

[1]Interested readers can see Vermeir et al. (2021). The authors claim that a gap exists between theoretical methods of designing routes and their practical application to real-world road networks.

[2]Interested readers can see Estrada et al. (2011) where planners' expertise on mobility patterns in a city is used to develop transit routes for real-world road networks.

and ordering during the agglomeration. The proposed TBA method is formulated as an optimization problem, and various algorithms are proposed to solve it. The application of the proposed TBA method demonstrates that the trip-making behavior of a city's population (or mobility patterns) can be efficiently identified as a set of corridors. Each corridor is a straight-line segment and represents the spatial agglomeration of trips. Since transit route sets are developed using a city's mobility patterns as input, these corridors are ideal candidates for initial transit routes or proto-transit routes.

Note that the set of corridors obtained using the TBA method does not necessarily lie along the roads of a city's existing network. Moreover, the number of corridors formed for a large trip dataset can be large. These observations lead to the development of the following two processes, which form the second and third steps of the proposed method of designing transit route sets: (i) mapping process, and (ii) selection process. The mapping process is required because the transit route set, unlike corridors, is generally provided over existing road networks (e.g., bus systems). Therefore, the proposed mapping process should convert each corridor (or proto-transit route) into a candidate route using the road network. The mapping process is formulated as an optimization problem and incorporates the properties a planner desires in a transit route. The selection process is necessary because not all corridors are required to be developed as transit routes, as the marginal gains from additional corridors generally reduce as the number of corridors increases. Therefore, the proposed selection process chooses a subset of candidate routes (or mapped corridors obtained after the mapping process) to serve as the designed set of transit routes. The selection process is formulated as an optimization program and incorporates the properties a planner desires in a transit route set. The proposed three steps, namely, the trip-based agglomeration method, the mapping process, and the selection process, form the core of the proposed method of designing a set of transit routes for large cities.

The efficacy of the proposed method for designing a transit route set is demonstrated by applying it to large-scale, real-world road networks (one with tens of thousands of nodes and links) for three cities. The cities are chosen so that data on trips, road network, and existing bus route network are publicly available. In this work, TBA, mapping, and

selection processes are used on millions of trips to finally obtain 40 to 106 transit routes. Since no existing methods design transit route sets for large cities, and no large benchmark network for transit design exists, the designed transit routes are compared with existing bus routes of these cities. The comparison is based on the structure and performance of the two sets of transit routes (existing and those designed from the processes of this thesis). The results show that the proposed methodology produces a set of designed road-based transit routes that have structural properties similar to existing routes, indicating that the designed routes are spatially realistic. The designed routes, however, have better demand satisfaction characteristics.

In addition to the proposed three processes, an optional add-on step has been developed that may help improve the designed transit route set. The proposed add-on step is based on eliminating routes through substitution. The proposed route elimination problem is a new type of substitution problem that has not been explored in the operations research literature. This novel problem is referred to here as the deletion-substitution problem (DSP). The proposed DSP identifies the largest subset of routes that can be eliminated without impacting the total demand satisfied by the route set. The identified routes can be eliminated, giving the planner an opportunity to introduce new routes in their place, thereby increasing the total demand satisfied by the same number of routes. The proposed add-on step may play an important role when the unsatisfied travel demand by the designed transit route set is significant.

Overall, the work proposed in this thesis makes important theoretical and methodological contributions to urban mobility and planning by: (i) proposing a novel trip-based agglomeration method to efficiently extract the city's mobility patterns using a large trip dataset, (ii) proposing a novel mapping and selection processes, that along with the trip-based agglomeration process design a transit route set in reasonable computation time, (iii) demonstrating the scalability of the proposed method of designing a transit route set for large cities (i.e., one with large road network comprising tens of thousands of nodes and links), and (iv) modeling a novel substitution problem that arises from route elimination, exploring its properties and demonstrating its application on real-world problems.