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A Data Driven Approach to State Transportation Investment Decisions: a Transportation Project Investment and Evaluation Resource (T-Pier)

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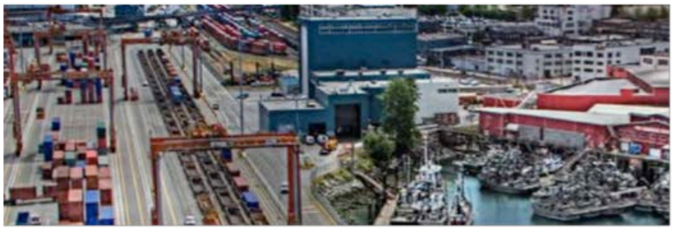

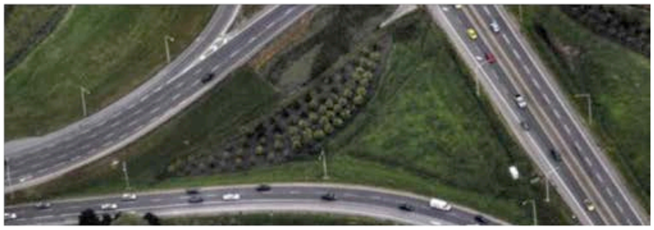

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16. Abstract: One of the challenges for transportation decision makers is to select link improvement or capacity expansion in the network under the constraint of budget such that various objectives of the decision maker, for example, total system travel time is minimized, social welfare (consumer surplus) is maximized, or total system emission is minimized, while accounting for the route choice behavior of users. Such type of investment decision-making involves the need to considering two entities, i.e., decision makers and road users, which make the decision-making process difficult. One of the approaches to addressing this two-hierarchical problem is by using bi-level programming built upon numerical methods and application algorithms such that optimal investment decisions are made in a network design problem. To test the approach, the model is applied to small and medium size example networks and the optimum results are presented. The data that was incorporated include the budget, cost function, time period of investments, modal network, free flow travel times by link, number of lanes and capacity by link, and origin destination matrices of the network. The results from the study has potential to efficiently make capacity expansion decision making for transportation planning and applications.

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Transportation Investment Decision Making in a Network Design Problem Context

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Table of Contents

List of Tables

List of Figures

Abbreviations

AHP	Analytical Hierarchy Process
AMPA	Albuquerque Metropolitan Planning Area
ARC	Atlanta Regional Commission
BLPP	Bi-Level Programming Problem
CAMPO	Capital Area Metropolitan Planning Organization
CCRPC	Chittenden County Regional Planning Commission
CG	Conjugate Gradient Projection
CLM	Congested Lane Mile
CNDP	Continuous Network Design Problem
CORE	Coastal Region Metropolitan Planning Organization
DOT	Department of Transportation
EJ	Environmental Justice
ETA	Equitable Target Area
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
FW	Frank Wolfe Algorithm
FY	Fiscal Year
GA	Genetic Algorithm
GAMPO	Georgia Association of Metropolitan Planning Organizations
GDOT	Georgia Department of Transportation
GP	Gradient Projection
GRG	Generalized Reduced Gradient
GRTA	Georgia Regional Transportation Authority
HEAT	Highway Economic Analysis Tool
HERST-ST	Highway Economic Requirements System-State Version
H-J	Hook-Jeeves
IT3	Investing in Tomorrow's Transportation Today
KDP	Key Decision Points
LLP	Lower-level Problem
LOS	Level of Service
LRTP	Long Range Transportation Plan
MAP-21	Moving Ahead for Progress in the 21st Century

MCDM	Multiple Criteria Decision Making
MICA	Multimodal Investment Choice Analysis
MOCO	Multi-Objective Combinatorial Optimization
MoDOT	Missouri Department of Transportation
MPO	Metropolitan Planning Organization
MTP	Metropolitan Transportation Plan
NADO	National Association of Development Organizations
NCDOT	North Carolina Department of Transportation
NDP	Network Design Problem
NRI	Network Robustness Index
NTR	Network Trip Robustness
OD	Origin Destination
PPP	Project Prioritization Process
RPO	Rural Planning Organization
RTP	Regional Transportation Plan
SAB	Sensitivity Analysis Based
SIS	Strategic Intermodal System
SIT	SIS Investment Tool
SPASM	Sketch Planning Analysis Spreadsheet Model
SPOT	Strategic Planning Office of Transportation
STEAM	Surface Transportation Efficiency Analysis Model
STIP	Statewide Transportation Improvement Program
SWTP	Statewide Transportation Plan
TIP	Transportation Improvement program
TOPSIS	Technique for Order Preference by Similarity to an Ideal Situation
TRAC	Transportation Review Advisory Council
TSTT	Total System Travel Time
ULP	Upper-level Problem
USDOT	United States Department of Transportation
VHT	Vehicle Hours of Travel
VMT	Vehicle Miles Traveled

EXECUTIVE SUMMARY

One of the challenges for transportation decision makers is to select link improvements or capacity expansion in transportation networks under a budget constraint such that that various objectives of the decision maker such as total system travel time is minimized, social welfare (consumer surplus) is maximized, or total system emissions are minimized, while accounting for the route choice behavior of users. Such types of investment decision making in the context of network design problems can be solved using optimization techniques. This type of optimization problem is particularly difficult to solve since two hierarchical decision making entities are involved (decision makers and road users). Both these players have different objectives. The road users select their routes such that their individual travel costs are minimized while planners seek to make the best link improvements within the network in such a way that planning objectives are achieved (typically decision makers little influence on the users' route choices). Making improvements without constraining traffic flow patterns as a reaction to investments with the user's behavior may lead to situations where congestion is increased by improving the capacity of a given link. Thus, the planner has to predict the user's collective response for each link improvement to the existing network. The problem becomes even more complex when decision needs to be made in a multi-year planning context. The objective of this research is to propose numerical methods and application algorithms such that optimal investment decisions are made in a network design problem. The problem is formulated as a bi-level network design problem where the upper level problem determines the optimal link capacity expansions subject to user travel behavior which is represented in the lower level using the classical Wardrop's user equilibrium principles. The upper level problem is an example of system optimum assignment. The upper level will give a trial capacity expansion vector which are then translated into new network capacities. This then invokes the lower level with new link capacities and the output is a vector of link flows which are passed to the upper level. This process is iterated using a Kth-best algorithm until convergence is achieved. The model is applied to small and medium sized example networks and the optimum results are presented. The data that was required to complete this project

included the planning (investment) budget, cost function, time period of investments, modal network, free flow travel times by link, number of lanes and capacity by link, and origin destination matrices of the network. The results from the study have the potential to significantly enhance the efficiency of network capacity expansion decision making for transportation planning applications.

CHAPTER 1. INTRODUCTION

Background

One of the challenges for transportation engineers and planners is to select link improvement or link addition to the existing network under the constraint of budget such that social welfare is maximized, while accounting for the route choice behavior of network users. This type of optimization problem is particularly difficult to solve since two sets of decision makers, i.e., planners and road users, with different objectives are inherently involved. The road users desire to separately select their routes such that their individual travel costs are minimized while the planners seek to make the best link improvements within the network but have no control over the users' route choices. Making improvements without constraining the flow pattern to be in accord with the user's behavior may lead to situations where congestion is increased by improving the capacity of a given link (Braess, Nagurney, & Wakolbinger, 2005). Thus, the planner has to predict the user's collective response for each link addition or link improvement to the existing network.

The purpose of this study is to achieve a single objective optimal solution by choosing optimal decision variables in terms of capacity expansion values. This decision affects the road users' behavior and had to be considered while assigning traffic to the network. The problem was formulated as a bi-level problem, upper and lower level, which reflected the different objectives between the planners and the network users. According to game theory, this problem followed that of the Stackelberg game (Fisk, 1984). In the Stackelbeg game, the planners (the leader) decide optimal value of decision variables under considering the route choice behavior of the users (the follower). Thus, the planners' decision was the upper level problem (ULP) and the users' travel behavior was the lower level problem (LLP). The decision maker may have many different objectives such as minimizing total system travel time, emissions, accessibility, mobility, reliability, safety, etc. in a given transportation network. For this project, the minimization of total system travel time (cost) was chosen as the decision maker's objective that is subject to the users' travel behavior. This behavior was represented in the lower level which is based on Wardrop's first principle (Sheffi, 1985), "no user can experience a lower travel time by unilaterally changing routes". Therefore, the user's equilibrium (UE) was employed for lower level problem.

Literature Review

An extensive review of the literature was conducted to determine the current state of practice and art for project prioritization. The review is divided into four sections: i) the project prioritization process at multiple jurisdictional levels (federal to local); ii) the academic literature on the project selection process; iii) an overview of performance measures in transportation as seen from decision maker's objective; and iv) solution methodologies for bi-level optimization problems in transportation networks.

Project Prioritization Process at Multiple Jurisdictional Levels

Literature review pertains project prioritization process at multiple jurisdictional levels was drawn by assessing transportation planning process at the state-, MPO-, and local-level. This following section will first describe the project prioritization process at the state-level.

State-Level Transportation Planning

This review of transportation project prioritization processes begins with a review of statewide practices. By US federal mandate, each state in the union is required to maintain and update a statewide transportation plan as codified in Code 23 of Federal Regulations, Part 450, Section 214 (23CFR 450.214) (Georgia Department of Transportation, 2005). The state-level project prioritization process was conducted by examining transportation project prioritization process in Georgia, Oregon, Ohio, Maryland, Florida, and Missouri. The selection of these study cases was somewhat arbitrarily; however, it also represents a comparative analysis across different regions in the U.S.

State of Georgia

Project prioritization process in the State of Georgia was largely based upon reviewing the Statewide Strategic Transportation Plan, the 2005-2035 Georgia Statewide Transportation Plan, and the Statewide Transportation Improvement Program for FY 2014-201 to find out for any indication of a transportation project prioritization process for which the state of Georgia might utilize. None of these plans provide a clear description of a prioritization process for transportation improvement projects. The plans only vaguely indicate that a formal prioritization process is used to choose transportation projects that are most important to the communities in which they serve.

Statewide Strategic Transportation Plan

For the Georgia Statewide Strategic Transportation Plan 2010-2030, a new approach to transportation improvements is described which directly relates to the project prioritization process in which the state undertakes. Previously, the statewide strategic transportation plan took a "call for projects" approach to allocate transportation funds to predetermined categories. The restructured approach, called Investing in Tomorrow's Transportation Today (IT3), is "out-come driven, return-on-investment oriented, and based on best practices from the public and private sectors." In application to the Georgia Statewide Strategic Transportation Plan 2010-2030, "IT3 makes the business case for transportation improvements to all modes as appropriate and most efficient, and it establishes a discipline for investing to achieve performance outcomes based on available funding" (Georgia Department of Transportation, 2010).

The Georgia Statewide Strategic Transportation Plan indicates general priorities for safety, transit, freight, roadway, rail, aviation, port, and pedestrian and bicycle. The plan, however, does not provide any methodology for how priorities should be determined. The plan makes a strong case for "getting the most out of the network Georgia already has". Maintenance of existing systems and services is a high priority for the state.

2005-2035 Georgia Statewide Transportation Plan

The 2005-2035 Georgia Statewide Transportation Plan (SWTP) does not provide a clear prioritization process ranking transportation projects. The SWTP, however, did inquire transportation project priorities as perceived by the public within the plan's public involvement process. As part of the plan development, public meeting attendees participated in exercises in which they ranked transportation priorities for both the region and state. The exercise revealed that the reduction of traffic congestion was a top priority for the public at both the region and state scale. This exercise also revealed that the public's highest funding priorities by mode are state and local highway systems and public transit. The highest funding priorities by need are mobility/accessibility, system maintenance, and economic development (Georgia Department of Transportation, 2005).

Project Prioritization and Selection Process

Although not described directly within the statewide plans reviewed, a transportation project prioritization process does exist for the state of Georgia. The foundation for the project prioritization process for the Georgia Department of Transportation (GDOT) is clearly defined performance measures derived from statewide goals. The current project prioritization process focuses on projects which GDOT categorizes as "Roadway New Capacity", including road widenings, extensions, etc. The GDOT is currently working to expand the prioritization process to include project categories for "Roadway Operations" and "Economic Development" (Beagan & Van Dyke, 2008). The performance measures framework is shown below.

Table 1. Performance Measures Framework

Statewide Goal	**Performance Measure**
Preservation	Percent structurally deficient deck area of existing bridges, Percent lane miles of pavement with PACES rating below 10
Safety	Reduction in crash rates (by crash severity)
Congestion	Delay reduction by vehicle miles traveled (VMT)
Connectivity	Change in travel time on non-interstate truck route, an NHS intermodal connector, and/or the STRANET

Access and Mobility	Project Impact to an activity center area, Project consistent with local/regional transportation and land use plan, Does the project exceed required minimum access management standards and/or is the project subject to the requirements of a local access management plan?
Economic Impact	Change in gross state product as a result form VHT savings in 2035 as calculated with the GA HEAT equations

(Source: Beagan & Van Dyke, 2008)

Weighting System

Following extensive stakeholder contribution, weighting systems are developed in order to scale each performance measure by the level of significance that each contributed to particular SWTP goals. Separate weighting systems were created for the Atlanta MPO (the Atlanta Regional Commission), non-Atlanta MPOs, and rural areas of the state of Georgia (Beagan & Van Dyke, 2008). The weighting system for the Atlanta MPO is shown below.

Table 2. Weighting system for Atlanta MPO

SWTP Goal	**Performance Measures**	**New Capacity**	**Traffic Operations**	**Economic Development**
Preservation	Bridge – SD	2.5	0.0	2.0
	Pavement – PACES	2.5	0.0	2.0
Safety	Crash Reduction	5.0	10.0	2.0
Congestion	Delay Reduction – VHT	70.0	70.0	70.0
Connectivity, Access and Mobility	Travel Time – Intermodal Connector, Truck Route, STRAHNET	4.0	2.5	2.0
	Activity Center	4.0	10.0	2.0
	Land Use Plan	3.0	0.0	2.0
	Access Management	4.0	0.0	3.0
Economic Development	Gross State Product	2.5	2.5	7.5
	Economic Policy Area	2.5	5.0	7.5
	Benefit/Cost	0	0.0	0.0
Total Weight		100.0	100.0	100.0

(Source: Beagan & Van Dyke, 2008)

Scoring System

The project prioritization process for the GDOT involves a scoring system. The scoring system is based upon a 100 point scale. Quantifiable performance measures are scored relative to each other within each of the three geographically defined areas. Each project is compared relatively to the best performer within each performance measure category. Then, a weighting is applied to this value to obtain a final score for a particular project within a specific performance measure. Qualitative measures are awarded points on a yes or no basis. After each project is relatively compared and weighted for each performance measures, a final overall score can be summed for each project. A score closer to 100 is given higher priority than scores closer to 0 (Beagan & Van Dyke, 2008).

Table 3. Scoring Example: Safety – Crash Reduction

Project Listing	Crashes Reduced	Relative Comparison	Assigned Weight (Atlanta)	Crash Points
Project 1	52	52/52=1.00	5	(1.00)*5=5.0
Project 2	25	25/52=0.48	5	(0.48)*5=2.5
Project 3	3	3/52=0.06	5	(0.06)*5=0.3
Project 4	13	13/52=0.25	5	(0.25)*5=1.3
Project 5	45	45/52=0.87	5	(0.87)*5=4.4

(Source: (Beagan & Van Dyke, 2008)

Performance Measures and Other Tools

The HERS-ST (Highway Economic Requirements System-State Version) tool is used by GDOT to assist in the project prioritization process (U.S. Department of Transportation Federal Highway Administration, 2002). The tool was originally used by the Federal Highway Administration (FHWA) to estimate highway investment needs for the US prepared for a biennial report to the US Congress (Beagan & Van Dyke, 2008). The tool functions to review the impacts of alternative levels of highway investment and program structure on highway condition, performance, and user impacts. By simulating highway conditions and performance levels, the HERS-ST model selects projects to implement. The model is designed to exclusively select projects in which benefits exceed initial costs. Benefits include reductions in user costs, agency maintenance costs, and externalities for the life of the project. Costs entail the initial capital costs of the project (U.S. Department of Transportation Federal Highway Administration, 2002).

Project Selection Methods in Other States

A review of state departments of transportation (DOTs) indicates that the project prioritization process can either be characterized as either a scorecard method or a ranking method. A scorecard method involves the awarding of specific amounts of points to varying levels of successful fulfillment of targeted objectives, while a ranking method involves the ranking of projects by the net economic impact of each project.

Generally, there are few formal methodologies for transportation project prioritization or ranking by state departments of transportation. There is currently not one tool in use to compare and rank projects across modes.

In awarding the provision of TIGER funds, USDOT makes a "mode neutral" decision. The USDOT only considers projects with a benefit-cost ratio greater than one. Different methodologies, however, are used in each state for benefit-coast analysis making comparisons between states for a single mode a difficult task. In order to make comparisons between states, USDOT evaluators study a state's unique benefit-cost analysis method and make revisions in order for a possible comparison between states. The decision making process for TIGER funding also includes public and private stakeholder input in addition to benefit-cost analysis. A current lack of a transparent methodology for prioritization is necessary to make truly "mode neutral" decisions (Goodchild, Wygonik, & McMullen, 2014).

Generally, scoring criteria include safety, maintenance and preservation of the system, environmental considerations, freight connectivity/mobility, economic development, financial programing, congestion reduction, and quality of life. Different DOTs apply different metrics in scoring these general criteria. Some DOTs may assign a range of points to criteria, while others may use yes or no responses (Goodchild et al., 2014). A review of several states prioritization processes follows.

Oregon

The state of Oregon maintains a detailed statewide freight plan which identifies the multiple components in the prioritization process. Currently the Oregon Department of Transportation does not detail the specifics on comparison, prioritization, or ranking of projects. In the past, the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) ranking algorithm was used as part of a tool developed to rank priority of projects. This tool calculates final weighted scores for each project based off evaluation criteria (Goodchild et al., 2014).

Ohio

The Transportation Review Advisory Council (TRAC) for the state of Ohio establishes the project selection process for major new capacity projects which are those projects valued over $12 million. The TRAC defines criteria and scoring for major new capacity projects providing identical consideration to road, transit, intermodal, and freight projects. Because scoring criteria is applied equally to each mode, modal benefits can be compared across modes. For example, conversion factors are provided to express truck volumes as TEUs in order to compare measures of volume and capacity for freight across modes (Goodchild et al., 2014).

Maryland

The state of Maryland defines six critical transportation issues. The prioritization process employs a scorecard which does not make distinction between modes. The Maryland scorecard methodology is multimodal, and uses a single scorecard for all modes. The final prioritization list is dependent on counties, stakeholders, funding availability, and project size. A “balancing act” is made to create this final prioritization list (Goodchild et al., 2014).

Florida

The state of Florida identified a network of high priority transportation systems statewide in 2003, referred to as the Strategic Intermodal System (SIS). The SIS is multimodal including airports, seaports, railways, freight terminals, highways, and waterways. The intent of the SIS was to direct state resources on transportation facilities that would most strengthen economic competitiveness and quality of life for the state of Florida. The state works with MPOs, government agencies, and stakeholders in order to identify priority projects to include in the SIS Multimodal Cost Feasibility Plan (Goodchild et al., 2014).

The SIS Investment Tool (SIT) was created to prioritize multimodal projects, however, the tool has only been used for the prioritization of highway capacity expansion projects. The SIT is available online for users to adjust the weightings of criteria and observe how adjustments affect prioritization results. The SIT involves 24 prioritization measures which have assigned weights based on the importance of the measure to meeting SIS goals (safety and security, system preservation, mobility, economics, and quality of life) (Goodchild et al., 2014).

Missouri

The MoDOT developed a framework for prioritization of road and bridge projects, referred to as Transportation Planning and Decision Making. The project prioritization framework involves the scoring of projects upon the expected ability of a project to meet the objectives and goals set by the MoDOT. MoDOT, RPOs, and MPOs establish weights and point values for each goal. The weighted average is calculated for each project and classified into low, medium, and high priority groups. Three representatives from the state’s 19 transportation regions are authorized to make decisions in the project prioritization process. Collectively, these decision makers can choose to adjust weights for each objective. This process allows “flexibility to address regional concerns” while providing a planning tool to frame the process. The individual 19 transportation regions of the state perform project prioritization independently for smaller regional projects (Goodchild et al., 2014).

MPO-Level Project Prioritization Process

Following the extensive review of project prioritization process in the State of Georgia and brief summaries of project prioritization process in Ohio, Oregon, Maryland, Florida, and Missouri, this following section will briefly describe the review of project prioritization process at the Metropolitan Planning Organization (MPO)-level. As recognized, the federal government requires the formation of a MPO when an urbanized area consists of a population of 50,000 or more. The MPO develops the long range metropolitan plan and the short-range transportation improvement program (TIP) in which project prioritization process might be explicitly incorporated. The review will put emphasizes on MPOs in Georgia followed by brief review of MPO project prioritization practices in North Carolina, Washington, Pennsylvania, and New Mexico.

Georgia Association of Metropolitan Planning Organizations

The Georgia Association of MPOs (GAMPO) consists of 15 MPOs in the state of Georgia and represent over 75% of the state's population. All transportation projects included in the TIP of each Georgia MPO is incorporated into the Statewide Transportation Improvement Program (STIP) (Timmerman, Yamala, McDuffie, & Dunn, 2011).

The TIP must cover capital and non-capital surface transportation projects or projects phases which are proposed for federal transportation funding inside the MPO jurisdiction. These projects include transportation enhancements, safety projects from the State's Strategic Highway Safety Plan, trails projects, pedestrian walkways, and bicycle facilities. The TIP must also include all regionally significant projects requiring an action by the FHWA or the FTA, no matter the source of funding. The federally required transportation planning conducted by the MPOs is funded by FHWA planning funds which require a 20% match split in half between the MPO and GDOT. Beginning in 2011, however, GDOT discontinued providing the 10% match (Timmerman et al., 2011).

Atlanta Regional Commission

The Atlanta Regional Commission (ARC) PLAN 2040 Chapter 3 on Process does not directly define a prioritization process which the Atlanta MPO follows. Chapter 3 of PLAN 2040 does, however, provide information on "project and program selection". Four Key Decision Points (KDPs) guide the selection of roadway and transit expansion projects "into the constrained element of the plan". This project selection process is a performance based approach. Using assumptions and forecasts for the year 2040, transportation performance was compared between a future build alternative and future no build alternative (Atlanta Regional Commission, 2014a).

The March 2014 RTP Update of PLAN 2040 was guided by a collaborative process between technical and policy focused stakeholders. Coordination continues amongst the ARC, Georgia Regional Transportation Authority (GRTA), and GDOT in directing policy for transportation project prioritization (Atlanta Regional Commission, 2014a).

The performance framework of the RTP is referred to as the Decision-Making Framework for the PLAN 2040 Transportation Update. "The Decision-Making Framework is a guideline for prioritizing the RTP and measuring performance, and established system wide measures, which are consistent with MAP-21 and the SSTP." This framework is used for both transit and roadway investments (Atlanta Regional Commission, 2014a).

The project evaluation process for the March 2014 RTP Update focuses on assessing current conditions rather than projecting future impacts of roadway projects. A current conditions assessment identifies the ability of current priorities to address current needs, is more credible to stakeholders, and produces fact based results.

The evaluation process used by the ARC follows the guidelines of MAP-21 using a streamlined and performance-based program requiring the planning process to be performance based (Atlanta Regional Commission, 2014a).

National Performance Goals are established by MAP-21. These performance goals include safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays. These National Performance Goals informed the SSTP Performance Metrics incorporated into the Regional Transportation Plan (RTP). SSTP Performance Metrics include average number of workers reaching major employment centers by car or transit in 45 minutes, annual congestion cost, average commute time, number of people taking reliable trips per day, number of traffic fatalities, peak-hour freeway VMT, and peak-hour freeway speed (Atlanta Regional Commission, 2014a).

Of the four KDPs which guide the RTP Performance Framework, KDP3 is most informative to project prioritization as KDP3 addresses project-level evaluation of roadway and transit expansion. Overall benefit-cost ratios were calculated for each project based on changes in performance between 2040 Build and 2040 No-Build travel demand model scenarios. Benefit-cost analysis results informed decisions for priorities for each roadway expansion project (Atlanta Regional Commission, 2014b).

ARC Strategies

The ARC considered tradeoffs in investing in one transportation priority over another. As needs exceed available revenue, investments amounts in maintenance, system efficiency, and expansion becomes important (Atlanta Regional Commission, 2014).

The total cost for the financially constrained RTP (PLAN 2040) is about $58.6 billion (in 2014 dollars). This total investment was organized into three priority areas: infrastructure modernization, demand management, and system expansion. The infrastructure modernization priority area involves projects and programs which maintain, operate, and improve the efficiency of existing infrastructure. This area of priority investment encompasses 71% ($41.5 billion) of PLAN 2040. The ARC indicates that Infrastructure Modernization is “the highest regional priority”. Projects of this priority include resurfacing roads and operating regional transit. The TIP groups projects classified as infrastructure modernization as “AR-1**” (Atlanta Regional Commission, 2014).

The demand management priority area involves plan elements focused on reducing and shortening vehicular trips. Demand management is 3% ($1.9 billion) of PLAN 2040. The system expansion priority area involves projects which accommodate future expected growth of 3 million in population by 2040. System expansion investments are 26% ($15.2 billion) of PLAN 2040 (Atlanta Regional Commission, 2014).

ARC Equitable Target Area

The ARC developed the Equitable Target Area (ETA) Index in order to identify environmental justice (EJ) communities within the MPO boundaries. EJ communities are protected by Title VI of the Civil Rights Act of 1964 and Presidential Executive Orders 12898 and 13166. The ARC applies the ETA Index to identify and help EJ communities.

Other MPOs

As mentioned, the project also conducted analyses of other MPOs, namely Puget Sound Region in Washington, North Carolina Capital Area Metropolitan Planning Organization, Coastal Region Metropolitan Planning Organization, Augusta-Richmond County Planning Organization, North Central Pennsylvania, and Albuquerque Metropolitan Planning Area.

Puget Sound Region (Washington State)

The MPO for the Puget Sound Region in the state of Washington ranks projects using a scorecard method. The scorecard includes nine ranking criteria. The ranking criteria are given a relative score from one to five. A score is determined for each project on the basis of ranking criteria; however, a cost-benefit ratio is additionally used to compare projects further (Not clear how the scorecard is combined with the benefit-cost analysis) (Goodchild et al., 2014).

North Carolina Capital Area Metropolitan Planning Organization (CAMPO)

The NCDOT uses a tool called the Strategic Prioritization Process which produces a data driven evaluation and ranking of projects for roadway, bicycle and pedestrian, rail, public transportation, ferry, and aviation. The Strategic Prioritization Process facilitates project prioritization for the STIP. In North Carolina, project prioritization begins with the MPO’s development of the Metropolitan Transportation Plan (MTP). The role of the North Carolina Capital Area Metropolitan Planning Organization (CAMPO) in the Strategic Prioritization Process is to select and submit projects from the MTP and to assign local priority points to the most important projects to the MPO. CAMPO develops a ranking process for each transportation mode for the selection of projects to be submitted to SPOT. Performance measures and funding availability drive the ranking process for each mode. NCDOT provides a weighting for three categories of projects: statewide mobility, regional impact, and division needs. Each project within the Strategic Prioritization Process are classified into the appropriate group. The number of local prioritization points available to each MPO is bade on the MPO’s population. Each MPO can assign 4 points as a minimum and 100 points maximum to a project (Capital Area Metropolitan Planning Organization, n.d.).

NCDOT Strategic Planning Office of Transportation (SPOT) developed a data driven, transparent project prioritization process. The process was centered on three goals: safety, mobility, and infrastructure health.

Projects are organized by goal and then by scope (statewide, regional, and subregional) within each goal. Quantitative data points are given greater weight at statewide projects and lesser weight for regional and subregional projects. Local input point are given greater weight at sub-regional projects (National Association of Development Organizations Research Foundation, 2011).

Coastal Region Metropolitan Planning Organization (CORE)

The Coastal Region Metropolitan Planning Organization (CORE) is the MPO for the Savannah metropolitan area in Chatham County, Georgia. CORE's Long Range Transportation Plan (LRTP), called CORE Connections 2035 Framework Mobility Plan, lists transportation improvement priorities. These priorities include complete streets; sidewalks, bike lanes, and greenways; transit service; safety; new roadways; maintenance; road widenings; and traffic operations improvements. Prioritization is separated by mode. In general, each mode has first, second, and third priority projects. First priority projects are those projects which construction had been programed in previous TIPs but have still not been implemented. Second priority projects are those projects that have significant regional impacts. Third priority projects are those projects in the previous TIPs with high benefit-cost ratios (Coastal Region Metropolitan Planning Organization, 2013). A prioritized list of projects was developed from a list of needs which were evaluated against goals and performance measures (Davis, Cote, Huie, Young, & Plain, 2009).

Augusta-Richmond County Planning Organization

The Augusta-Richmond County Planning Commission serves the Augusta-Aiken metropolitan area which covers spans across the Georgia and South Carolina boarder. Project priorities vary between South Carolina and Georgia. The South Carolina Policy Committee informs local governments on issues and projects within the South Carolina domain of ARTS (Turnbull, 2006).

Rural Planning Organizations

Rural planning organizations (RPOs) generally assist state DOTs in statewide and regional planning. The NADO (National Association of Development Organizations) Research Foundation surveyed several RPOs and small MPOs in regards to project prioritization. About 56 percent of respondents used a combination of qualitative and quantitative ranking criteria, 26 percent used only qualitative criteria, and 18 percent used only quantitative criteria. The state DOT provided the criteria used to select and rank projects for the regional TIP for 12 percent of respondents, while the RPOs determined ranking criteria at a regional level for 36 percent of respondents (National Association of Development Organizations Research Foundation, 2011).

North Central Pennsylvania

North Central Pennsylvania Regional Planning established a Prioritization Committee to develop weight and selection criteria. A software called Decision Lens was used to help with creating the weighting. Decision Lens provided comparisons between proposed criteria. A total score is awarded for each project based off 14 elements of “overall transportation criteria”. In order of importance, these elements include: safety, job creation and community benefits, transportation planning and project support, project location factors, and transportation benefits (National Association of Development Organizations Research Foundation, 2011).

Albuquerque Metropolitan Planning Area

The Project Prioritization Process (PPP) developed by the Albuquerque Metropolitan Planning Area (AMPA) is an objective and data driven approach to evaluation and comparison of transportation projects. The PPP is used to identify projects for the TIP (short range). The PPP is used as a tool to select projects for inclusion in the TIP. The PPP converts the goals and objectives of the region’s long-range transportation plan, called the 2035 Metropolitan Transportation Plan (MTP), into performance measures to analyze, compare, and contrast potential projects for the MTP and the TIP. The three goals of 2035 MTP that form the basis of PPP are: preserve and improve regional quality of life, mobility of people and goods, and support economic activity and growth. Objectives with associated performance measures define each goal as related to the PPP. Project scoring is completed by staff. Scoring for the goal of mobility of people and goods is separated by mode. After scoring, the projects are organized into two lists for comparison. One list organizes projects by mode and another list provides a complete inventory of all scored projects to be compared across modes (Mid-Region Metropolitan Planning Organization, 2012).

Local Transportation Planning

Project prioritization process was also conducted at the local-level, particularly at the county level as described in this following section using the cases of several counties in Georgia, i.e., DeKalb, Cobb, South Fulton, and North Fulton.

Georgia Case Studies

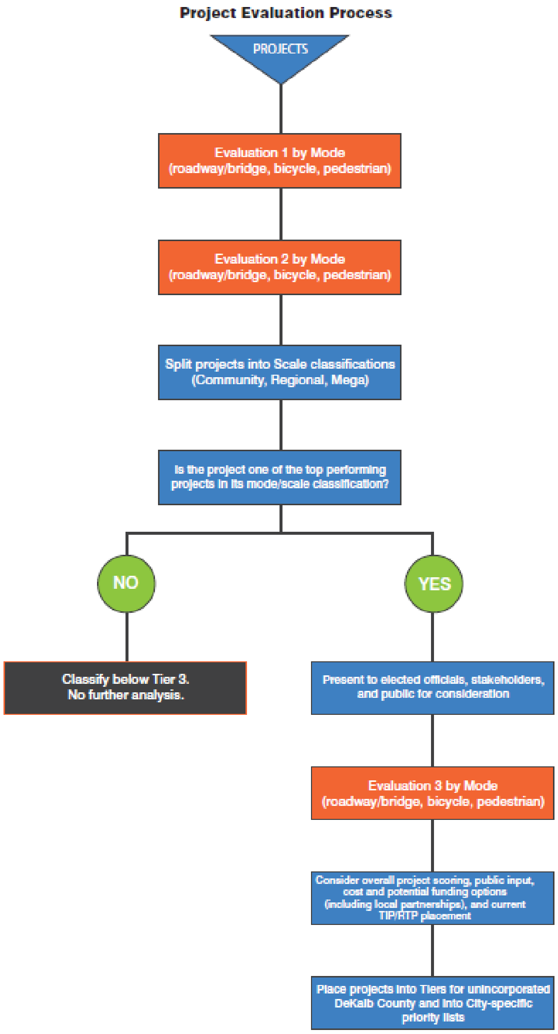
Connect Atlanta

Chapter 5 of the Connect Atlanta plan describes the transportation project evaluation process. Project goals were developed by reviewing previous studies and by receiving feedback from stakeholder interviews and public meetings. As a result, the following goals were developed: provide balanced transportation choices, promote health and safety, prepare for growth, maintain fiscal sustainability, create environmental sustainability, preserve neighborhoods, and create desirable places for all citizens. Metrics (criteria) were developed to measure the extent each goal was being fulfilled; separate by mode. Each project was evaluated based on the percentage to which a goal could be completely fulfilled by the project in question. Candidate project scores were then organized into overall priority rating tiers: high, middle, and low. The project list came from projects from the TIP, the RTP, and previous transportation projects and studies by the City of Atlanta (Connect Atlanta, 2008)

DeKalb 2014 Transportation Recommendations

Transportation projects were evaluated with a three round process with each round narrowing the list from about 3,000 projects to a final recommended list. Projects were organized into categories based on mode: roadway (corridor), roadway (intersection), bicycle, and pedestrian. The first round of evaluation scored projects on geographic location or project type which were derived from project vision and goals. For the second round of evaluation, projects were scored based on technical merit. Combining scores from the first and second rounds of evaluation, total possible points were 100. After the second round of evaluation, projects were organized from highest scores to the lowest scores. The highest performing projects advanced to the third round of evaluation. The third round of evaluation sought feedback from elected officials, stakeholder committees, and the general public. Estimated costs, the scores from the first and second rounds of evaluation, and the sponsoring local government were considered for this final round of evaluation (DeKalb County, 2014).

Figure 1. Project evaluation process of DeKalb 2014 transportation recommendations



(Source: DeKalb County, 2014)

Cobb County Comprehensive Transportation Plan

Cobb County took an approach in which projects were identified, evaluated, and prioritized. Projects were first identified by a needs analysis which resulted in the county’s Needs Based Plan. Projects were next organized by project type: roadway capacity expansion, roadway optimization and operations, transit, and sidewalks and multiuse trails. Each project was then evaluated and scored on the basis of congestion relief and prevention as the key factor. The criteria used to score projects included percent overcapacity measure, TTI, delay, safety, cost, 2006 Thoroughfare Plan (roadways), cost per rider (transit), key corridors, and buffer analysis of generators (pedestrian). Following the scoring process, projects were ranked by time from highest to lowest scores. Available funding is then distribute to the highest ranking projects (Carter & Burgess, Inc., 2008).

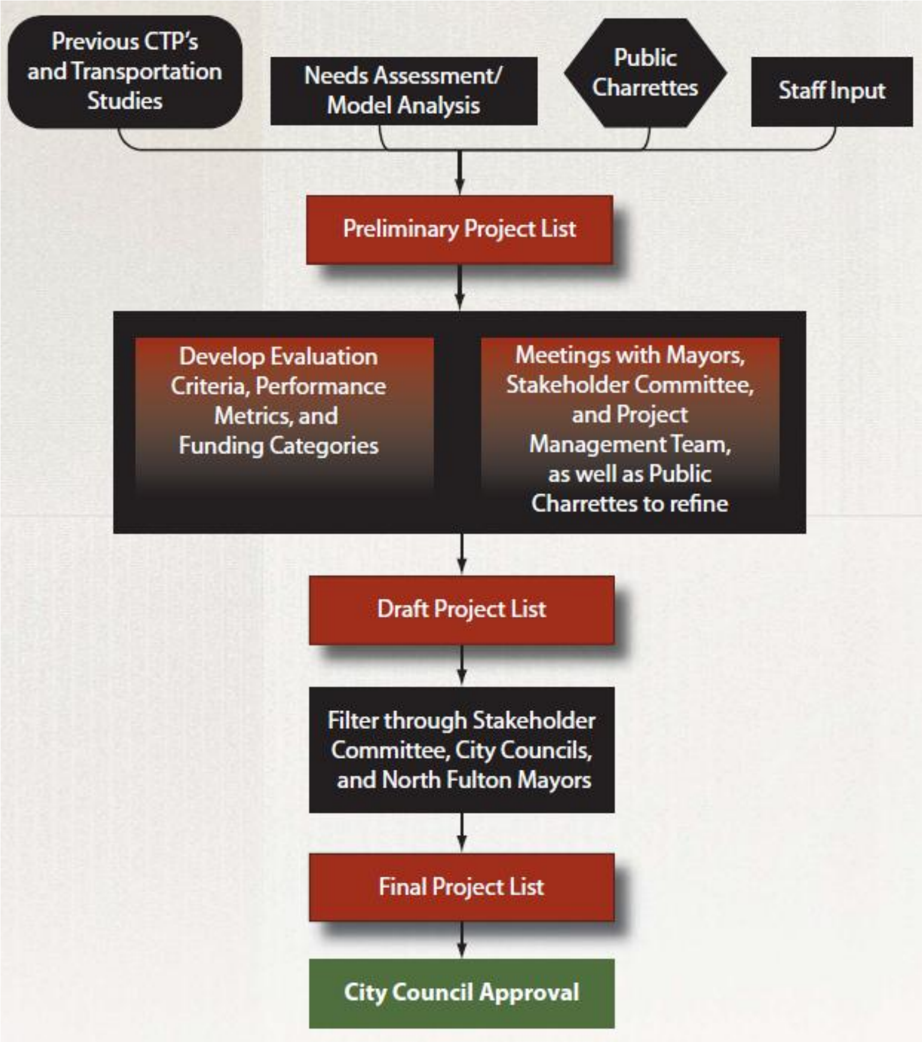
South Fulton County Comprehensive Transportation Plan

An extensive list of aspirational projects was created from previous studies, traffic and crash data, needs assessment analyses, and stakeholder and community input. Projects were organized into two groups: regional and local. Only regional projects were prioritized. Evaluation criteria were developed based off the goals and objectives of the plan. Each objective had one or two related performance measurement criteria. Projects that "best aligned" with the stated goals and objectives would rank the highest. Each performance measure was scored on a scale from one to three. A score of three better met an objective than a score of one. The combination of scores from all performance measures provided a project's total score. Total project scores were used to rank the projects in a priority order (Arcadis, 2013).

North Fulton County Comprehensive Transportation Plan

A preliminary project list was created after consulting previous comprehensive transportation plans and studies, conducting a needs assessment and model analysis, holding public charrettes, and receiving staff input. The next step was to develop evaluation criteria, performance metrics, and funding categories. An evaluation matrix was used to evaluate projects in relation to the priorities of the North Fulton TRIP. Evaluation criteria for the matrix included reduction in vehicular congestion, creation of new connections, improvements to bicycle, pedestrian, and transit modes, and environmental and social impacts. Following the production of a draft project list, the stakeholder committee, city councils, and North Fulton mayors reviewed and commented on the first list. A final project list was created and sent to city council for approval (Kimley-Horn and Associates, Inc., 2010).

Figure 2. Project selection process as applied in North Fulton Comprehensive Transportation Plan



(Source: Kimley-Horn and Associates, Inc., 2010)

Academic Literature on Project Prioritization Process

Inherent to the analyses of practices of project prioritization process at the state-, MPO-, and local-level as described in the previous section, this following section describes the review of academic literature on project prioritization process.

Berechman and Paaswell (2005) explains a methodological approach for consistent and transparent project evaluation resulting in raking/prioritization. The major objective of the study was to inform a group of stakeholders to make rational and systematic choices based on economic and transportation grounds in an environment where pertinent data is lacking, no comprehensive regional transportation plan and objectives are defined, and the decision-making environment is fragmented. The intent of his research was to answer the question "are these projects worth doing? Are any better than others?" The evaluation process for transportation investment projects includes the identification and measurement of benefits from projects (both direct and indirect), identification and measurement of costs associated with investments, distribution of benefits and costs by population and location, and environmental effects of projects. Estimation of transportation benefits from a project can be indicated by the expected number of riders at the completion of project construction and the amount of time saved per user. Berechman and Paaswell used a Goal Achievement Matrix to rank projects for prioritization.

Kulkarni et al. (2004) describes a needs based methodology for highway project prioritization. The research presents a formal decision analysis in which a multi-attribute need function is used to objectively assess the need for investment in a candidate project. The multi-attribute need function evaluates multiple deficiencies of highway segments and takes into consideration the varying importance of different deficiencies. Attributes are the objectives to maintaining an efficient highway system.

Transportation authorities must determine order to allocate limited public funds. Joshi and Lambert (2007) describe project prioritization as a multi-objective combinatorial optimization (MOCO) problem. Mathematical models and graphical tools developed in the past do not consider equity issues but only focus on performance efficiency and resource allocation. Joshi and Lambert focused on "identifying useful quantitative metrics for comparing diverse projects, developing a spatial network and network-level equity metrics for the region under consideration"

Novak, Sullivan, and Scott (2012) illustrate an approach for evaluating and ranking roadway projects using a network based, spatial performance metric called the Network Trip Robustness (NTR). Rather than focusing on localized benefits exclusively, the NTR includes the interests of all users of the road network. The NTR also includes network topology and connectivity and changes in traffic flow on individual road links as affected by dynamic rerouting.

The NTR is derived from the Network Robustness Index (NRI) which is the change in total vehicle hours of travel (VHT) on the transportation network as a result of the removal of a single road link. The study applied the NTR metric to the Chittenden County Regional Planning Commission (CCRPC) in Vermont. The results of the NTR application revealed roadway projects providing the greatest expected travel time benefits for the entire network. “The methodology used in this research can be categorized as a multiple criteria approach that directly incorporates user equilibrium dynamic traffic optimization into the routing choices of the individual travelers on the road network to ultimately rank-order the candidate roadway projects with respect to which projects provide the largest system-wide travel time benefits”.

The Puget Sound Regional Council (PSRC) developed an approach to project prioritization which is based on the weighting of multiple goals with multiple measures derived from stakeholder input (Outwater, Adler, Dumont, Kitchen, & Bassok, 2012). Because all benefits cannot be converted into a single monetary value, a decision making process involving multiple criteria was used rather than a traditional benefit-cost analysis. In order to generate stakeholder derived weightings to the multiple goals, the analytic hierarchy process (AHP) was adopted.

The AHP process obtains the relative priorities of stakeholders across multiple goals by using a set of paired comparisons of the goals. Weights are derived upon the implicit judgments made by stakeholders. In order to determine the ways in which quantitative performance measures satisfy goals, the relative importance of each measure in relation to a particular goal must be determined. A conjoint-based approach was developed to determine the relative importance of each measure in relation to a particular goal. Conjoint exercises were designed to derive the relative importance of each performance measure to achieve each goal.

Shelton and Medina present a clear and systematic approach to ranking transportation projects (2009). Project prioritization is a multiple criteria decision making (MCDM) process. The use of the analytic hierarchy process (AHP) to determine the weighting of criteria and Technique for Ordered Preference by Similarity to Ideal Solution (TOPSIS) to determine performance ratings of alternatives is applied in the study. Five common criteria used for goals and objectives in a ranking process include mobility, financial feasibility, connectivity, environmental, and safety.

The AHP was used in order to derive the relative weights or importance of a set of criteria. This process allows the integration of judgments for both qualitative and quantitative criteria. Decision makers were asked to make pairwise comparisons; one criterion against another. The TOPSIS is used to rank and select alternatives through distance measures. TOPSIS is based on the displaced ideal point. The compromise solution is the shortest distance from the positive ideal solution and the farthest from the negative ideal solution. The TOPSIS method only requires a decision maker's input for weighting criteria and performance measures but is otherwise an automated process. Personal biases do not influence final rankings as decision makers only input weighting criteria.

Transportation performance measures are used by most states and regional planning authorities to inform the planning process and assist in the allocation of resources and the prioritization of projects (Spence & Tischer, n.d.). Project prioritization is generally mode specific rather than across modes. An ideal multimodal tradeoff analysis involves the prioritization of projects across multiple modes in order to determine the better investment decision.

Mode neutral performance measures, such as benefit-cost analysis and goal achievement, should be incorporated at the start of the planning process for a multimodal tradeoff analysis. Mode neutral approach compares different modes with an unbiased assessment. Person miles of travel is a mode neutral alternative to the commonly used vehicle miles of travel. The benefit-cost analysis produces a single ration of monetized benefits to monetized costs. The benefit-cost analysis involves the comparison of ratios to choose the project with the best ratio.

Cost effectiveness models attempt to determine the amount that a given project aligns with predefined goals or performance in relation to cost. The least cost planning approach involves the identification of the project with the lowest costs which meets a given performance goal. Legislation in the State of Washington requires the use of the least cost planning approach.

A multi-criteria analysis assesses several alternatives simultaneously upon a common set of objects and ranks the alternatives. Stated objectives with criteria can be weighted to obtain project scores and overall rankings. The Multimodal Investment Choice Analysis (MICA) Model is a combination of benefit-cost and multi-criteria analyses which "measures the performance of projects relative to metrics and ranks projects based on weights assigned to the metrics to determine the optimal set of projects for a given funding level and policy scenario." Transportation Decision Analysis Software (TransDec) quantifies the amount a project meets performance objectives. Several regional and project specific analysis tools are used including Sketch Planning Analysis Spreadsheet Model (SPASM), Surface Transportation Efficiency Analysis Model (STEAM), VISSIM, Real Accessibility Index, and Highway Economic Analysis Tool (HEAT) amongst others.

Overview of Performance Measures in Transportation

Following review of academic literature pertains project prioritization process, this section describes overview of performance measures in transportation in light of what the MAP-21, a federal law signed by President Obama in 2012, put emphasizes on.

Performance measures, defined as indicators of system effectiveness and efficiency, are increasingly becoming a central focus in transportation planning in the United States (Pei, Fischer, & Amekudzi, 2010). They are the key in determining if a roadway network is sustainable for the future. Sustainability is the measure of impacts of the transportation system on the economy, environment, and in general social well-being. It is measured by system effectiveness and efficiency, and the impacts of the system on the natural environment (Mihyeon Jeon & Amekudzi, 2005). Congestion, emissions, accessibility, mobility, reliability, and safety are crucial performance indicators of a sustainable transportation network.

Congestion levels have a direct impact on travel times within a network. When a portion of a network becomes overly congested, travel times increase and level of service (LOS) decreases. The effects of congestion can then spill into other parts of the network and reduce overall travel times and LOS. Emissions have a negative impact on the environment. It is estimated that 15% of carbon dioxide in the world is emitted from motor vehicles (Nagurney, 2000). Carbon dioxide is known as the global warming gas. Vehicles are also responsible for 50% of nitrous oxide and 90% of carbon monoxide (Nagurney, 2000). Accessibility refers to how suitable a public transport network is for allowing users to go from the point that they enter the network to the point that they exit the network in a reasonable amount of time (Murray, Davis, Stimson, & Ferreira, 1998). Mobility has multiple attributes. Some include having access to places of desire, benefiting from travel to social contacts, maintaining networks, and potential travel (Alsnih & Hensher, 2003). Reliability of a network refers to the ability of the network and the corresponding links to operate under capacity. This offers a path to the user of a reliable nature (Yim, Wong, Chen, Wong, & Lam, 2011). Safety is of critical importance in transportation. The main goal of safety within a network is to reduce the annual number of crashes to a fraction of the current levels (Dijkstra, 2013).

Selection of Project for Budget Allocation

Transportation departments have to select a limited number of road improvement projects for allocation of funds among thousands of prospective choices given a fixed budget. To find an optimum selection of projects from a limited set of projects, (Melachrinoudis & Kozanidis, 2002) applied a mixed integer knapsack solution to project selection maximizing the total reduction in the expected number of accidents under a fixed budget constraint. The majority of decisions dealing with project selection involve immediate costs while benefits spread over many years into the future. (Brown, 1980) applied dynamic programming to obtain a set of projects which provide an optimum, taking into consideration not only present costs but also the benefits that accrue over several years into the future.

Recently much attention has been focused on multilevel programming, a branch of mathematical programming that can be viewed as either a generalization of minimization-maximization problems or as a particular class of Stackelberg games with continuous variables. The network design problem with continuous decision variables, representing link capacities, can be cast into such a framework. Marcotte (1986) gives a formal description of the problem and then develops various suboptimal procedures to solve it. Gradient based methods were used to solve a continuous network design problem in a transportation network where Wardrop's first principle was used for traffic assignment (Chiou, 2005). Three test networks were employed to ensure that the methods were sound. A genetic algorithm approach (Ceylan & Bell, 2005) was used to solve the upper level portion of the bi-level problem for the optimal capacity expansion values.

Bi-level Optimization for Network Design Problem

As briefly mentioned in the introductory part of this report, the persistent issue was to addressing bi-level optimization problem involving two hierarchical decision making entities, i.e., decision makers and road users, that each have their own objectives. This section therefore briefly describes literature review pertains bi-level optimization approach that is considered as a useful approach for problems with conflicting objectives within a hierarchical structure. It originated from the fields of game theory and decision making and describes a number of problems in transportation planning and modeling.

The bi-level problem has hierarchal framework that involves two separate optimization problems at different levels. The first problem has a feasible solution set and is called the upper-level problem which is also known as the leader problem. The solution set is determined by the second optimization problem.

The second problem is the lower-level problem or the follower problem. This concept can be extended in order to define multi-level programs with any number of levels (Vicente & Calamai, 1994). Bi-level formulations of the network design problem are non-convex and non-differentiable and therefore getting global optimum solution is not easy (Yan & Lam, 1996). These problems are difficult to solve and designing efficient algorithms is still considered to be one of the most challenging tasks in transportation (Meng, Yang, & Bell, 2001). Therefore, several solution approaches have evolved over the past few decades. Initial approaches used heuristic algorithms, which may give near optimal solution or local optimum solutions (Allsop, 1974; Steenbrink, 1974), or methods like equilibrium decomposed optimization (Suwansirikul, Friesz, & Tobin, 1987), which are computationally efficient but result in suboptimal solutions. Gershwin & Tan (1978) formulated the continuous network design problem (CNDP) as a constrained optimization problem in which the constrained set was expressed in terms of the path flows and performed their method on small networks. Marcotte (1983) and Marcotte & Marquis (1992) presented heuristics for CNDP on the basis of system optimal approach and obtained good numerical results. However, these heuristics have not been extensively tested on large-scale networks generally. Regarding the sensitivity based approach applied to bi-level optimization problem, Falk & Liu (1995) investigated theoretic analysis for general non-linear bi-level optimization problem and proposed a descent approach in terms of the bundle method to solve the non-linear bi-level problem where the gradient of the objective function can be obtained when the sub gradient information of the lower level are available. (Chiou, 1999) explored a mixed search procedure to solve an area traffic control optimization problem confined to equilibrium network flows, where good local optima can be effectively found via the gradient projection method.

In 2011, a bi-objective model was developed that optimized capacity reliability and travel time reliability performance measures (Chen et al., 2011). These performance measures give the supply and demand of a roadway network's reliability. A study was performed in 2013 utilizing bi-level optimization that took into consideration the increasing congestion and limited budget obstacles (Baskan, 2013). Optimal link capacity expansion values were found by minimizing the total system travel time as well as the associated link investment costs within roadway networks. The minimization of total system travel time is a key objective when using bi-level optimization in transportation planning. Multiple works have been conducted on this very topic (Ben-Ayed, Boyce, & Blair III, 1988; Gao, Wu, & Sun, 2005).

CHAPTER 2. METHODOLOGY

The remaining sections of this report are organized as follows. A discussion on the bi-level optimization problem is presented along with the network design problem (NDP) formulations for the ULP and LLP with all of the mathematical formulas and their corresponding notations. Then the next section describes solution algorithms and along with the steps that must be taken for both the ULP and LLP. The results are presented as an experimental test incorporating the transportation design problem developed in the methodology. Five test networks are used to verify that the transportation design problem worked correctly and then the algorithm is applied to five real networks (Sioux Falls, SD; Anaheim, CA; Chicago, IL; Atlanta, GA; and Montgomery County, MD). The final section draws conclusions about the results based on the research objectives.

Bi-level Programming Problem (BLPP) Description

An optimization problem constrained by another optimization problem is called a bi-level programming problem (BLPP). From the mathematical point of view it is a problem with hierarchical structure where two independent decision-makers appear. One can consider this problem as a sequential game, which has its origin in the Stackelberg game theory. That is, optimal reaction vector y of the second player (“follower”) is included in the decision making of the first player (“leader”). Leader’s reaction vector is denoted as x. This rule can be represented in a mathematical form of the bi-level program as follows:

$$\begin{cases} \min\limits_{x\in R^{n},\ y\in R^{m}} F(x,y) & (1) \\ s.t. \quad G(x,y) \leq 0 & (2) \\ \qquad\ H(x,y) = 0 & (3) \\ \qquad \begin{cases} y = argmin_{y}\ f(x,y) & \qquad (4) \\ \quad s.t. \quad g(x,y) \leq 0 & \\ \qquad\qquad h(x,y) = 0 & \end{cases} & \end{cases}$$

Equations (1) - (3) describe the leader's decision sub problem, while (4) represent the follower's decision sub problem. For the comprehensive description, $F(x, y), f(x, y): R^n \times R^m \rightarrow R$ are the leaders and follower's objective functions, respectively. Further, $G(x, y), H(x, y): R^n \times R^m \rightarrow R^p$ represent inequality and equality constraint set in the leader's sub problem, respectively, and $g(x, y), h(x, y): R^n \times R^m \rightarrow R^q$ are inequality and equality constraint set in follower's sub problem, respectively. To build up a complete picture of the problem, it is necessary to define some more terms. The relaxed feasible set for BLPP is defined as $\Omega = \{(x, y): G(x, y) \leq 0, H(x, y) = 0, g(x, y) \leq 0, h(x, y) = 0\}$. The follower's feasible set for the decision variables x of the leader's problem defined for every $x \in X$ is specified as $\Omega(x) = \{y : y \in Y, h(x, y) = 0, g(x, y) \leq 0\}$ while the rational follower's reaction set for every $x \in X$ is defined as $M(x) = \{y : y \in argmin \{f(x, y) : y \in \Omega(x)\}\}$. Finally, it is essential to define the inducible region or feasible set for BLPP as $IR = \{(x, y): (x, y) \in \Omega, y \in M(x)\}$. This is the set over which the leader may optimize. All the definitions assume a bounded space, where the optimal solution can be found. A solution (x, y) is feasible if $(x, y) \in IR$ and a solution $(x^*, y^*) \in IR$ is an optimal solution if $\forall (x, y) \in IR, F(x^*, y^*) \leq F(x, y)$.

Problem formulation

The transportation network design problem (NDP) can be represented as a leader–follower game where the transport planner makes network planning decisions, which can influence, but cannot control the users' route choice behavior. The users make their route choice decisions in a user optimal manner. This game can be formulated as a bi-level programming model, where the upper-level problem is to determine the optimal capacity improvement to each link in a given set of candidate links, in order to minimize total system travel time (TSTT), subject to a given budget limit, and the lower-level problem represents a UE traffic assignment problem that describes users' route choice behavior. Before formulating the bi-level model, I list the symbols used in the model:

Table 4. Problem

Notation		Explanation
A	:	Set of arc a
I	:	Set of trip origins, $i \in I$
J	:	Set of trip destinations, $j \in j$
IJ	:	Set of origin-destination pairs on the network, , $(i,j) \in IJ$
k	:	The complete set of available paths in the network
k^{ij}	:	The set of paths in the network between I-J pair $(i,j), \forall(i,j) \in IJ$
f_k^{ij}	:	Flow on path r, connecting each Origin-Destination (O-D) pair (i-j)
q_{ij}	:	Demand between each Origin-Destination (O-D) pair $\forall(i,j) \in IJ$
$t_a(x_a, y_a)$	:	Travel cost on link a as a function of flow and capacity expansion
x_a	:	Flow for link a
α_a	:	Constant, varying by facility type (BPR function)
β_a	:	Constant, varying by facility type (BPR function)
$\delta^r_{a,ij}$	:	Binary variable which $\{1, \text{if link a } \in \text{A is on path k } \in \text{k}^{\text{ij}}\text{:} 0, \text{otherwise}\}$
d_a	:	represents the monetary cost of capacity increments per unit of enhancement
θ	:	denotes a user defined factor converting investments costs to travel cost
$g_a(y_a)$	:	improvement cost function for link 'a'
y_a	:	Capacity expansion for link 'a' (nonnegative real value)
$TSTT$	:	Total System Travel Time
B	:	Budget (nonnegative real value)

The upper-level optimization problem (ULP)

The planner aims to minimize the total system travel time in the NDP. Thus the upper-level problem can be formulated as

$$Minimize\ TSTT = \sum_{a \in A} (x_a t_a(x_a, y_a)) \tag{5}$$

Subject to

$$\sum_{a \in A} g_a(y_a) \leq B \tag{6}$$

$$y_a \geq 0: \forall_{a \in A} \tag{7}$$

The objective function (5) represents the total system travel time where x_a is determined by the lower-level UE problem which will be presented in the next section. Constraint (6) guarantees that the total improvement cost does not exceed the total given budget. Constraint (7) ensures that the capacity improvement index y_a for each candidate links are positive.

The lower-level user equilibrium traffic assignment problem (LLP)

The upper level shown in equations (5-7) will give a trial capacity expansion vector y_a and will be translated into new link capacities. Based on the new link capacity values, the link flows can be computed by solving the following formulation:

$$Minimize\ TT = \sum_{a \in A} \int_0^{x_a} t_a(x_a, y_a)dx \tag{8}$$

Subject to:

$$q_{ij} = \sum_{k \in k^{ij}} f_k^{ij}\ \forall(i,j) \in IJ \tag{9}$$

$$x_a = \sum_{(i,j) \in IJ} \sum_{k \in K^{ij}} \delta_{ak}^{ij} f_k^{ij}, \quad \forall_a \in A \tag{10}$$

$$f_k^{ij} \geq 0, \quad \forall_k \in k^{ij}, \qquad \forall(i,j) \in IJ, \tag{11}$$

$$q_{ij} \geq 0, \quad \forall(i,j) \in IJ \tag{12}$$

Equation (8) represents the objective function of UE problem. Constraint (9) defines the demand conservation condition. Constraint (10) defines the relation between link flow and path flow. Constraint (11) and (12) requires non negativity path flow and travel demand respectively. An important feature of this problem, and more generally of bi-level programs, is the hierarchical relationship between two autonomous, and possibly conflictual, decision makers. Mathematical program in equation (5-7) and (8-12) are connected using common variables, namely capacity improvement index y_a and flows x_a. Also, the decision of the planner cannot be computed until flows are known. These flows are not in the direct control of the planner, but the solution of a mathematical program parameterized in the capacity improvement vector y_a. This yields the bi-level formulation as follows:

$$
\left\{
\begin{array}{ll}
\min\limits_{x\in R^{n},\ y\in R^{m}} \ TSTT = \sum\limits_{a\in A}\left(x_a t_a(x_a, y_a)\right) & (13) \\
s.t. \quad \sum_{a\in A} g_a(y_a) \le B & (14) \\
\qquad y_a \ge 0 : \forall_{a\in A} & (15) \\
\left\{
\begin{array}{l}
x_a = \ argmin_{x_a} \sum\limits_{a\in A} \int_0^{x_a} t_a(x_a, y_a)dx \\
s.t. \quad q_{ij} = \sum_{k\in k^{ij}} f_k^{ij} \ \forall (i,j) \in IJ \\
x_a = \sum\limits_{(i,j)\in IJ} \sum\limits_{k\in K^{ij}} \delta_{ak}^{ij} f_k^{ij}, \quad \forall_a \in A \\
\quad f_k^{ij} \ge 0, \ \ \forall_k \in k^{ij}, \ \forall (i,j) \in IJ, \\
\quad q_{ij} \ge 0, \ \ \forall (i,j) \in IJ
\end{array}
\right. & (16)
\end{array}
\right.
$$

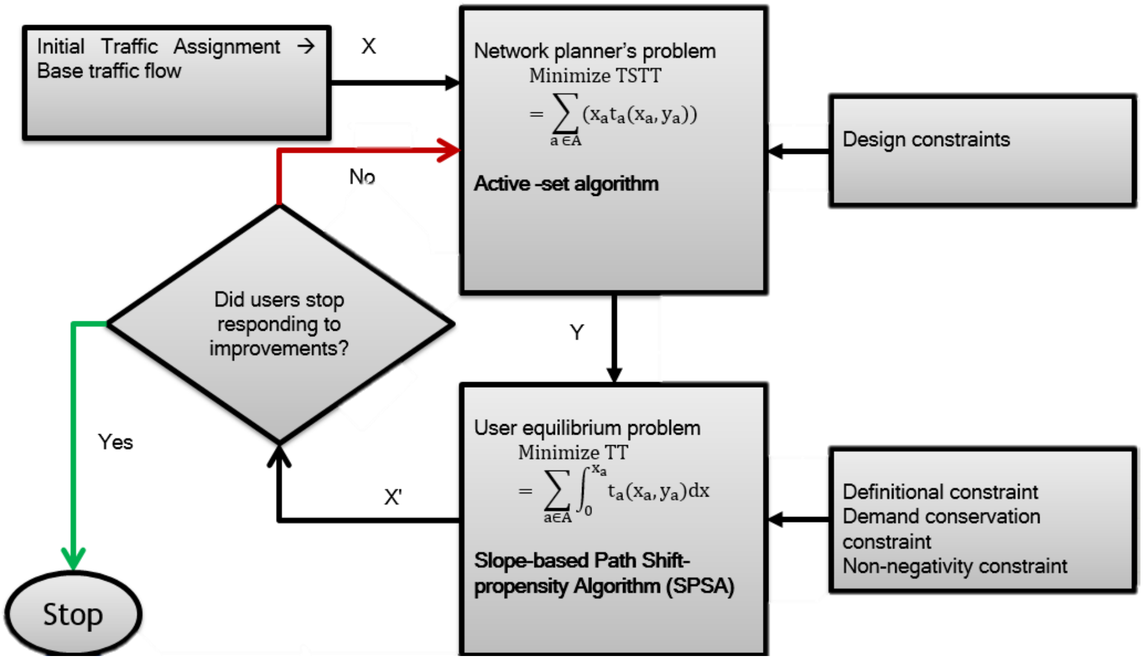
For this given BLPP problem, the follower's feasible set for the decision variables y of the leader's problem defined for every $y \in Y$ is specified as:

$\Omega(y) = \{x : x \in M(y)\}$ while the rational follower's reaction set for every $x \in X$ is defined as $M(y) = \{x : x \in \ argmin_{x_a} \sum_{a\in A} \int_0^{x_a} t_a(x_a, y_a)dx\}$. Therefore, the induced region set for BLPP is defined as $IR = \{(y, x): g_a(y_a) \le B \ , \ y_a \ge 0 \ , \ x \in M(y)\}$. This is the set over which the leader may optimize. All the definitions assume a bounded space, where the optimal solution can be found. A solution (y, x) is feasible if $(y, x) \in IR$ and a solution $(y^*, x^*) \in IR$ is an optimal solution if $\forall (y, x) \in IR, F(y^*, x^*) \le F(y, x)$.

Solutions approach

This section discusses the solution algorithms for the ULP and LLP. The ULP was performed by means of FMINCON function in MATLAB. It uses the Generalized Reduced Gradient (GRG) algorithm for optimizing nonlinear problems. The steps of The GRG algorithm are presented in Table 5. The upper level objective function is solved using FMINCON tool in MATLAB which will give a trial capacity expansion vector (y_a). Then this vector will be translated into new network capacities. The new network will be transferred to the lower level. The LLP provides new (x_a) vector based on the capacity enhancement vector (y_a). This link flows are passed to the upper level. The upper level objective function will be computed and it provides the new trial capacity (y_a). This trial capacity will be passed to the lower level. This procedure is repeated until convergence. The flowchart of the solution approach is given in Figure 3.

Figure 3. Flowchart of the Solution Approach



The LLP incorporates Frank Wolfe Algorithm (FW) (3) to perform traffic assignment. The FW search algorithm is used for convergence of the objective function to its minimum value using the associated direction vector's move size. The objective function is the sum of the integrals of the link performance functions. The steps of the Frank-Wolfe algorithm are presented in Table 6.

Table 5. Steps of the GRG2 Algorithm

Step 1. Given a feasible point $x_1 \in X, \epsilon \geq 0, \bar{\epsilon} \geq 0$; positive integer M; $k := 1$.

Step 2. Compute

$$\nabla c(x_k)T = \begin{bmatrix} A_B \\ A_N \end{bmatrix},$$

where the partition satisfies that $A_B \in \Re^{m \times m}$ is nonsingular;

Compute λ (multiplier satisfying):

$$\frac{\partial f(x)}{\partial x_B} = \frac{\partial C^T(x)}{\partial x_B} \lambda$$

Therefore, the reduced gradient $(\tilde{g}_k)$ can be expressed as the gradient of the Lagrangian function at the reduced space:

$$\tilde{g}(x_N) = \frac{\partial}{\partial x_N} [f(x) - \lambda^T c(x)],$$

Step 3. If $\|\tilde{g}_k\| \leq \in$ then stop;

let $\bar{d}_k = -\tilde{g}_k$; and $\alpha = \alpha_k^{(0)} > 0$.

Step 4.

$x_N = (x_k)_N + \alpha \bar{d}_k$;

$x_B = (x_k)_B; j := 0$.

Step 5. $x_B = x_B - A_B^{-T} c(x_B, x_N)$;

compute $c(x_B, x_N)$;

if $\|c(x_B, x_N)\| \leq \bar{\epsilon}$ then go to Step 7;

$j := j + 1$; if $j < M$ go to Step 5.

Step 6. $\alpha := \alpha/2$, go to Step 4.

Step 7. If $f(x_B, x_N) \geq f(x_k)$ then go to Step 6.

$x_{k+1} = (x_B, x_N), k := k + 1$; go to Step 2.

Table 6. Steps of the FW algorithm

Step 0: Initialization

Perform all-or-nothing assignment based on $t_a = t_a(0)$ ∀a. A new flow vector $\{x_a\}$ will be generated. Set counter $n = 1$.

Step 1: Update

Set $t_a = t_a(x_a)\ \forall a$

Step 2: Finding Direction

Perform all-or-nothing assignment based on $\{t_a\}$.

A new auxiliary flow vector {x'ₐ} will be generated.

Step 3: Line search

Find α_n $(0 \leq \alpha \leq 1)$ that solves equation (16):

$$\min z(x) = \sum_a \int_0^{x_a + \propto (x'^n_a - x^n_a)} t_a(w)dw$$

The line search problem solved using bisection algorithm (Bolzano search). The converge criteria for bisection method defined as the distance between the lower bound and upper bound of the current section in bisection iterations.

Step 4: Move

$$x_a^{n+1} = x_a^n + \propto_n (x'^n_a - x_a^n), \forall a$$

Step 5: Convergence test

If the convergence criterion is met, stop and accept the current solution $\{x_a^{n+1}\}$, as the set of equilibrium link flows. If the convergence criterion is not met, set $n = n + 1$ and go to step 1.

The convergence tested using equation (18):

$$\frac{\sqrt{\sum_a (x_a^{n+1} - x_a^n)^2}}{\sum_a x_a^n} \leq k$$

CHAPTER 3. RESULTS

This section discusses the results obtained from the methods covered in the previous section. Numerical analysis has been conducted in order to compare the results obtained with other alternatives from previous literatures (Friesz, Cho, Mehta, Tobin, & Anandalingam, 1992; Meng et al., 2001; Suwansirikul et al., 1987). Five example networks were chosen to perform the comparisons. The networks chosen are covered in the following pages.

Test Network 1

As a simple example, the test network shown in the Figure 4 was used as a reference to compare the results to the similar network from the literature. The network data, link attributes, and demand are adopted from the study by (Suwansirikul et al., 1987). The upper level objective function for this network is given in equations (9-10). Table 7 presents the necessary input data that for the first test network.

Figure 4. Test Network 1 (5-Link)

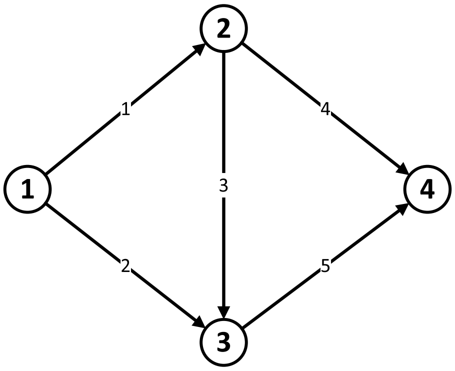


Table 7. Data for Test Network 1 (5-Link)

$$t_a(x_a,y_a) = A_a + B_a\left(\frac{x_a}{C_a + y_a}\right)^4$$

$$TSTT(y) = \sum_a (t_a(x_a,y_a).x_a + 1.5d_a y_a^2$$

Arc a	A_a	B_a	C_a	d_a
1	4	0.60	40	2

2	6	0.90	40	2
3	2	0.30	60	1
4	5	0.75	40	2
5	3	0.45	40	2

Table 8 shows the capacity expansion, objective values for upper and lower level, link flows, and marginal changes in the flow by iterations. Four sub tables show the variations of mentioned variables by different demands. When demand equals 100, the procedure converges near 3 iterations. When demand equals 300, the procedure converges near 14 iterations. Both the upper and lower level objective values decrease as more iterations are applied. Users stop responding to the new improvements when convergence is achieved. This is evident in the marginal flow columns, which converge to zero. Link three does not require any capacity expansion. This indicates that the original capacity satisfies the demand and there is no need for further improvement.

Table 8. Results from Test Network 1 (5-Link) with Changing Demand

Demand from node 1 to 4 = 100:

	objective value		Capacity Expansion Unit Vector					Link Flows					Marginal Changes in Flows				
Itr	**ULP**	**LLP**	**y1**	**y2**	**y3**	**y4**	**y5**	**x1**	**x2**	**x3**	**x4**	**x5**	**Δx1**	**Δx2**	**Δx3**	**Δx4**	**Δx5**
Base		963.71						52.5	47.5	5.72	46.8	53.2					
1	1200.35	956.78	1.33	1.21	0	0.97	1.09	52.6	47.4	5.86	46.7	53.3	0.07	-0.07	0.14	-0.07	0.07
2	1200.35	956.77	1.33	1.21	0	0.97	1.1	52.6	47.4	5.88	46.7	53.3	0.01	-0.01	0.02	-0.01	0.01
3	1200.35	956.77	1.34	1.21	0	0.97	1.1	52.6	47.4	5.88	46.7	53.3	0	0	0	0	0
4	1200.35	956.77	1.34	1.21	0	0.97	1.1	52.6	47.4	5.88	46.7	53.3	0	0	0	0	0

Demand from node 1 to 4 = 150:

	objective value		Capacity Expansion Unit Vector					Link Flows					Marginal Changes in Flows				
Itr	**ULP**	**LLP**	**y1**	**y2**	**y3**	**y4**	**y5**	**x1**	**x2**	**x3**	**x4**	**x5**	**Δx1**	**Δx2**	**Δx3**	**Δx4**	**Δx5**

Base		1834.36						78.8	71.2	8.58	70.2	79.8					
1	3155.76	1641.69	5.94	5.58	0	4.75	5.16	79.1	70.9	9.21	69.9	80.1	0.29	-0.29	0.63	-0.34	0.34
2	3155.4	1641.6	6	5.51	0	4.68	5.23	79.2	70.8	9.45	69.8	80.2	0.12	-0.12	0.24	-0.12	0.12
3	3155.35	1641.57	6.03	5.48	0	4.65	5.26	79.2	70.7	9.54	69.7	80.3	0.04	-0.04	0.09	-0.05	0.05
4	3155.35	1641.56	6.04	5.47	0	4.64	5.26	79.3	70.7	9.57	69.7	80.3	0.02	-0.01	0.03	-0.01	0.02
5	3155.35	1641.56	6.05	5.47	0	4.64	5.27	79.3	70.7	9.58	69.7	80.3	0.01	-0.02	0.01	0	0
6	3155.35	1641.56	6.05	5.46	0	4.64	5.27	79.3	70.7	9.58	69.7	80.3	0	0	0	0	0
7	3155.35	1641.56	6.05	5.46	0	4.64	5.27	79.3	70.7	9.58	69.7	80.3	0	0	0	0	0

Demand from node 1 to 4 = 200:

	objective value		Capacity Expansion Unit Vector					Link Flows					Marginal Changes in Flows				
Itr	**ULP**	**LLP**	**y1**	**y2**	**y3**	**y4**	**y5**	**x1**	**x2**	**x3**	**x4**	**x5**	**Δx1**	**Δx2**	**Δx3**	**Δx4**	**Δx5**
Base		3841.48						105	94.9	11.4	93.6	106					
1	7086.93	2526.97	12.7	12.1	0	10.7	11.4	106	94.4	12.7	92.9	107	0.54	-0.54	1.22	-0.68	0.68
2	7084.89	2526.61	12.8	11.9	0	10.5	11.6	106	94.1	13.3	92.6	107	0.3	-0.3	0.64	-0.34	0.34
3	7084.33	2526.47	12.9	11.8	0	10.4	11.7	106	93.9	13.6	92.4	108	0.16	-0.16	0.34	-0.18	0.18
4	7084.17	2526.4	12.9	11.8	0	10.4	11.7	106	93.8	13.8	92.3	108	0.08	-0.08	0.18	-0.1	0.1
5	7084.13	2526.37	13	11.8	0	10.4	11.7	106	93.8	13.9	92.3	108	0.04	-0.04	0.08	-0.04	0.04
6	7084.12	2526.36	13	11.7	0	10.4	11.7	106	93.8	13.9	92.3	108	0.02	-0.02	0.04	-0.02	0.02

7	7084.12	2526.35	13	11.7	0	10.3	11.7	106	93.8	14	92.3	108	0.02	-0.02	0.02	0	0
8	7084.12	2526.35	13	11.7	0	10.3	11.7	106	93.7	14	92.3	108	0.02	-0.02	0.02	0	0
9	7084.12	2526.35	13	11.7	0	10.3	11.7	106	93.7	14	92.3	108	0	0	0	0	0
10	7084.12	2526.35	13	11.7	0	10.3	11.7	106	93.7	14	92.3	108	0	0	0	0	0

Demand from node 1 to 4 = 300:

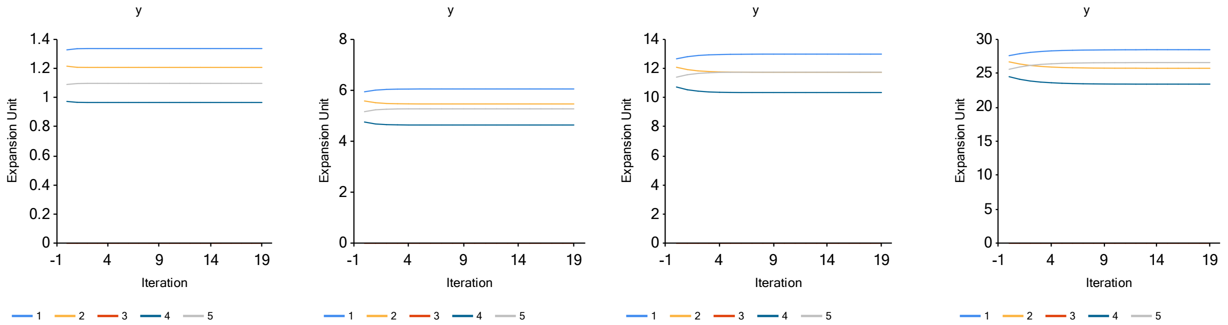
	objective value		Capacity Expansion Unit Vector					Link Flows					Marginal Changes in Flows				
Itr	**ULP**	**LLP**	**y1**	**y2**	**y3**	**y4**	**y5**	**x1**	**x2**	**x3**	**x4**	**x5**	**Δx1**	**Δx2**	**Δx3**	**Δx4**	**Δx5**
Base		18203.59						158	142	17.2	140	160					
1	21221.9	4768.99	27.6	26.7	0	24.5	25.6	159	141	19.4	139	161	1.02	-1.02	2.28	-1.26	1.26
2	21212.01	4767.84	27.9	26.4	0	24.1	25.9	159	141	20.9	138	162	0.66	-0.66	1.5	-0.84	0.84
3	21207.72	4767.24	28.1	26.1	0	23.9	26.1	160	140	21.9	138	162	0.45	-0.45	0.99	-0.54	0.54
4	21205.87	4766.9	28.2	26	0	23.7	26.3	160	140	22.6	137	163	0.3	-0.3	0.63	-0.33	0.33
5	21205.09	4766.72	28.3	25.9	0	23.6	26.4	160	140	23	137	163	0.21	-0.21	0.45	-0.24	0.24
6	21204.72	4766.6	28.3	25.8	0	23.5	26.5	160	140	23.3	137	163	0.12	-0.12	0.27	-0.15	0.15
7	21204.58	4766.53	28.4	25.8	0	23.5	26.5	160	140	23.5	137	163	0.09	-0.09	0.18	-0.09	0.09
8	21204.51	4766.49	28.4	25.8	0	23.5	26.5	161	139	23.6	137	163	0.06	-0.06	0.12	-0.06	0.06
9	21204.48	4766.47	28.4	25.8	0	23.4	26.5	161	139	23.7	137	163	0.03	-0.03	0.09	-0.06	0.06
10	21204.47	4766.45	28.4	25.8	0	23.4	26.5	161	139	23.7	137	163	0.03	-0.03	0.06	-0.03	0.03

11	21204.46	4766.43	28.4	25.7	0	23.4	26.6	161	139	23.8	137	163	0.03	-0.03	0.03	0	0
12	21204.46	4766.43	28.4	25.7	0	23.4	26.6	161	139	23.8	137	163	0	0	0.03	-0.03	0.03
13	21204.46	4766.42	28.4	25.7	0	23.4	26.6	161	139	23.8	137	163	0.03	-0.03	0.03	0	0
14	21204.46	4766.41	28.5	25.7	0	23.4	26.6	161	139	23.8	137	163	0	0	0	0	0
15	21204.46	4766.41	28.5	25.7	0	23.4	26.6	161	139	23.8	137	163	0	0	0	0	0

Figure 5 shows the graphical results for the capacity expansion vector, flow, and objective values for the upper and lower levels as the demand increases. The network users' reaction to the design changes was evaluated by iteration. This reaction guides the direction of the search for the optimal design. Also, more demand required more iterations in order to find the optimal solution. When demand was equal to 100, convergence occurred after the second iteration. When demand was equal to 300, convergence occurred after 13 iterations. The demand was increased to 150, 200 and 300 to test the sensitivity of the algorithm to the demand variable. The results from the literature and the current procedure were shown in Table 9 for the small 5 link network.

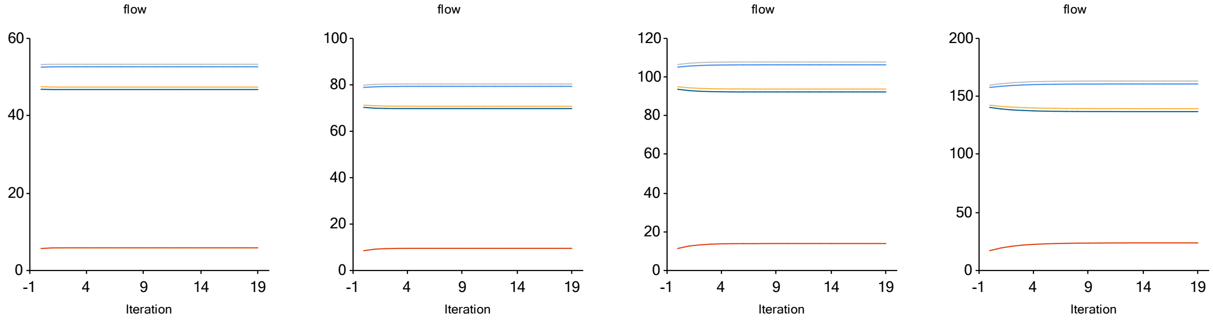
Figure 5. Results of Test Network 1 (5-Link)

Expansion vectors (y)



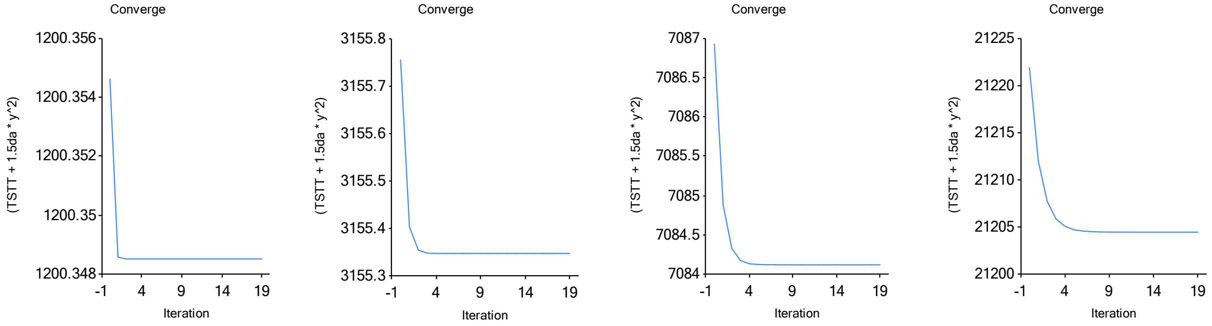
(a) demand 1 to 4 = 100 (b) demand 1 to 4 = 150 (c) demand 1 to 4 =200 (d) demand 1 to 4 = 300

flow:



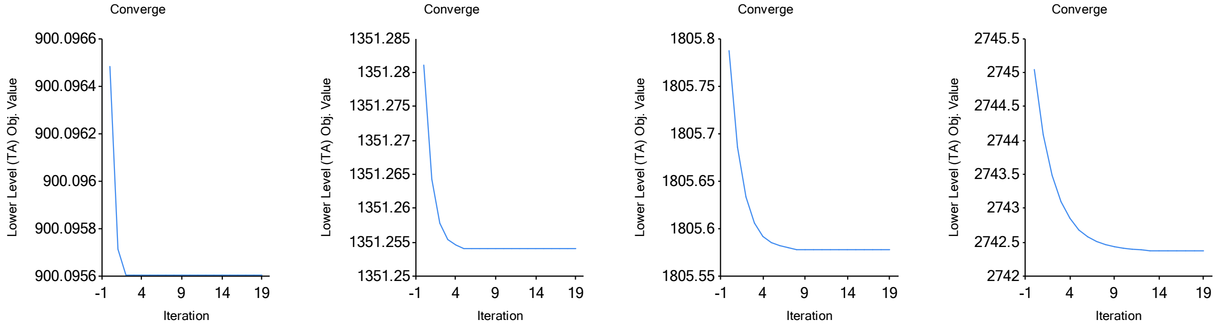
(a) demand 1 to 4 = 100 (b) demand 1 to 4 = 150 (c) demand 1 to 4 =200 (d) demand 1 to 4 = 300

Convergence of Upper Level objective value:



(a) demand 1 to 4 = 100 (b) demand 1 to 4 = 150 (c) demand 1 to 4 =200 (d) demand 1 to 4 = 300

Convergence of Lower Level objective value:



(a) demand 1 to 4 = 100 (b) demand 1 to 4 = 150 (c) demand 1 to 4 =200 (d) demand 1 to 4 = 300

Table 9. Test Network 1 after 20 Iterations

	Case	MINOS	Hooke-Jeeves (H-J)	EDO	Mathew	Current Study
1	**Demand =100**					
	y_1	1.34	1.25	1.31	1.33	1.33
	y_2	1.21	1.20	1.19	1.22	1.21
	y_3	0.00	0.00	0.06	0.02	0.00
	y_4	0.97	0.95	0.94	0.96	0.96
	y_5	1.10	1.10	1.06	1.10	1.10
	Z	1200.58	1200.61	1200.64	1200.58	1200.58
2	**Demand =150**					
	y_1	6.05	5.95	5.98	6.08	6.06
	y_2	5.47	5.64	5.52	5.51	5.46
	y_3	0.00	0.00	0.02	0.00	0.00
	y_4	4.64	4.60	4.61	4.65	4.64
	y_5	5.27	5.20	5.27	5.27	5.27
	Z	3156.21	3156.38	3156.24	3156.23	3156.21
3	**Demand =200**					
	y_1	12.98	13.00	12.86	13.04	12.98
	y_2	11.73	11.75	12.02	11.73	11.73
	y_3	0.00	0.00	0.02	0.01	0.00
	y_4	10.34	10.25	10.33	10.33	10.34
	y_5	11.74	11.75	11.77	11.78	11.74
	Z	7086.12	7086.21	7086.45	7086.16	7086.11
4	**Demand =300**					
	y_1	28.45	28.44	28.11	28.48	28.47
	y_2	25.73	25.75	26.03	25.82	25.71
	y_3	0.00	0.00	0.01	0.08	0.00
	y_4	23.40	23.44	23.39	23.39	23.41
	y_5	26.57	26.56	26.58	26.48	26.55
	Z	21209.90	21209.91	21210.54	21210.06	21209.90

Table 9 shows the results of current procedure after 20 iterations. The MINOS, Hooke-Jeeves and EDO algorithms came up with nearly identical solutions. The objective values of current solution shows better results. MINOS had the closet results to the current study. The expansion for the link 3 in optimal solution should be zero. However the EDO and Mathew approach have some values, which can indicate the small gap to the convergence. The diagrams of expansion, flow and objective function of upper level and lower level were presented in Figure 5. The results however were close to all other studies in case 2 and 3. This was happening because of the fact that the flows were converging in those case just after a couple of iterations.

Test Network 2

The test network shown in the Figure 6 consists of 6 nodes and 16 links, where two OD pairs from nodes 1 to 6 and nodes 6 to 1 are considered. Three cases of travel demand levels are used for illustration where case 1 = 2.5 - 5.0, case 2 = 5.0 - 10.0, and case 3 = 10.0 - 20.0. The travel time and investment cost functions are adopted from (Suwansirikul et al., 1987) together with the details of data input for each link.

Figure 6. Test Network 2 (16-Link)

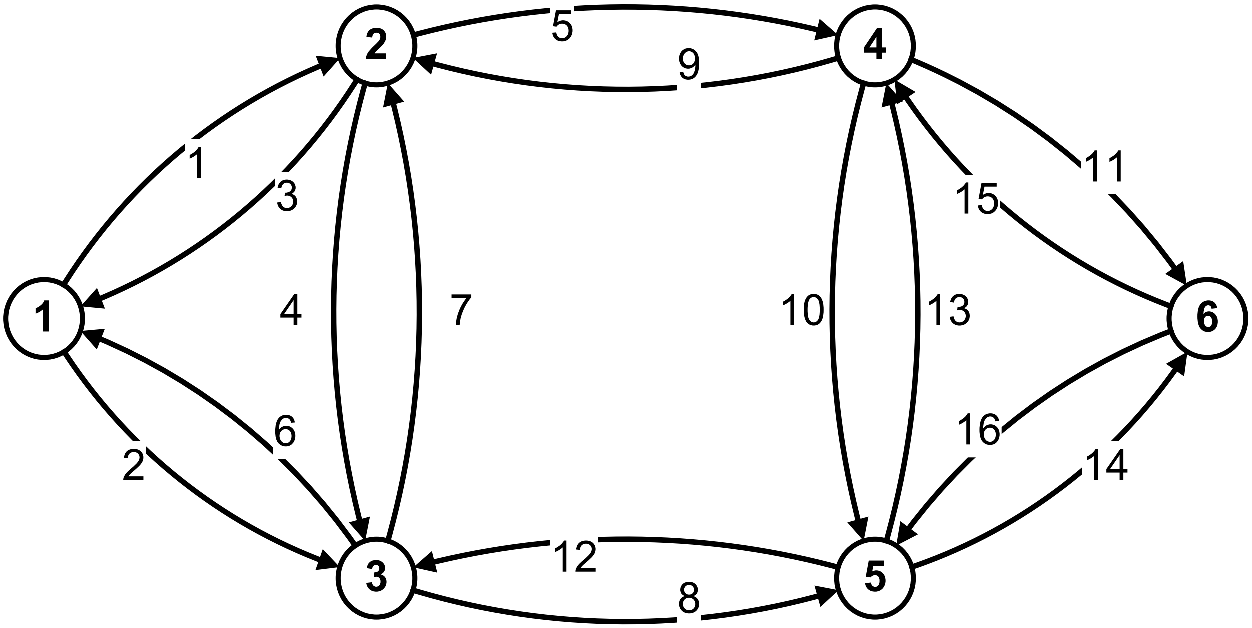
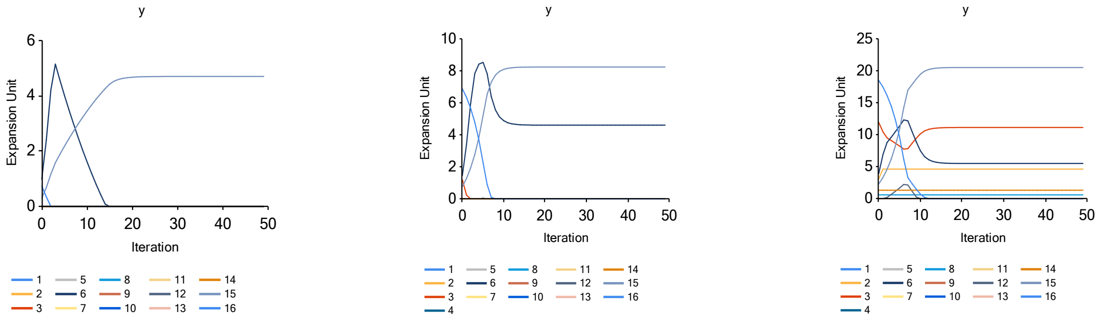


Figure 7. Test Network 2 (16-Link) Results

Expansion vectors (y)

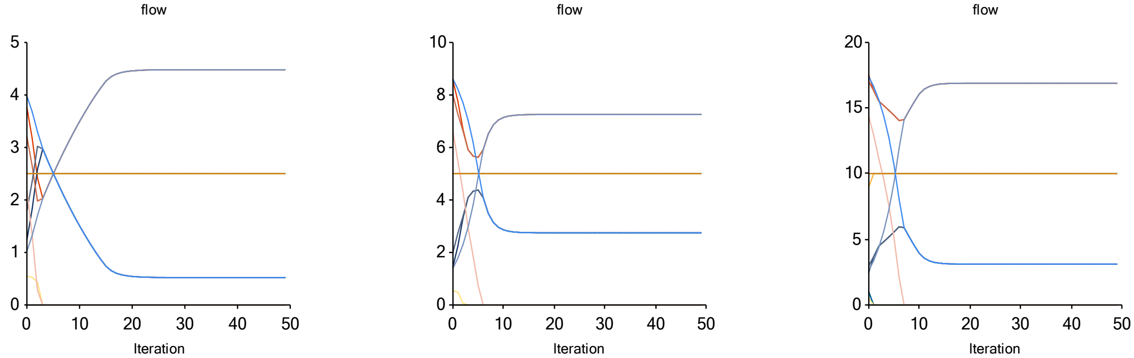


(a) Demand 1-6=2.5, Demand 6-1=5

(b) Demand 1-6=5, Demand 6-1=10

(c) Demand 1-6=10, Demand 6-1=20

flow:

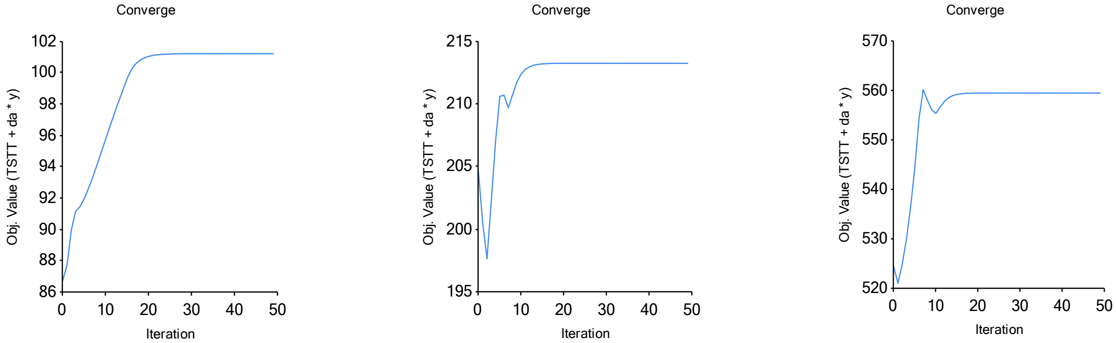


(a) Demand 1-6=2.5, Demand 6-1=5

(b) Demand 1-6=5, Demand 6-1=10

(c) Demand 1-6=10, Demand 6-1=20

Convergence of Upper Level objective value:

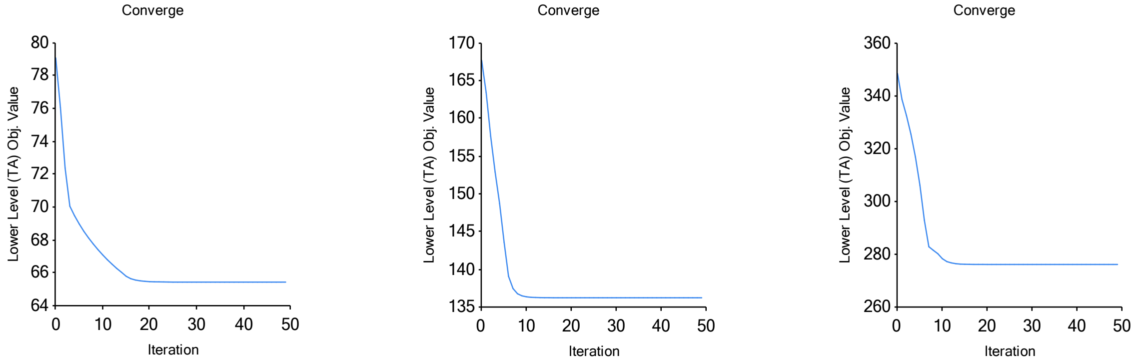


(a) Demand 1-6=2.5, Demand 6-1=5

(b) Demand 1-6=5, Demand 6-1=10

(c) Demand 1-6=10, Demand 6-1=20

Convergence of Lower Level objective value:



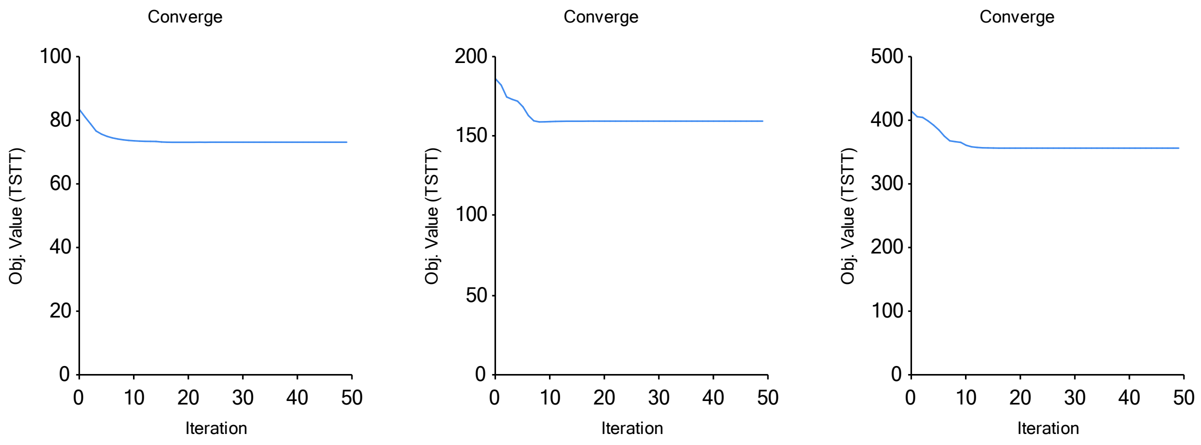
(a) Demand 1-6=2.5, Demand 6-1=5

(b) Demand 1-6=5, Demand 6-1=10

(c) Demand 1-6=10, Demand 6-1=20

The objective function value of ULP and LLP and also the flows are converging in all three different demand cases. The objective value of graph (a) converges after the second iteration, while the same value for graph (c) converges to its minimum after nine iterations. While the LLP has a decreasing objective value trend before convergence, the ULP has an increasing pattern. This behavior can be described by the elements of the objective function: The last part of the equation (9) is investment cost function. If the investment cost function is removed from the ULP graphs of Figure 7, the TSTT graph will remain as shown in Figure 8. The TSTT is decreased as the procedure converging. This means the congestion on the network was decreased.

Figure 8. Total System Travel Time for Test Network 2



(a) Demand 1-6=2.5, Demand 6-1=5

(b) Demand 1-6=5, Demand 6-1=10

(c) Demand 1-6=10, Demand 6-1=20

Table 10 compares the results from this study to the literature. For case 1, the closest results come from IOA. In this study the ULP objective value is reduced in very first iterations, and then starts increasing. So if the ULP objective value is the main concern, the decision maker may stop going further and choose the solution in iteration that gives the minimum ULP objective value. The flow and marginal changes in flow, ULP and LLP objective value, and capacity expansion vector are also shown in Table 10.

Table 10. Comparison of Results between Test Network 2 and Previous Literatures

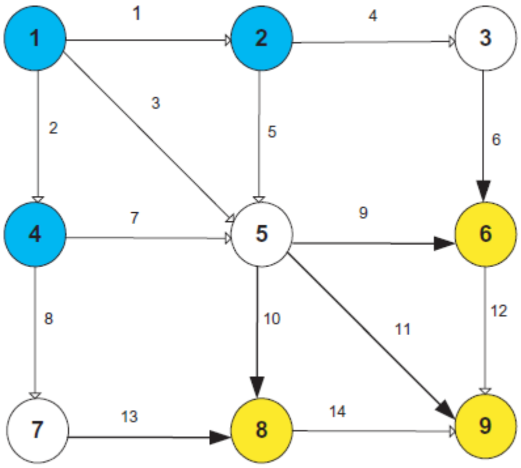
	Case 1					Case 2					Case 3				
	Demand (1,6)=2.5 Demand (6,1)=5.0					Demand (1,6)=5.0 Demand (6,1)=10.0					Demand (1,6)=10.0 Demand (6,1)=20.0				
	MINOS	H-J	EDO	IOA	Current Study	MINOS	H-J	EDO	IOA	Current Study	MINOS	H-J	EDO	IOA	Current Study
y_1															
y_2											4.61	5.4	4.88	4.55	4.61
y_3							1.2	0.13			9.86	8.18	8.59	10.65	11.11
y_4															
y_5															
y_6	5	0.3	1.84			6.58	3	6.26	6.95	4.6	7.71	8.1	7.48	6.43	5.49
y_7		0.3	0.02										0.26		
y_8											0.59	0.9	0.85	0.59	0.59
y_9															
y_{10}															
y_{11}															
y_{12}															
y_{13}															
y_{14}											1.32	3.9	1.54	1.32	1.31
y_{15}	1.33	0.1	0.02	4.44	4.69	7.01	3	0.13	5.66	8.23	19.14	8.1	0.26	19.36	20.48
y_{16}		0.3	1.84			0.22	2.8	6.26	1.79	0	0.85	8.4	12.52	0.78	0
Z	92.1	90.1	92.41	100.25	101.21	211.25	215.08	201.84	210.86	213.24	557.14	557.22	540.74	556.61	559.44

In current study, the results are close to the ones from MINOS, H-J and EDO approach at bi-level iteration five. However, with more bi-level iterations, the results become more similar to numbers from the IOA study. The bi-level convergence criterion is based on the flows. After about thirty iterations for case one and twenty iterations for cases two and three, users stopped responding to improvements. It was concluded that the MINOS, H-J and EDO approaches probably stopped after about five iterations. In case one, link six had the highest need for improvements until iteration four. However, this trend changed when the flows converged and the entire budget gradually allocated to link sixteen. Again the results from MINOS, H-J and EDO have the budget allocated to link six. The current study and the three stated studies were similar until iteration four.

Test Network 3

The third test example is a grid network as shown in Figure 9. 9-node grid network, which contains 9 nodes and 14 links and is adapted from Chiou et al. *(14)* for bi-level programming for the continuous transport network design problem. In this numerical test, it includes 9 OD pair travel demands and 5 selected links for capacity expansions.

Figure 9. 9-node grid network



As it seen from Table 11, all the solution heuristics yielded similar results and the computational performance of this methodology is compared by observing the number of Frank Wolfe (FW) evaluations, which eliminates the bias of the computing platforms. In addition, the literature supports such comparison in the form of a number of FW evaluations for design (Chiou, 2005). Although the number of FW evaluations by this methodology is much higher than the other algorithms, its solution obtained gives lower objective function value. The computational results for scaling travel demand tests are summarized in Table 12.

Table 11. Comparison of results for 9-node grid network

Case	SAB	GP	CG	QNEW	PT	EDO	Current Study
y6	0	0	0	0	0	0.0002	0
y9	0	0	0	0	0	0.0002	0
y10	0	0	0	0	0	0.0002	0
y11	0	0	0	0	0	0.0002	0
y13	128.087	128.103	137.445	137.445	127.793	137.445	75.15
Zy	4110.02	4110.02	4109.55	4109.55	4110.05	4109.56	3891.69
FW Itr.	15	12	8	4	9	17	34

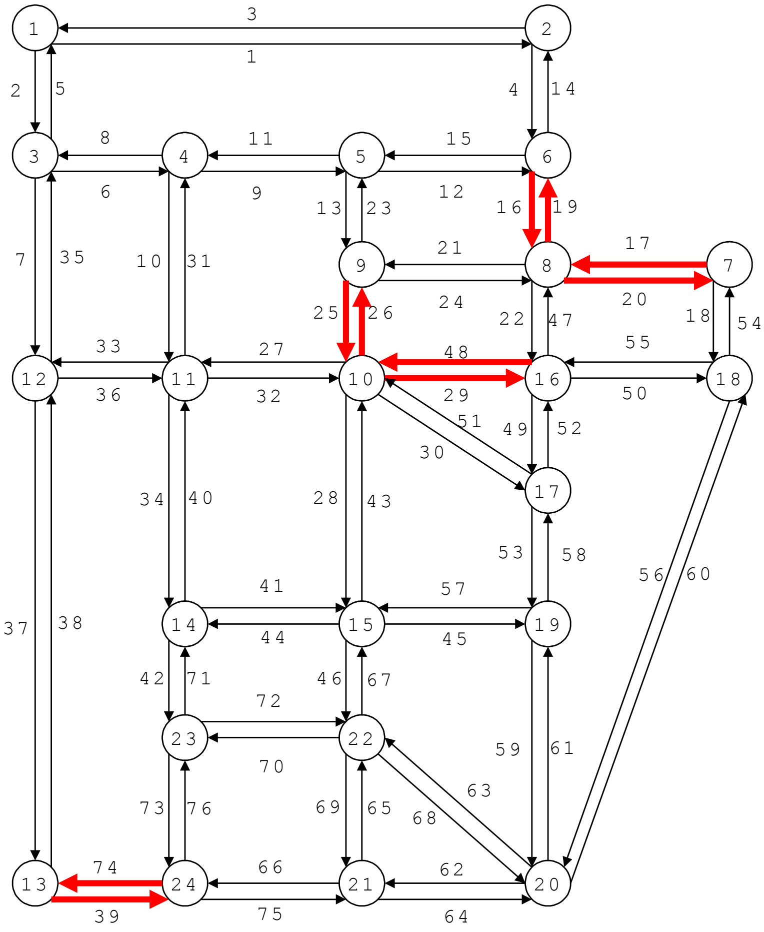
Table 12. Comparison of results on 9-node grid network with scaling factors

Scalar	SAB	GP	CG	QNEW	PT	EDO	Current Study
0.8	3043.18	3042.91	3042.91	3042.91	3043.27	3042.91	3027.90
0.9	3549.36	3549.02	3549.02	3549.02	3549.45	3549.02	3451.21
1.1	4634.97	4632.38	4632.38	4632.38	4632.38	4666	4346.82
1.2	5137.64	5135.28	5135.29	5135.29	5135.29	5195.64	4729.88
1.3	5700.01	5703.21	5697.22	5697.22	5697.22	5731.73	5378.90
1.4	6240.73	6244.02	6237.98	6237.98	6237.98	6269.12	5974.95
1.5	6858.2	6781.51	6781.51	6781.51	6781.51	6844.09	6544.21

Test Network 4

The fourth test network is the Sioux Falls network, as shown in Figure 10, which is probably the most extensively used test network for the continuous network design problem (CNDP). The network details and input parameters are adopted from the study by (Suwansirikul et al., 1987). The Sioux Falls network has 24 nodes, 76 links, and 528 nonzero OD pairs. Among the 76 links, ten links (Links 16, 17, 19, 20, 25, 26, 29, 39, 48 and 74) are the candidate links for capacity expansion. Note that candidate links are marked by red arrow in Figure 10.

Figure 10. Sioux Falls network



The optimal capacity expansion vector and the corresponding system cost is found using the proposed methodology and compared with other existing algorithms such as Hook-Jeeves (H-J), EDO, SA, sensitivity analysis based (SAB), gradient projection (GP), conjugate gradient projection (CG), quasi-Newton projection (Qnew), and Paratan version of gradient projection (PT) (Chiou, 2005), Genetic algorithm model (GA). The link expansion values and the objective function values from all these models and current study solution are tabulated in Table 13. It can be seen clearly from these results that the SA and GA are able to produce relatively good results; and among all the models current study approach is able to produce the best solution. It should be noted that in spite of relative closeness of objective function values the links expansion values are not consistent. This confirms that the problem has multiple optimal solutions. As it has been mentioned in (Suwansirikul et al., 1987), the multiple local optima exist due to the non-convexity of CNDP and evidently each method leads to a different solution to the CNDP.

In order to study the performance of the solution approach with respect to other models, sensitivity studies are conducted. Network design is done at several demand levels. The base demand is multiplied by a factor (0.8, 1.2, 1.4, and 1.6) and the method is applied. The total system cost and the number of Frank–Wolfe iterations performed under these demand levels are tabulated in Table 14. Although the number of FW evaluations by current study is much higher than the other algorithms (except IOA and GA), its solution obtained gives the lowest objective function value.

Table 13. Comparison of results for Sioux Falls network

Case	H-J	H-J	EDO	SA	SAB	GP	CG	QNew	PT	GA	Current Study
y16	4.8	3.8	4.59	5.38	5.74	4.87	4.77	5.3	5.02	5.17	5.13
y17	1.2	3.6	1.52	2.26	5.72	4.89	4.86	5.05	5.22	2.94	1.35
y19	4.8	3.8	5.45	5.5	4.96	1.87	3.07	2.44	1.83	4.72	5.13
y20	0.8	2.4	2.33	2.01	4.96	1.53	2.68	2.54	1.57	1.76	1.32
y25	2	2.8	1.27	2.64	5.51	2.72	2.84	3.93	2.79	2.39	2.98
y26	2.6	1.4	2.33	2.47	5.52	2.71	2.98	4.09	2.66	2.91	2.98
y29	4.8	3.2	0.41	4.54	5.8	6.25	5.68	4.35	6.19	2.92	4.89
y39	4.4	4	4.59	4.45	5.59	5.03	4.27	5.24	4.96	5.99	4.45
y48	4.8	4	2.71	4.21	5.84	3.76	4.4	4.77	4.07	3.63	4.97
y74	4.4	4	2.71	4.67	5.87	3.57	5.52	4.02	3.92	4.43	4.4
Zy	82.5	82.61	84.5	81.89	84.38	84.15	84.86	83.19	84.19	81.74	80.99

Table 14. Comparison of results for Sioux Falls network for different demand model

Scalar	SAB	GP	CG	QNew	PT	EDO	IOA	GA	Current Study
0.8	51.76	48.38	48.78	48.84	48.81	49.51	53.58	48.92	48.15
FW Itr.	14	10	3	4	9	7	28	59	29
1	84.21	82.71	82.53	83.07	82.53	83.57	87.34	81.74	80.99
FW Itr.	11	9	6	4	7	12	31	77	35

1.2	144.86	141.53	141.04	141.62	142.27	149.39	150.99	137.92	135.80
FW Itr.	9	11	10	7	9	12	31	67	36
1.4	247.8	246.04	246.04	242.74	241.08	253.39	279.39	232.76	229.22
FW Itr.	15	9	6	5	7	17	16	78	36
1.6	452.01	433.64	408.45	409.04	431.11	427.56	475.08	390.54	380.91
FW Itr.	14	9	9	9	11	19	40	83	40

Test Network 5

The final numerical test for demonstration is conducted on a larger grid network with 25 nodes and 44 links as shown in Figure 11, which is expanded from the 9-node grid graph and served as a general testing for computational efficiency. Computational results for the 25-node graph are summarized in Table 15 and Table 16. Again, the current study gave similar solutions to CNDP. Further tests are conducted by scaling the travel demands. As it seen from Table 16, the proposed methodology again converged to the similar values as the other models did.

Figure 11. 25-node grid network

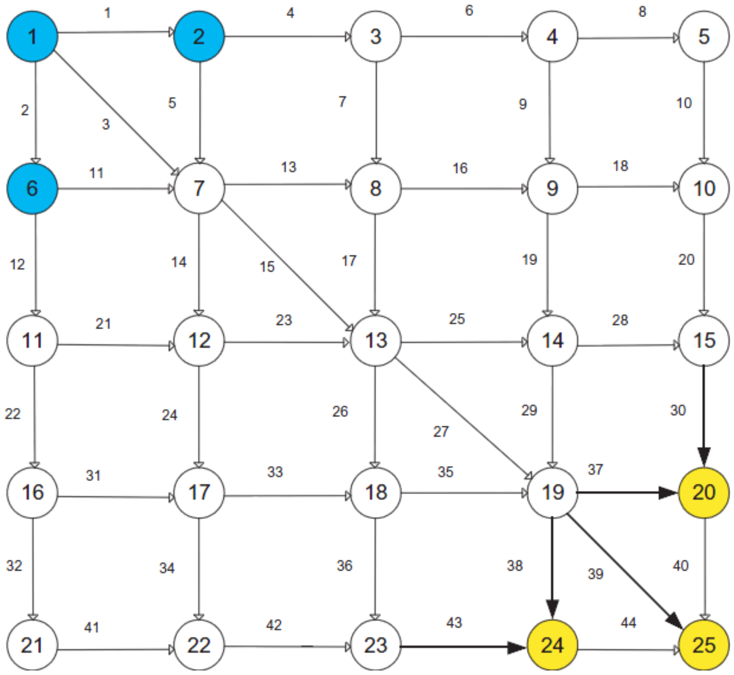


Table 15. Comparison of results on 25-node grid network

Case	SAB	GP	CG	QNEW	PT	EDO	Current Study
y30	0	0	0	0	0	0.0007	0
y37	0	0	0	0	0	0.0007	0
y38	0	0	0	0	0	0.0007	0
y39	0	0	0	0	0	0.0007	0
y43	477.836	479.778	493.953	493.953	478.253	499.324	387.46
Zy	10155.4	10155.2	10154.5	10154.5	10155.4	10168.2	10364.55

Table 16. Comparison of results on 25-node grid network with scaling factors

Scalar	SAB	GP	CG	QNEW	PT	EDO	Current Study
0.8	7590.19	7590.06	7590.19	7590.19	7590.36	7589.71	8108.75
0.9	8888.89	8888.77	8888.91	8888.91	8889.07	8888.25	9226.66
1.1	11452	11440.9	11441.1	11441.1	11441.3	11452.6	11378.61
1.2	12643.1	12632.5	12626.3	12626.3	12626.3	12642.9	12500.24
1.3	13833.7	13831.6	13831.7	13831.7	13832.1	13834.1	13683.70
1.4	15195.7	15185.6	15185.7	15185.7	15186.4	15198.3	14937.38
1.5	16371.6	16354.6	16354.6	16354.6	16354.8	16371.2	16253.29

CHAPTER 4. APPLICATION TO REAL NETWORKS

The algorithm has been applied to real networks for the purpose of testing the computational performance and real world applicability. The results showed that the UL objective function increases and LL objective function decreases respectively and becomes constant on convergence which is expected. Around 1000 iterations are applied and from the figure, it can be seen that dissimilarity between the link flow vectors reduces with each iteration and similarity is observed after about 10 iterations. It is also observed that with increase in budget values, the objective function and average travel time decreases but the average speed increases. The congested lane mile (CLM) that is the number of lanes per mile which will remain congested will decrease with increase in budget value. From these results, it can be inferred that this algorithm has real world applicability. The details of the network are given in Table 17.

Table 17. Nodes and links data of the five real networks

Network	Nodes	Links	Zones	O-D pairs with non-zero demand
Sioux Falls	24	76	24	576
Anaheim	416	914	38	1,416
Chicago Sketch	933	2,950	387	93,135
Washington DC	1,752	4,420	225	50,625
Atlanta	1,102	2,295	144	20,736

The following are the results after applying it to five different networks:

Sioux Falls, SD

This network is also used as a test network (Test Network 4). In Figure 12, we find that LL objective function decreases with each iteration whereas UL objective function increases with each iteration. After around 10 iterations, both the UL and LL objective functions become constant thereby indicating that the algorithm is converged and the values do not change after any further iteration. In Figure 13, we find that the dissimilarity of link flow vectors decrease with each iteration and after about 10 iterations, the link flow vectors are all similar and they do not change with any further iteration. This shows that the flow values has been assigned to the network links and with further iteration the link flows will remain same. Figure 14 shows the different investment scenarios. It can be seen that with increasing budget, the objective function and the average travel time decreases whereas the average speed increases exponentially. The congested lane mile (CLM), which is the number of lanes per mile that is congested, also decreases with increasing budget but the decrease is non uniform. It can be observed that at the budget of 200 million, all the values become constant and with further increase in investment, no improvement can be expected.

Figure 12. Sioux Falls model LL and UL objective function values with increasing iteration

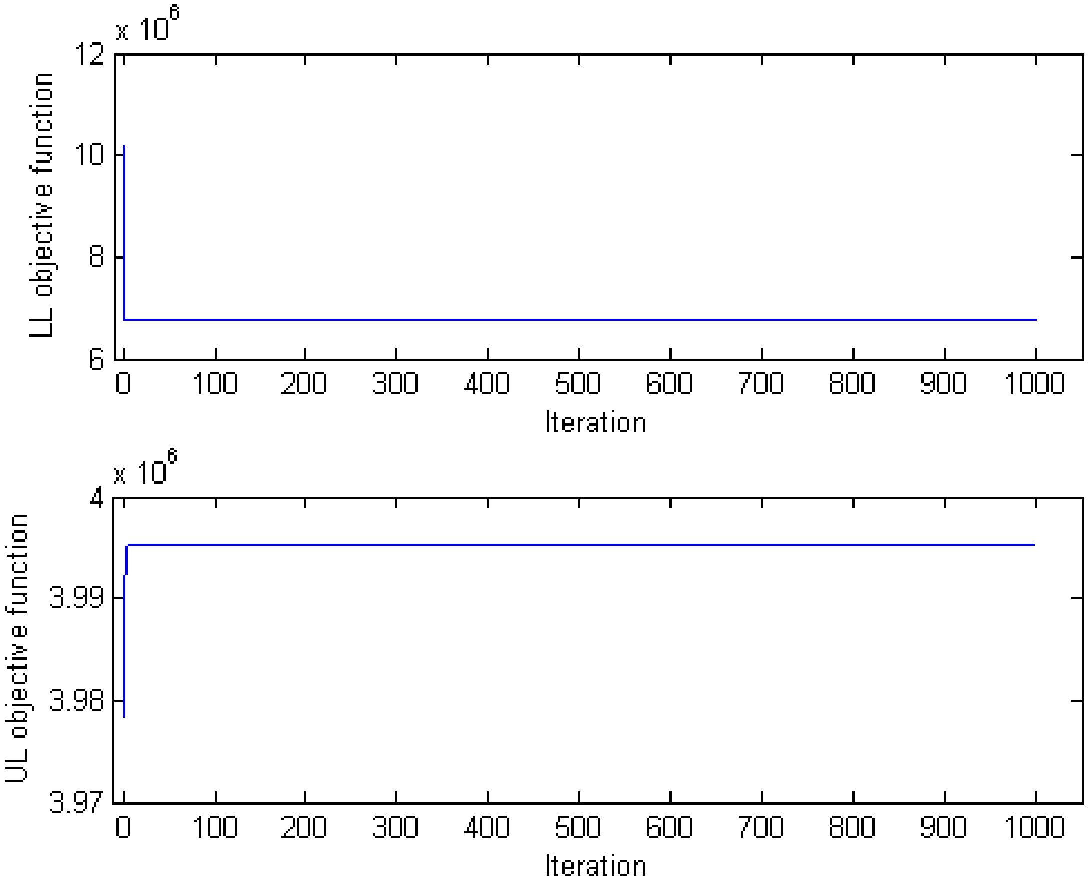


Figure 13. Sioux Falls model dissimilarity of link flow vectors with increasing iteration

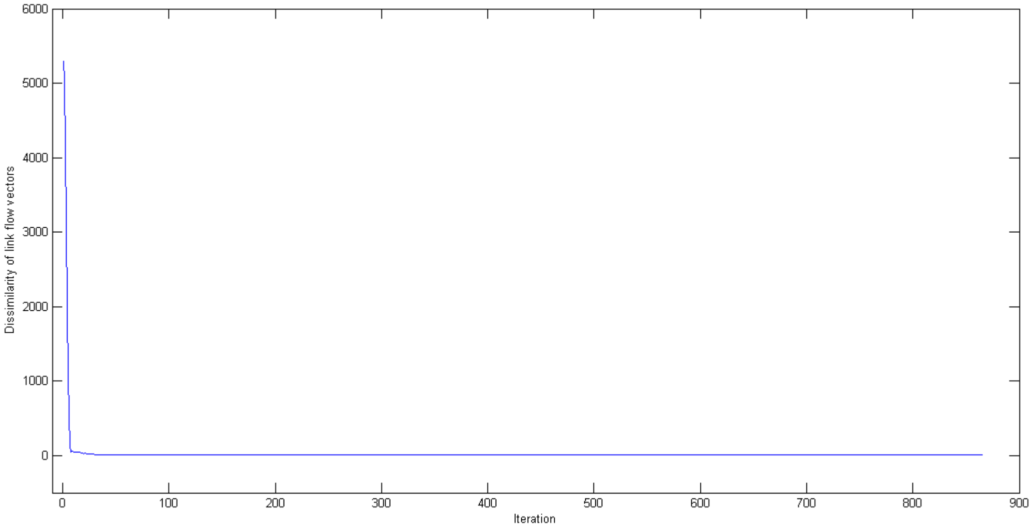
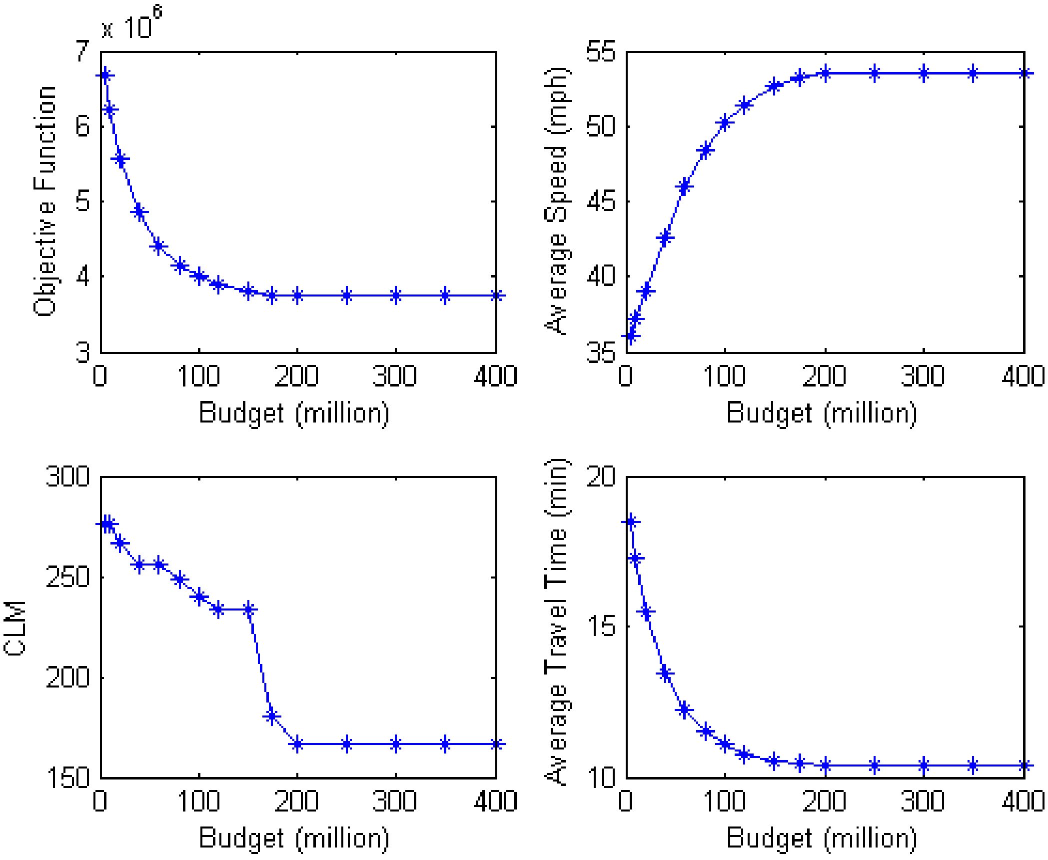


Figure 14. Sioux Falls model investment scenarios



Anaheim, CA

Figure 15 shows the structure of the Anaheim network. In Figure 16, we find that LL objective function decreases with each iteration whereas UL objective function increases with each iteration. After around 5 iterations, both the UL and LL objective functions become constant thereby indicating that the algorithm is converged and the values do not change after any further iteration. In Figure 17, we find that the dissimilarity of link flow vectors decrease with each iteration and after about 5 iterations, the link flow vectors are all similar and they do not change with any further iteration. This shows that the flow values has been assigned to the network links and with further iteration the link flows will remain same. Figure 18 shows the different investment scenarios. It can be seen that with increasing budget, the objective function and the average travel time decreases whereas the average speed increases exponentially. The congested lane mile (CLM), which is the number of lanes per mile that is congested, also decreases with increasing budget but the decrease is non uniform. It can be observed that at the budget of 250 million, all the values become constant and with further increase in investment, no improvement can be expected.

Figure 15. Anaheim network

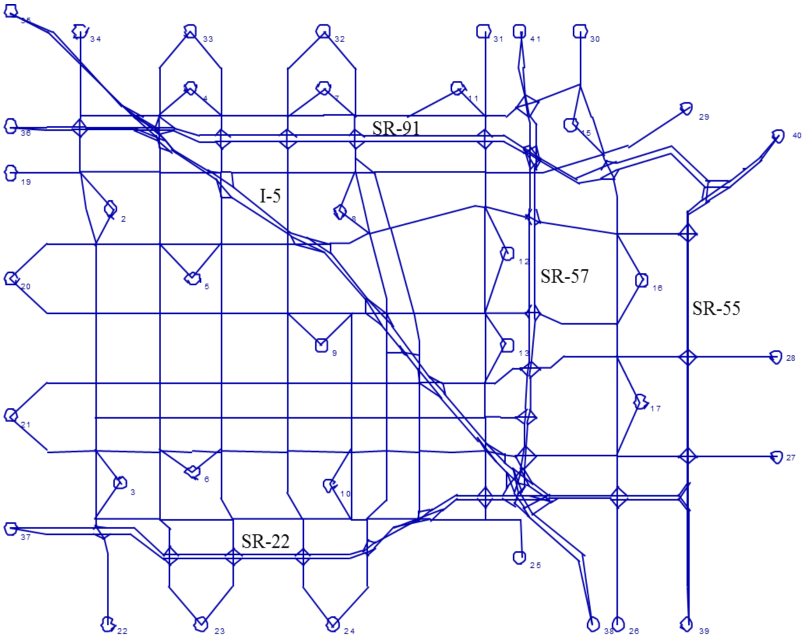


Figure 16. Anaheim model LL and UL objective function values with increasing iteration

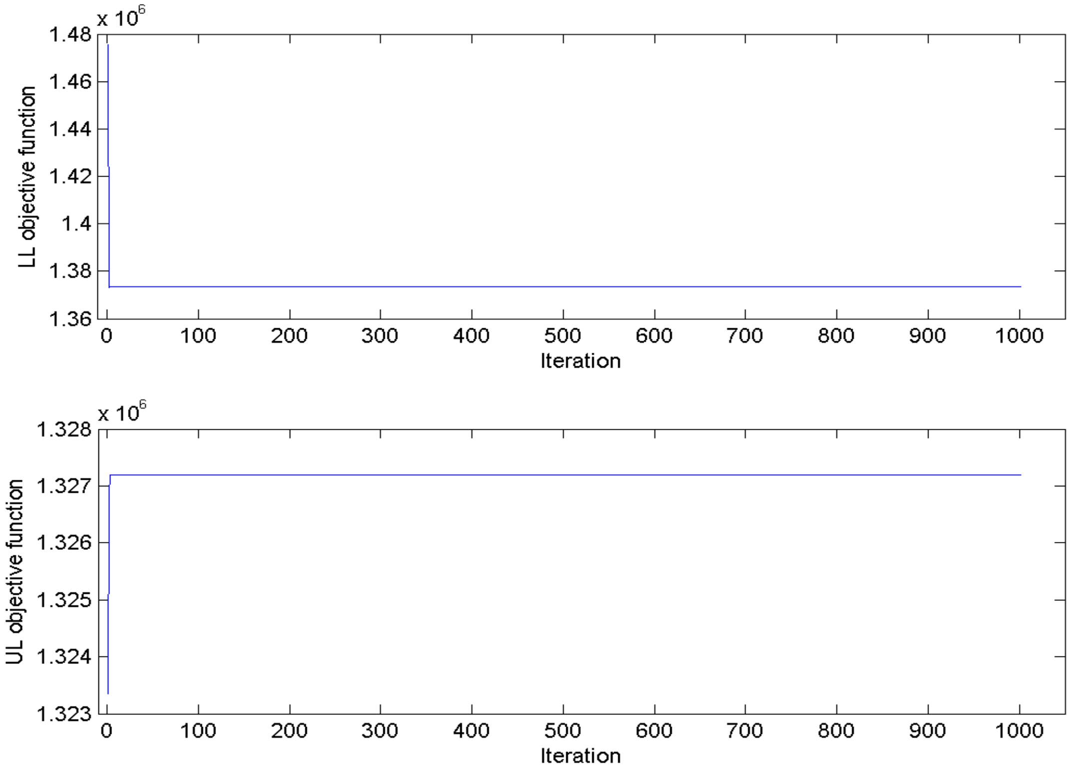


Figure 17. Anaheim model dissimilarity of link flow vectors with increasing iteration

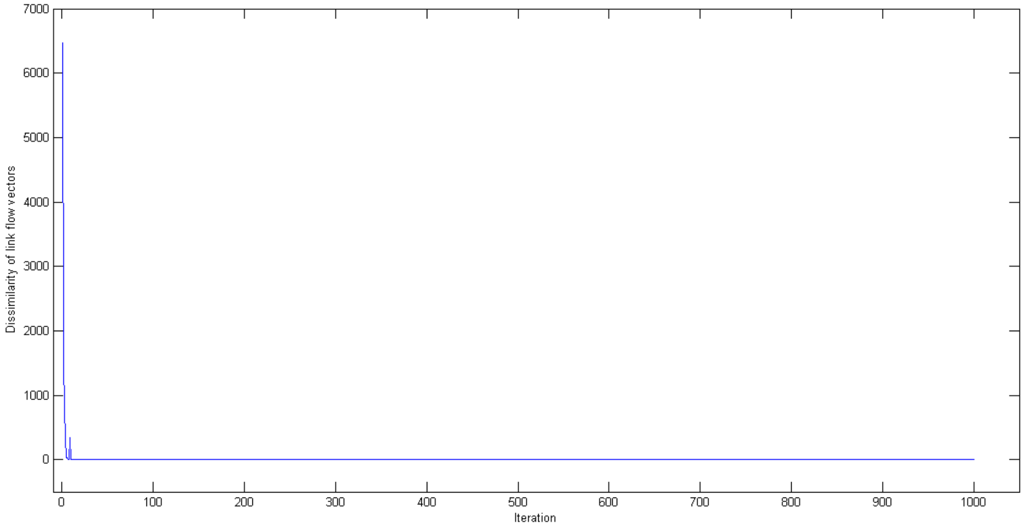
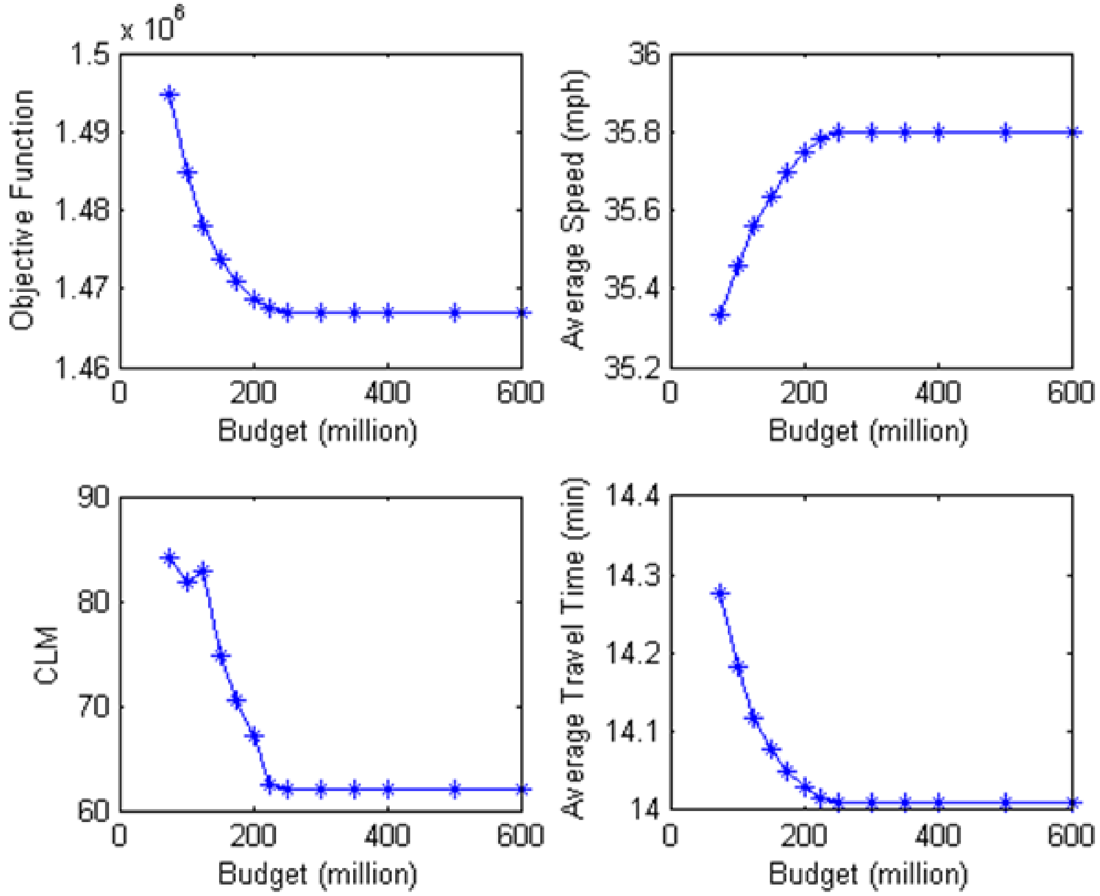


Figure 18. Anaheim model investment scenarios



Chicago, IL

Figure 19 shows the structure of the Chicago network. In Figure 20, we find that LL objective function decreases with each iteration whereas UL objective function increases with each iteration. After around 5 iterations, both the UL and LL objective functions become constant thereby indicating that the algorithm is converged and the values do not change after any further iteration. In Figure 21, we find that the dissimilarity of link flow vectors decrease with each iteration and after about 5 iterations, the link flow vectors are all similar and they do not change with any further iteration. This shows that the flow values has been assigned to the network links and with further iteration the link flows will remain same. Figure 22 and Figure 23 show the different investment scenarios. It can be seen that with increasing budget, the objective function and the average travel time decreases whereas the average speed increases uniformly. The congested lane mile (CLM), which is the number of lanes per mile that is congested, also decreases with increasing budget but the decrease is non uniform. It can be observed that at the budget of 600 million, all the values become constant and with further increase in investment, no improvement can be expected.

Figure 19. Chicago network

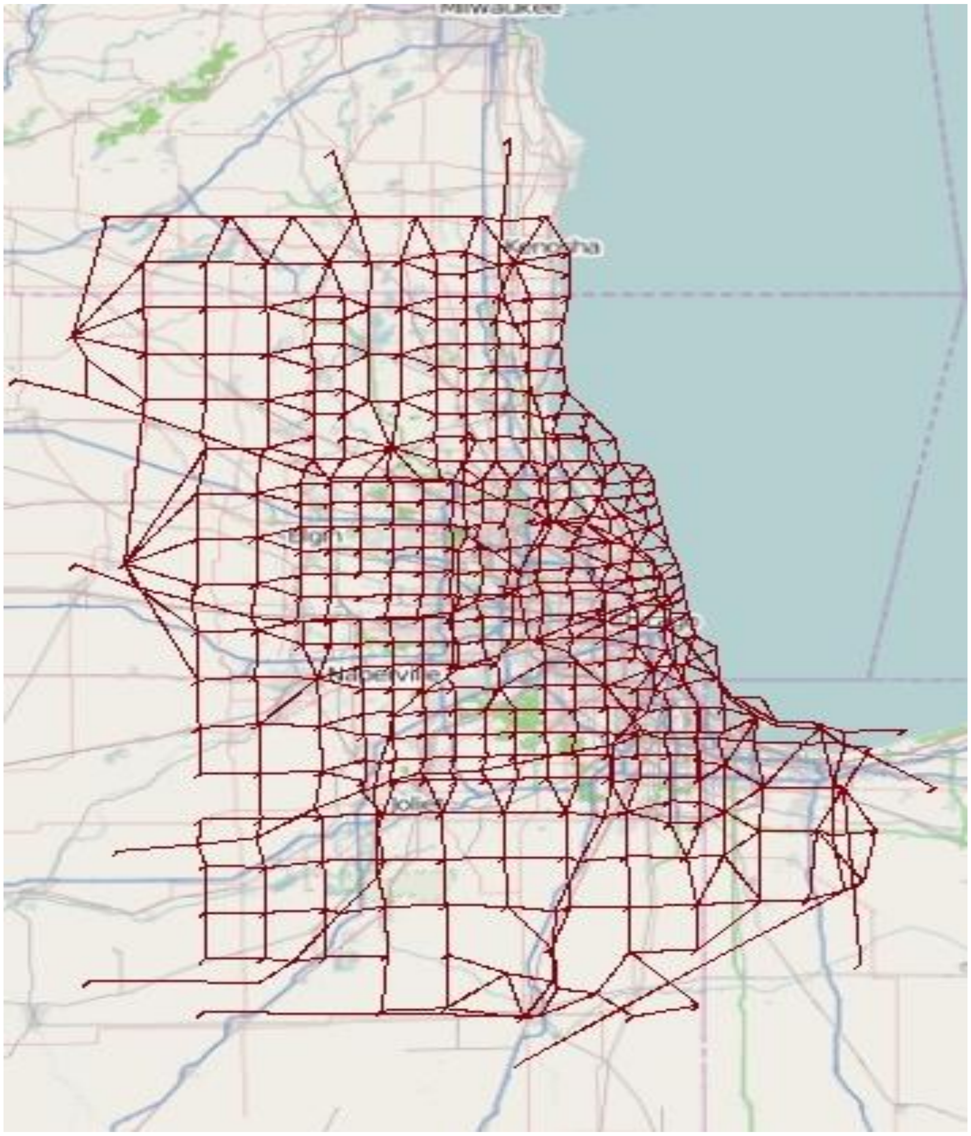


Figure 20. Chicago model LL and UL objective function values with increasing iteration

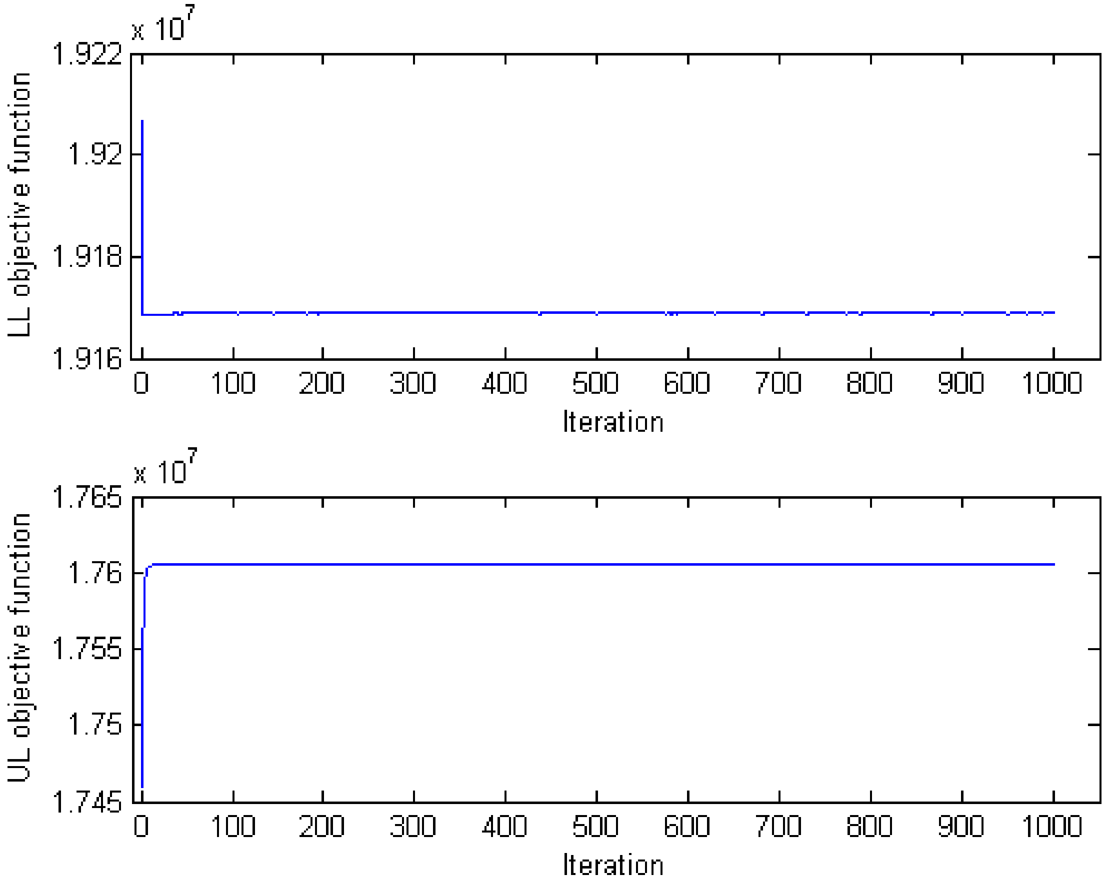


Figure 21. Chicago model dissimilarity of link flow vectors with increasing iteration

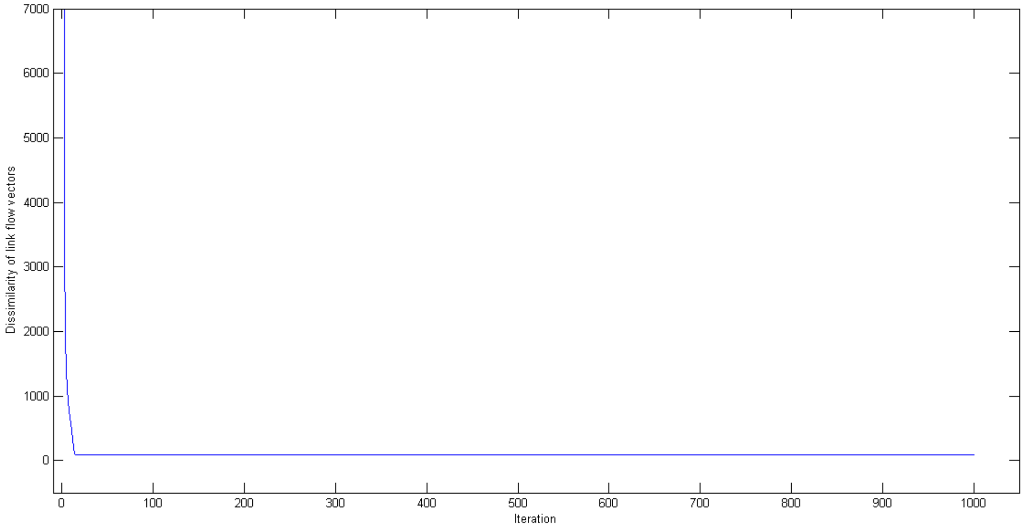


Figure 22. Chicago model investment scenarios

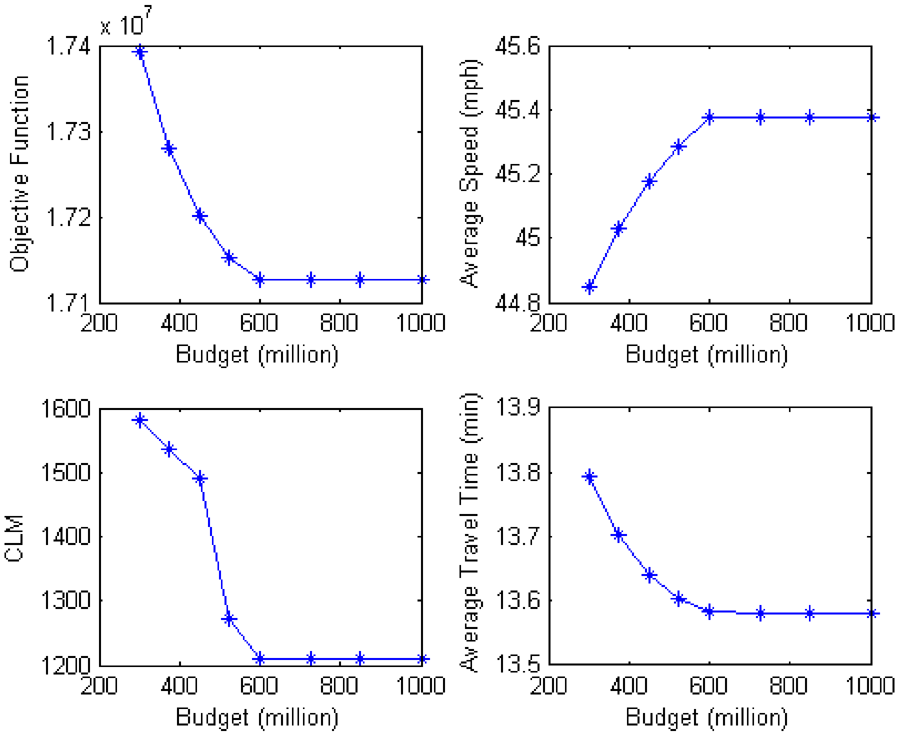
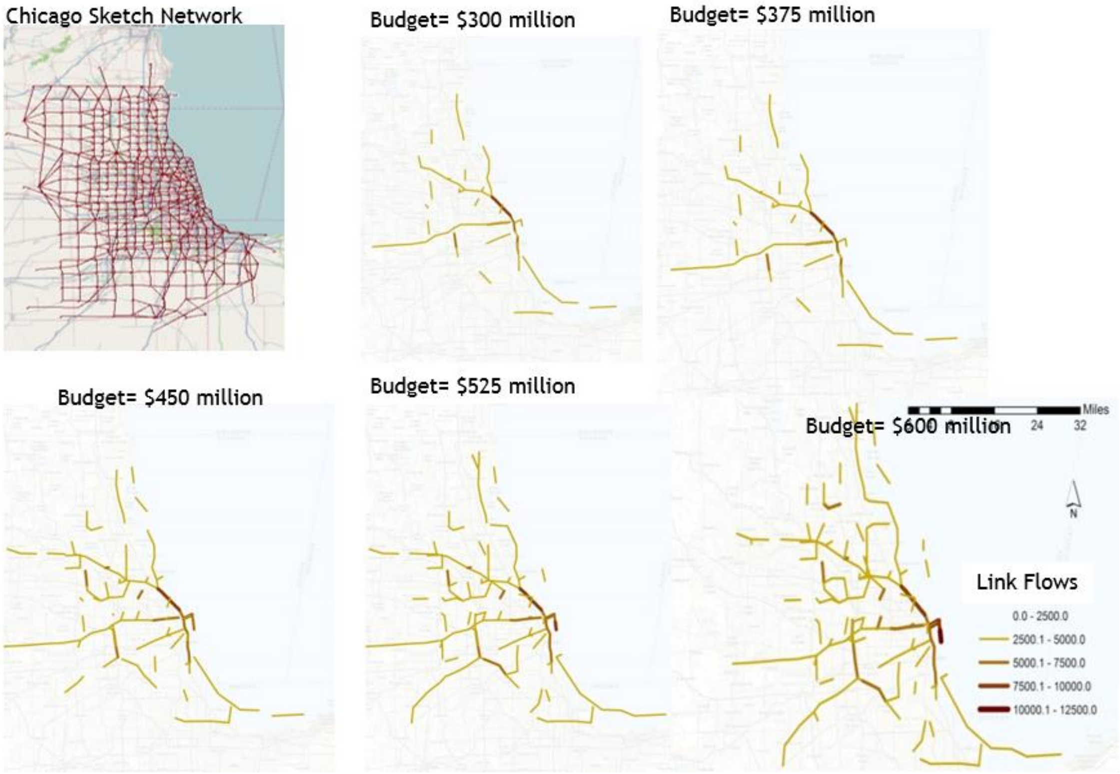


Figure 23. Chicago model investment scenarios under certain threshold



Montgomery County, MD

Figure 24 shows the structure of the Montgomery County network. Figure 25 shows the different investment scenarios. It can be seen that with increasing budget, the objective function and the average travel time decreases whereas the average speed increases but it is non-uniform. The congested lane mile (CLM), which is the number of lanes per mile that is congested, also decreases with increasing budget and the decrease is also non uniform. It can be observed that at the budget of 300 million, all the values become constant and with further increase in investment, no improvement can be expected.

Figure 24. Montgomery County Network

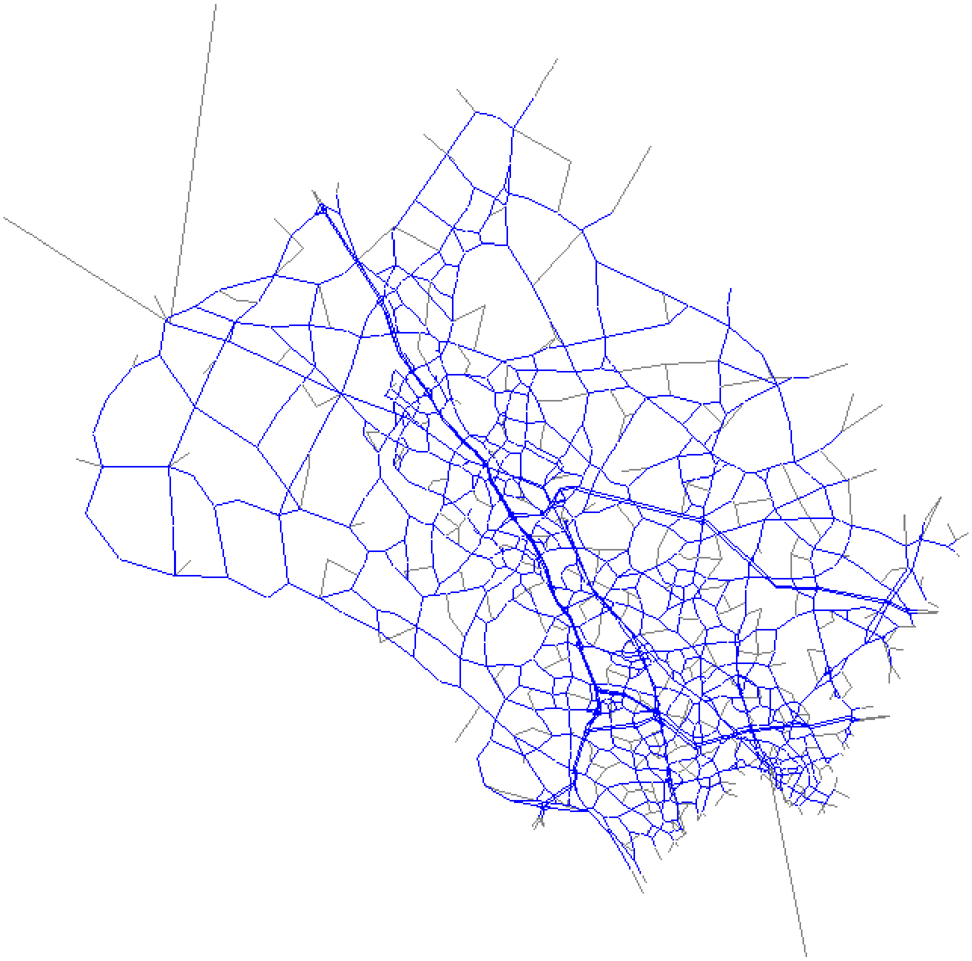
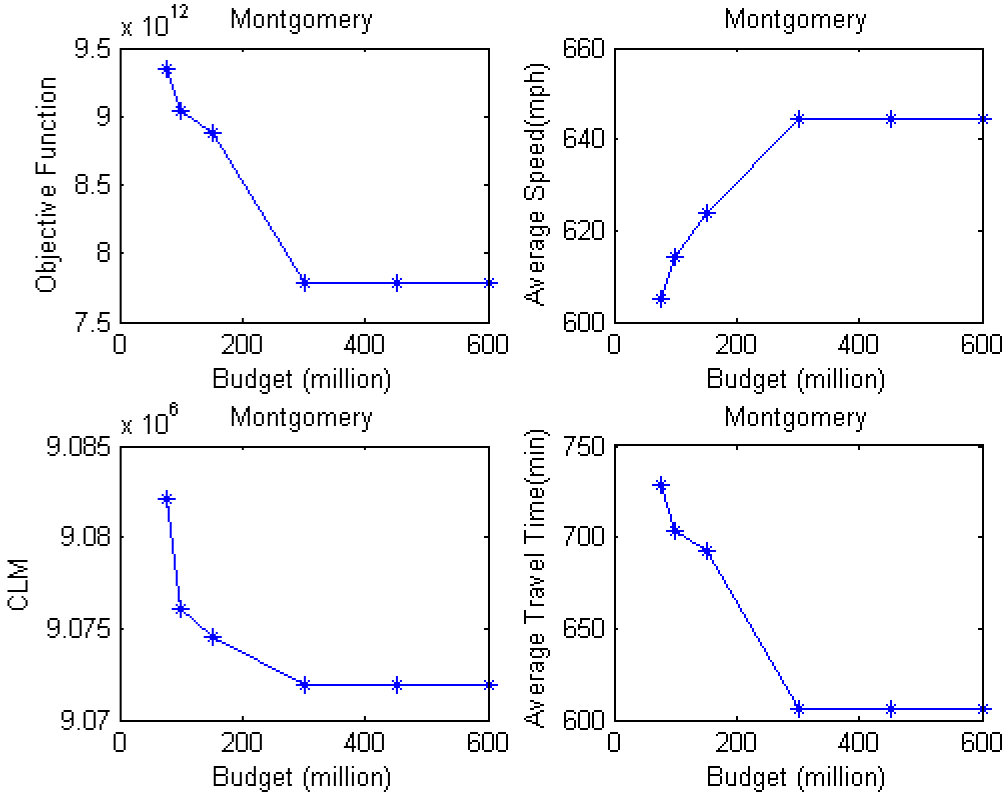


Figure 25. Montgomery County model investment scenarios

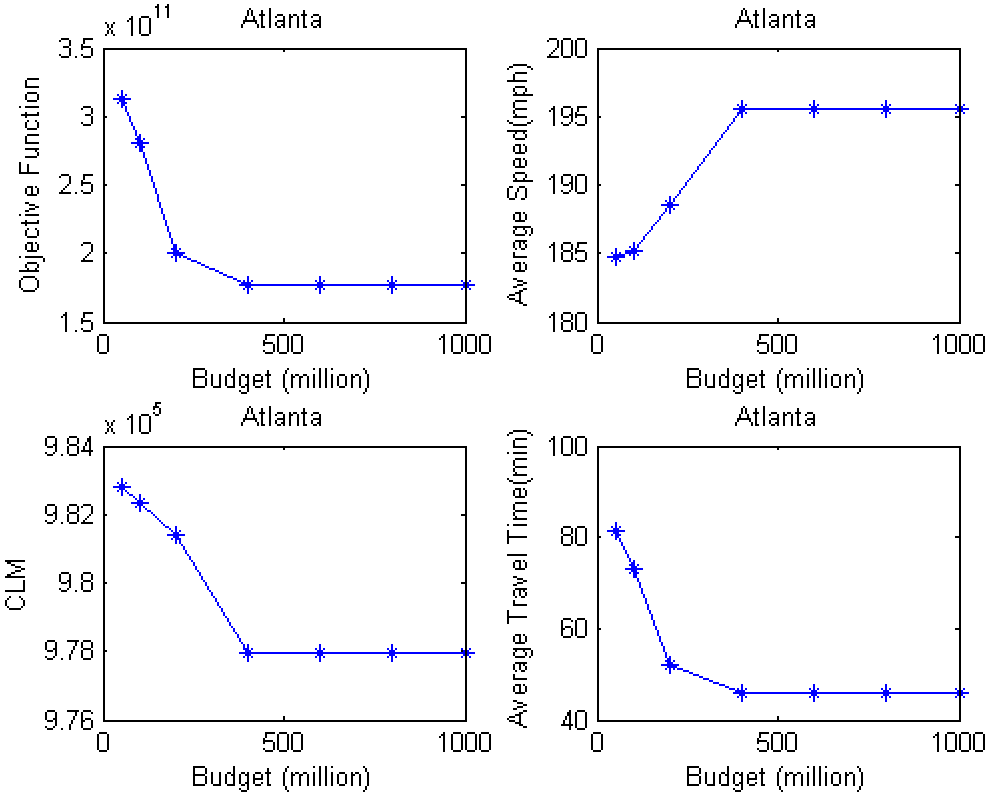


Atlanta, GA

Figure 26 shows the structure of the Atlanta network. Figure 27 shows the different investment scenarios. It can be seen that with increasing budget, the objective function and the average travel time decreases whereas the average speed increases but it is non-uniform. The congested lane mile (CLM), which is the number of lanes per mile that is congested, also decreases with increasing budget and the decrease is also non uniform. It can be observed that at the budget of 375 million, all the values become constant and with further increase in investment, no improvement can be expected.

Figure 26. Atlanta network

Figure 27. Atlanta model investment scenarios



CONCLUSIONS

Transportation agencies need a quantitative method for ranking their projects for budget allocation. In this study, a bi-level approach was used to address this issue. The objective for the upper level problem was defined as reducing the congestion. Other performance measures could be considered such as reducing pollution, improving accessibility, safety and other MOEs. The planner in upper level found the optimal projects for investment. The lower level problem involved finding the user's equilibrium via the Frank Wolfe algorithm.

The expansion capacity vectors were passed to the lower level in order to obtain the user's response. The methodology was validated by comparing the results with previous literatures within five separate test networks. The results provided a single optimal solution and after several iterations, the users in all test networks stopped responding to additional improvements defined in the upper level objective function. This means the flows, which are the convergence criteria within a bi-level optimization problem, achieved convergence. The presented results were similar to the results from other studies. It was found that the bi-level method required more iterations than several of the previous studies had shown. This implies that the number of bi-level iterations should not stop until the flows converge to constant values. The sensitivity analysis of the study is performed by designing the networks at different demand levels. The resilience of the solution when demand increases the design demand is also carried out. This advocates the use of current study as it offers a resilient solution.

The algorithm also has been applied to five real networks Anaheim, Sioux Falls, Atlanta, Chicago and Montgomery for the purpose of testing the computational performance and real world applicability. The results showed that the UL objective function increases and LL objective function decreases respectively and becomes constant on convergence. Similarity between the link flow vectors are observed on convergence. With increase in budget values, the objective function and average travel time decreases but the average speed increases. The congested lane mile decrease with increase in budget value. Hence it can be concluded that this algorithm has real world applicability.

Future Work

This methodology could be expanded for multi-objective problems. Since the decision makers usually deal with different objective viewpoints, they must attempt to satisfy all of the objectives in consideration. The correct approach should consider multi performance measures.

This study only considered the budget to be allocated without considering the time factor of money. Another aspect to consider is multi-year investment. The budget can be allocated during multi-year spans. The expected results would include the amount of budget that should be allocated for each year of the analysis period. Risk analysis could be performed due to the uncertainties in demand, discount rate, travel times and other parameters. Since a series of simulations would be incorporated into this approach, the computational performance would have to be considered.

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