MOUNTAIN-PLAINS CONSORTIUM

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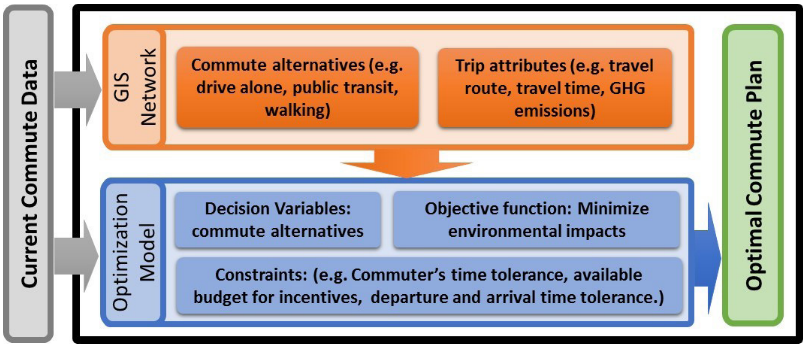
Business and Commute Optimization System: Development and Denver-based Case Study



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Disclaimer

ABSTRACT

Mitigating traffic congestion and reducing transportation emissions are among the leading goals of most local, regional, national, and international agencies. Several guidelines rely primarily on strategies that support the following: 1) mixed land-use and transit-oriented developments, 2) multimodal transportation systems, and 3) design of active transportation-friendly environments. While these approaches have successfully contributed to the reduction of transportation Green House Gas (GHG) and air pollution emissions, this research proposes to develop an innovative system that can add further improvements and provide more effective and individualized action plans. Specifically, this project focuses on developing and implementing a new system to identify the optimal selection of business commute alternatives to minimize negative environmental impacts, as well as commuting time and cost for commuters in Denver and, eventually, the United States. The project report is organized in three sections that focus on the following: 1) exploring student commute behavior at two universities and identifying opportunities to minimize commute GHG and air pollution emissions; 2) identifying optimal trade-offs of time and environmental impacts for businesses commuters; and 3) identifying the optimal selection of commuting alternatives for business employees in order to minimize GHG and air pollution emissions as well as commuting time and cost.

The first phase of the project was an exploratory pilot study performed at two universities, University of Colorado Denver and California State University at Fresno. In this pilot study, undergraduate students in four engineering classes completed a two-day travel survey eliciting their commute choices and preferences to and from campus. This phase of research presents the analysis and discussion of these survey results. It uncovers student commute patterns and explores preferences and potential incentives to understand commute travel mode values, concerns, and choices. Initial findings reveal a high reliance on individual automobiles and highlight significant opportunities to optimize student commute footprints. The findings presented in Section 1 include a supporting case study, which resulted in a publication (Clevenger et al. 2016).

This second phase of the project sought to develop and implement a novel and innovative optimization system capable of identifying optimal trade-offs among two important transportation objectives: minimizing negative environmental impacts and commute times. This system identifies each commuter’s optimal commute mode, such as drive existing vehicle, carpool, use public transit, bike, or walk, to achieve the aforementioned objectives. The system is designed to 1) maintain convenience, such as departure and arrival times, and commute duration; and 2) motivate commuters with incentives such as monetary gain, and greater awareness of burned calories, health benefits, and saved commute times and costs due to changes in commute behavior. A case study of students at University of Colorado Denver was used to verify the system performance and demonstrate its use. The case study results show that GHG and air pollution emissions can be minimized in the student community by up to 26%, while minimizing total commute time and cost for students. The findings of the second phase of the project resulted in a publication (Monghasemi et al. 2018), and are presented in Section 2.

The third phase of this project sought to develop an optimization model capable of identifying the optimal selection of individualized business commute alternatives in order to minimize GHG and air pollution emissions, commute time, and cost. This model identifies the optimal commute mode for each commuter (e.g., drive car, carpool, use public transit, or walk) that minimizes the aggregate negative environmental impacts, time, and cost for businesses while maintaining convenience. The optimization model is integrated with a geographical information system (GIS) to identify business commute attributes such as emissions and commute cost and time of each commute alternative. The performance of the developed optimization model is tested and verified using a case study of a student community at California State University at Fresno. Results of the case study illustrate the capabilities of the optimization model in minimizing business commute emissions, time, and cost. The findings of the third phase of the project resulted in a publication (Abdallah et al. 2017), and are presented in Section 3.

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1.1 Introduction

The Environmental Protection Agency (EPA) reported that the transportation sector in the United States accounts for 27% of total reported Green House Gas (GHG) emissions, second only to the electricity sector (Environmental Protection Agency 2013; U.S. EPA Office of Policy 2015). Passenger cars and light-duty trucks account for over half of the emissions from this sector, which includes sport utility vehicles, pickup trucks, and minivans. Drive-alone (single occupancy) trips have been increasing for many decades and are now the predominant mode of transportation during commuting. For example, in 1980, drive-alone trips accounts for 64.3% of commutes. However, by 2010, this percent had risen to 76.6% (American Association of State Highway and Transportation Officials 2013).

Research suggests that student commuters form a unique commuter population. Specifically, students are more likely to use alternative modes of transportation, particularly for their secondary commuter mode (Hu and Schneider 2014). While weather conditions influence the likelihood that university students will commute using alternative transportation modes, this effect is less pronounced with students than with the general commuter population (Nankervis 1999). In addition, parking prices, gender, and the existence of children can significantly influence student choice of transportation mode (Delmelle and Delmelle 2012). Students with an extra hour or more of commute time tend to visit their university less but stay longer when they are on campus. Nevertheless, research suggests that longer commute times may result in lower grades. However, the magnitude of the effect is uncertain (Kobus et al. 2015).

In addition to convenience, research suggests that heavy reliance on the automobile across commuter populations may be partly attributed to subsidization of automobile parking compared with the alternative forms of transportation (Shoup and Association 2005). In the case of students, however, even subsidized parking rates may be non-trivial. For example, at the University of Colorado Denver, student parking generally costs approximately $4.50 to $6.00 per day; at California State University, Fresno students can pay $93 per semester for a parking pass, which averages to $1.16 per day.

Research by Hamre and Buehler found that offering commuters transit benefits, showers or lockers, or bike parking as an alternative to paying for parking increased their likelihood to use transit, walk, or cycle to work. However, the existence of free parking seemed to offset this increased likelihood (Hamre and Buehler 2014). Similarly, research conducted by Yang et al. uncovered significant associations among the following: 1) walking time from home to transit stops and using worksite incentives for public transit, and commuting by public transit; 2) commuting distance and active commuting; and 3) the existence of free or low-cost recreation facilities around the worksite and using bike facilities to lock bikes at the worksite, and active commuting (Yang et al. 2015).

Despite the contribution of the aforementioned studies in understanding commute behavior and reducing commute environmental impacts, there is limited research on understanding the commute behavior of student communities and identifying innovative opportunities for minimizing GHG and air pollution emissions.

1.2 Research Objective

The primary objectives of this research are to 1) understand the commute behavior of students at University of Colorado Denver and California State University, Fresno, 2) investigate and compare commute patterns and preferences among select populations of engineering students at the aforementioned two campuses, and 3) identify opportunities for minimizing GHG and air pollution emissions for student communities. To accomplish these objectives, an online survey was conducted to gather information on student commute modes to and from campuses, commute times, and commute mode preferences. This research supports a broader objective, which is further developed in succeeding publications, to identify and develop individual incentives to optimize business commute footprints.

1.3 Methodology

Pilot data were collected using an online survey instrument, which was developed by the authors and designed to take students 10 minutes or less to complete. The data collected document real-world commute behaviors for 25 University of Colorado Denver and 38 California State University, Fresno (total population 63) undergraduate and graduate engineering students as they commuted to and from their respective campuses on two consecutive school days in May 2015. Survey participants were selected using a convenient sampling method and, therefore, response rate is not available. Students were asked three primary types of questions:

1) Commute mode choice options and choices
2) Commute arrival and departure times and locations and intermediate stops and their durations
3) Commute mode preferences and evaluation using pairwise comparisons

Data were analyzed using both descriptive and inferential statistics. Descriptive statistics were used to summarize and describe the data collected in terms of frequency, percentages, and distributions. Inferential statistics were performed using a series of analyses computed with SAS Release 3.4 (Basic Edition). The main objective of this analysis was to investigate relationships between proposed commuter scenarios (more desirable versus less desirable) and incentive levels for students at University of Colorado Denver and University of California, Fresno. Duplicate and erroneous (inconsistent ranking) data were omitted from these analyses. Due to the sample size as well as the simplifications and assumptions made during analysis, the statistical analyses, while informative regarding the participant populations, do not necessarily extend to any wider population.

1.4 Case Study Results and Analysis

The following sections use descriptive statistics to summarize and describe the survey findings regarding the commute duration, departure and arrival times, mode, and commuter chain for the students surveyed (respondents).

1.4.1 Duration and Distance

The survey was designed to collect from students' data regarding location and time using the crossroads of their point of origination, campus building destinations, and afternoon and morning departure and arrival times. The results of the survey showed that the majority of student commuters in the two study areas had travel times that ranged between 20-30 minutes, as shown in Figure 1.1. The distribution of travel times for respondents in the Fresno area was similar to the shape of a normal curve, while the distribution of travel times for respondents in the Denver area was skewed toward longer commute times. The average commute times and distances of the two study areas are summarized and listed in Table 1.1

and Table 1.2, respectively. Average commute times were higher in the Denver area. However, average commute distances were slightly lower. In general, commute distances are less dependent on mode of transportation. In the GIS model utilized for this case study, the different transportation modes utilized the same transportation network (i.e., cars, busses, bikes, and pedestrians used the same transportation network segments); therefore, travel distances were nearly identical for all transportation mode alternatives. In reality, bike routes and pedestrian bridges could change commuting distances.

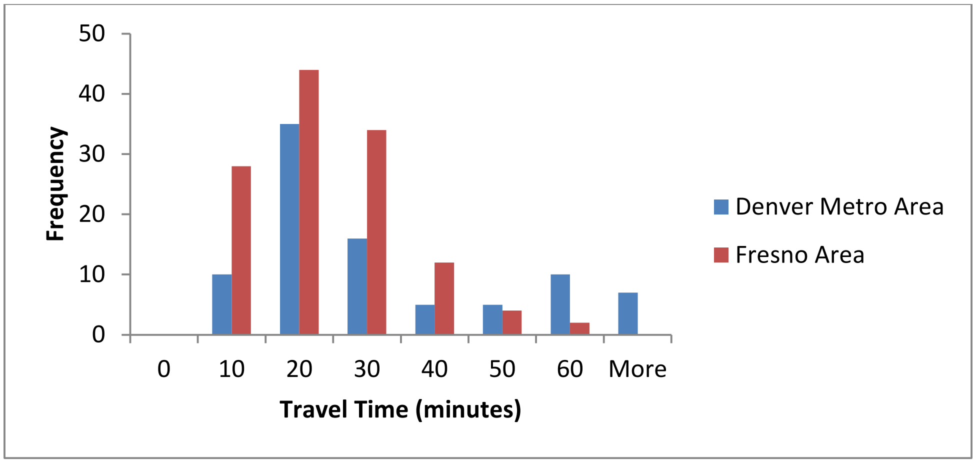


Figure 1.1 Frequency of commute travel times

Table 1.1 Average Commute Duration for Study Areas

Day	Denver, CO	Fresno, CA
Mean (minutes)	30	21
Standard Deviation (minutes)	20	12
Maximum (minutes)	75	60
Minimum (minutes)	5	3

Table 1.2 Average Commute Distance for Study Areas

Day	Denver, CO	Fresno, CA
Mean (miles)	3.51	3.60
Standard Deviation (miles)	2.98	2.92
Maximum (miles)	12.10	10.31
Minimum (miles)	0.40	0.42

1.4.2 Departure and Arrival Times

The average commute departure and arrival times for respondents in both study areas are listed in Table 1.3. In general, commute departure and arrival times were more closely grouped for students in Denver than in Fresno.

Table 1.3 Average Commute Departure and Arrival Times for Study Areas

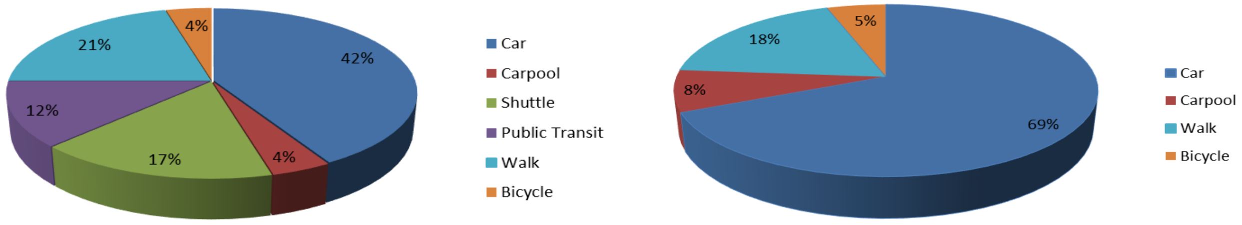
	Morning Commute		Afternoon Commute	
	Departure	Arrival	Departure	Arrival
		Denver		
Mean (Time of Day)	10:36 AM	11:15 AM	3:24 PM	4:14 PM
Standard Deviation (Minutes)	25	16	28	53
Minimum (Time of Day)	7:00 AM	7:15 AM	1:45 AM	8:00 AM
Maximum (Time of Day)	4:11 PM	4:29 PM	9:22 PM	9:46 PM
		Fresno		
Mean (Time of Day)	8:59 AM	9:22 AM	3:30 PM	4:03 PM
Standard Deviation (Minutes)	51	51	36	35
Minimum (Time of Day)	6:00 AM	6:14 AM	8:35 AM	8:40 AM
Maximum (Time of Day)	4:15 PM	4:32 PM	11:00 PM	11:40 PM

1.4.3 Trip Chains: Intermediate Stops

The survey was designed to collect data from students regarding their trip chains by reporting the number of stops during a commute taking longer than 10 minutes. In the literature, a trip chain can be defined as a tour that contains a number of trips with stops lasting 30 minutes or less. For this analysis, a trip chain was defined as any tour containing an intermediate stop. Given this definition, student commuters from both study areas produced trip chains. Students in Denver did not report stopping during their morning commutes to school, and only stopping 2% of the time during their afternoon commutes. In the Fresno area, although the percentages of trip-chained commutes are similar in mornings (8%) and afternoons (7%), slightly longer (two intermediate stop) chains are made in the afternoon. Most intermediate stops made in the morning, students noted, included stops to pick up food and beverages.

1.4.4 Mode

The survey was designed to collect data from students regarding modes of transportation by identifying their transportation mode (e.g., driving, walking, biking) to and from campuses. The variety in modes of transportation used by survey respondents are summarized in Figure 1.2. Results suggest that students in the Denver area tend to use a higher variety of travel modes compared with those surveyed in the Fresno area. A large percentage of Fresno respondents stated that their primary mode of transportation is the automobile. Although respondents from the Fresno area reported using a smaller variety of modes compared with respondents from the Denver area, they carpooled more than the Denver students. Of the carpool trips made in both study areas, most carpools involved a total of two occupants. Students walked approximately 3% more in Denver than in Fresno; however, students rode bicycles at relatively similar rates in the two areas.



(a)

(b)

Figure 1.2 Primary travel mode for Denver area student commuters (a) and Fresno area student commuters (b)

Although public transit is available in the two study areas, they differ significantly in service and variety of modes available. The Denver Metro area is served by The Regional Transit District (RTD). The primary modes used to provide transit are light rail and bus with a total of 138 regular fixed routes, which serve a service area of 2,340 square miles and a population of 2.87 million (U.S. Census Bureau 2010). Public transit provided in the Fresno area is primarily by bus. Two agencies provide service to the Fresno and Clovis area with some overlap between the agencies' service areas. The two agencies, Fresno Area Express (FAX) and the Clovis Stageline, provide 16 and four routes respectively. The two agencies serve approximately 135 square miles and a population of about 600,000 (U.S. Census Bureau 2010). Finally, while one respondent in the Fresno area reported access to a shuttle, no respondents in Fresno took the shuttle as a primary mode of travel.

1.4.5 Mode Preference

The survey was designed to collect data from students regarding mode preference by allowing them to rank four representative scenarios, including mode of transportation and duration. Scenarios were designed to suggest implied relationships between transportation mode and trip duration, rather than be representative of actual commute routes. Commute preference results ranked according to frequency of response are summarized in Table 1.4. While respondents agreed that riding the bus was the least desired mode of transportation, Denver students preferred riding a bike to all other modes of transportation; whereas, Fresno students' first choice was to "drive alone." Such preference differences could have significant implications for commuter incentives.

Table 1.4 Rank of Commute Scenario Preference Results by Study Areas

Commute Mode and Duration Scenario	**Denver, CO**	**Fresno, CA**
Riding a bike, resulting in a 17-minute door-to-door commute	1-Best	3
Driving alone, resulting in a 10-minute door-to-door commute	3	1-Best
Sharing a ride with a colleague, resulting in a 14-minute door-to-door commute	2*	2
Riding the bus, resulting in a 15-minute door-to-door commute	4-Worst	4-Worst

Note: *Frequency of response tied with Driving Alone scenario.

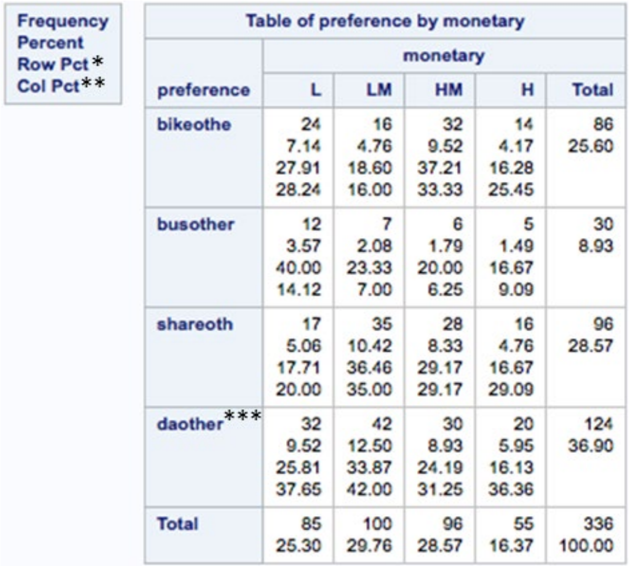
Both populations' preferences regarding modes of transportation did not correlate precisely to length of duration, suggesting that commute preferences reflect more than efficiency of transportation.

1.4.6 Incentives

The survey was designed to collect data from students regarding mode preference by reporting the necessary monetary incentive to be indifferent (have no preference) between pairs of transportation scenarios. To achieve this goal, students performed pair-wise comparisons among the various commute scenarios. Specifically, they were asked on the survey to complete the statement, "Receiving $____ (for the less desirable commute mode), causes me to feel indifferent between the following two commute options," for a total of six pair-wise comparisons across the four scenarios. Due to the open-ended nature of the questions, students provided a wide range of responses. Therefore, in order to perform a Chi-Square test to examine if any statistical differences exist between preferences, the authors objectively evaluated and coded student responses into categories of "low" (L), "low-medium" (LM), "high-medium" (HM), or "high" (H). In addition, the comparisons of more desirable options to less desirable options were combined under four subgroups showing primary preference. These subgroups, therefore, consisted of "driving alone to other," "riding a bike to other," "sharing a ride to other," and "riding a bus to other." Table 1.5 summarizes the data in terms of L, LM, HM, and H value placed by students when comparing the four commuter scenarios presented. The table is organized as a contingency table with rows ("monetary") ordinally scaled and columns ("preference") nominally scaled.

In Table 1.5, the frequency and percentage breakdowns are given for preference and monetary variables. For example, changing mode of transportation from riding bus to other option has the lowest overall percentage with 8.93% (see total column). On the other hand, the row percentage shows that 40% of the respondents who selected riding bus to other options preferred "Low" incentive values to change their mode of transportation from riding bus to other commute options.

Table 1.5 Level of Incentive Required by Students to Switch Commute Modes*



Frequency
Percent
Row Pct*
Col Pct**

Table of preference by monetary

	monetary				
preference	L	LM	HM	H	Total
bikeothe	24 7.14 27.91 28.24	16 4.76 18.60 16.00	32 9.52 37.21 33.33	14 4.17 16.28 25.45	86 25.60
busother	12 3.57 40.00 14.12	7 2.08 23.33 7.00	6 1.79 20.00 6.25	5 1.49 16.67 9.09	30 8.93
shareoth	17 5.06 17.71 20.00	35 10.42 36.46 35.00	28 8.33 29.17 29.17	16 4.76 16.67 29.09	96 28.57
daother***	32 9.52 25.81 37.65	42 12.50 33.87 42.00	30 8.93 24.19 31.25	20 5.95 16.13 36.36	124 36.90
Total	85 25.30	100 29.76	96 28.57	55 16.37	336 100.00

Notes: *Row Pct. is the percentage across L, LM, HM, and H
**Col Pct. is the percentage across the four modes (bikeofthe, busother, shareothe, and daother)
***da is drive alone (single occupancy vehicle)

Finally, the authors performed both a Jonckheere-Terpstra test and a Mantel-Haenszel analysis. Neither tests' results provided sufficient evidence to reject the null hypothesizes that "the distribution of the response variable does not differ among classes," nor "there is not an association between variables." In sum, no evidence was found to support an association between mode of transportation preferences and preferred financial incentives while adjusting for different locations. Additionally, preferred financial incentive levels (L, LM, HM, and H) did not statistically differ among the different commuter scenarios. Nevertheless, having two commute locations with a range of scenarios supported such tests.

1.5 DISCUSSION

Findings from this case study are primarily informative regarding lessons for future study and analysis of real-world commute patterns and preferences. The findings of this study are summarized as follows: 1) Duration and distance: Denver student commuters generally reported longer commutes in duration, but slightly shorter in distance than Fresno student commuters. This finding is consistent with higher congestion levels reported in Denver (Delay per Peak Auto Commuter: 49 person hours) versus Fresno (23 person hours) (Texas A&M Transportation Institute 2014). 2) Departure and arrival times: Denver student commuters generally reported having more similar start and end times for commuting than Fresno students. Further investigation is recommended to explore whether or not more synchronized commute schedules impact commute mode preferences or financial incentives. 3) Trip chains: Denver student commuters generally had shorter trip chains than Fresno student commuters. 4) Mode: A majority of Denver student commuters reported using cars as their primary mode of transportation. However, the percentage of students driving cars in Fresno was significantly higher than students in Denver. 5) Mode preference: Denver student commuters ranked bicycles as the most preferred commute alternative, while Fresno student commuters preferred driving alone (single-occupancy car). The authors documented weather conditions for the specific commute days surveyed. Weather in Fresno, CA, was, in fact, more conducive to biking on the days studied (in the 70s and sunny compared with high 50s and rainy). Such findings are consistent with existing research, which has indicated that student bicycle commuting is not highly influenced by weather patterns (Nankervis 1999). 6) Incentives: While the survey questions were potentially obstructive and in need of further revision, case study data were inconclusive in regard to the value students placed on switching between various modes of transportation.

While analysis of the case study data is informative regarding the two specific student populations, it is not possible to generalize the findings of this study. It's promising, however, that the findings show a high potential for minimizing GHG and air pollution emissions. Such outcomes can be achieved by optimizing the selection of commute alternatives (e.g., driving automobile, carpooling, using public transportation, biking) based on individualized commute tolerance (increase in commute time) and incentives (e.g., monitory incentives, burned calories, saved commute time). To study this opportunity, a business commute optimization system (BCOS) was developed, as shown in Figure 1.3. This system consists of a GIS model, which is integrated with an optimization model to generate an action plan of business commute modes that lead to minimum environmental impacts. For example, the student community at Fresno was analyzed to minimize negative environmental impacts based on various tolerances to commute-duration for all individuals ranging from zero to 40 minutes in five-minute increments, as shown in Figure 1.4. The results of BCOS for various student communities suggest that, as the commuters tolerate changes in the duration of their commute, BCOS recommends the use of green commute alternatives, such as walking, biking, and skateboarding, in order to minimize the negative environmental impacts of the transportation network. Such findings demonstrate that significant opportunity exists for minimizing GHG and air pollution emissions based on individualized action plans using such a system.

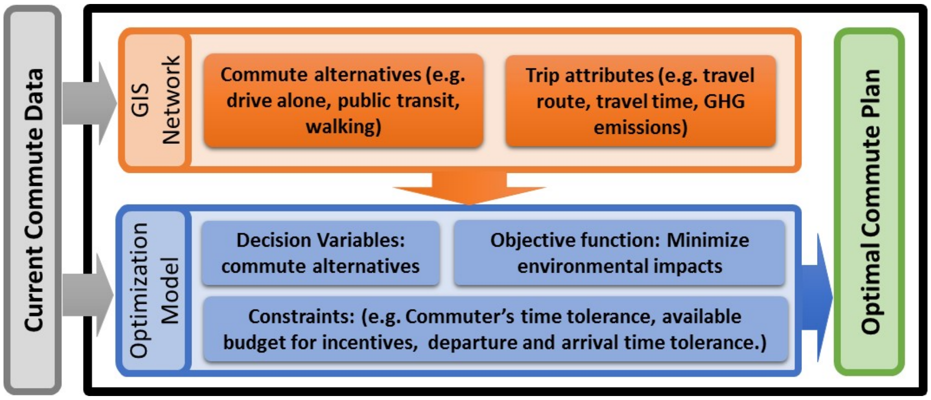
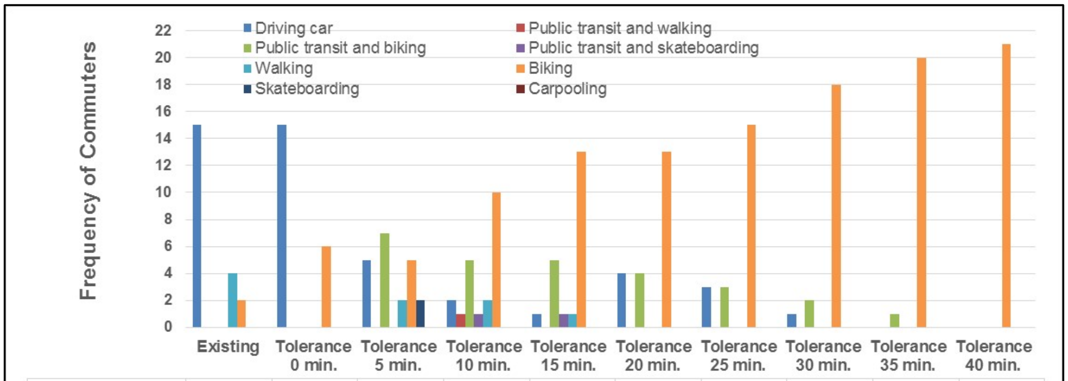


Figure 1.3 Layout of the Business Commute Optimization System (BCOS)



	Existing	Tolerance 0 min.	Tolerance 5 min.	Tolerance 10 min.	Tolerance 15 min.	Tolerance 20 min.	Tolerance 25 min.	Tolerance 30 min.	Tolerance 35 min.	Tolerance 40 min.
Equivelant cost of GHG Emissions and air pollution	$3.3	$3.4	$3.4	$3.0	$2.5	$2.4	$1.9	$1.1	$0.5	$0.0
Total Commute time (min)	325	264	291	361	433	468	533	680	765	828
Total commute cost	$146.5	$146.5	$123.2	$84.3	$53.4	$45.0	$38.2	$16.7	$0.6	$0.0

Figure 1.4 Sample of BCOS results for different travel tolerances of commuters

1.6 CONCLUSION

This section presented new information on student community behavior at the University of Colorado Denver and California State University in Fresno. An online survey was used to collect information on the following: 1) students' commute mode options and their selection of commute mode to and from campuses; 2) commute arrival and departure times and locations, and intermediate stops and their durations; and 3) commute mode preferences and evaluation using pairwise comparisons. A total of 63 undergraduate and graduate student responses were collected and analyzed in terms of duration and distance, departure and arrival times, trip chains, mode, and mode preferences. Two communities were studied to explore differences among commuting preferences. Such a case study demonstrates the challenges and opportunities for collecting and analyzing data to describe a population's commute patterns and preferences, and illustrates how successful data collection supports significant opportunities to minimize negative environmental impacts for various commuter populations. In future research, the authors will further develop and implement a system capable of minimizing GHG and air pollution emissions, as well as total commute time, based on various commute alternatives, monetary incentives, commuter tolerance, and individualized action plans.

2. TIME-ENVIRONMENTAL IMPACTS TRADE-OFF ANALYSIS FOR BUSINESS COMMUTERS

2.1 Introduction

The Environmental Protection Agency (EPA) reported in 2015 that the transportation sector accounts for 27% of the total greenhouse gas (GHG) emissions in the United States, second only to the electricity sector (Environmental Protection Agency 2017). The majority of the transportation emissions come from passenger vehicles and light-duty trucks, such as sport utility vehicles, pickup trucks, and minivans. This highlights the importance of studying commute needs of passenger vehicles and light-duty trucks and identifying innovative solutions that would significantly reduce the transportation related emissions while maintaining traveler convenience. Additionally, driving alone has been the primary mode of transportation in the United States for many decades with an increasing trend. The drive-alone commute share was reported to be 64.3% in 1980, and increased to 76.4% in 2013 (American Association of State Highway and Transportation Officials 2013). Several factors appear to contribute to the high modal share of drive-alone commutes in the USA. While the relative convenience of the automobile in driving alone commutes is an important factor, other factors include urban sprawl, relatively lower gas taxes and dependent prices, lower overall (or perceived) quality of public transportation systems, and drive-alone commute subsidies.

Different motives exist to minimize road congestion and GHG emissions. They vary from environmental concerns to energy dependency, public health, air and noise pollution, and urban sprawl (Kok et al. 2011). This highlights the importance of identifying transportation solutions that would optimize commute needs and improve efficiency of the transportation system. To this end, state departments of transportation (DOTs) are consistently active to reduce GHG emissions from the transportation sector using tools and guidelines such as 1) mixed land-use and public transit development (Ratner and Goetz 2013), 2) multimodal transportation systems (Reis et al. 2013), and 3) active-transportation modes (de Nazelle et al. 2010). Despite the existing GHG emission reduction strategies supported by the Federal Highway Administration (FHWA) and state DOTs, limited studies have been conducted to optimize commute plans of business commuters. Investigations on the influential factors in commute mode choice show that commute modes are often not optimized; these rely mainly on personal convenience, cost, and time rather than environmental impacts and costs.

2.2 Literature Review

The commute mode choices and their impacts have been extensively studied in the literature. To promote the use of alternative transportation modes for businesses, several studies have investigated the factors influencing commute mode choice behavior and their environmental impacts and costs. These studies are grouped and discussed in four categories as follows:

2.2.1 Commute Mode Choice Influential Factors

Several influential factors contribute to commute mode choice (Garvill 1999). These factors are reported as 1) commuter specific factors, such as age, gender, physical health condition, and education level; 2) commute mode specific factors, such as time, cost, safety, and perceived convenience; 3) commute specific factors, such as urban characteristics of origin and destination; 4) commute mode benefit factors, such as incentives for alternative commute modes; and 5) environmental factors, such as weather conditions.

Heinen et al. conducted an online survey to gather commute mode choice behavior of 4,000 respondents. They used the data to identify primary factors influencing bike commute choice. Their analysis showed that workplace conditions and facilities, e.g., presence of bicycle storage, locker room, and clothes changing and shower facilities, can highly motivate commuters to use biking (Heinen et al. 2013). Hamre and Buehler evaluated the relationship between commuter benefits and mode choice for the commute to work using preference data on 4,630 regular commuters in the Washington, DC, region. Their analysis suggested that benefits for public transportation, walking, and cycling seem to work best when car parking is not free (Hamre and Buehler 2014).

2.2.2 Impacts of Commute Mode Choices

Commuters' mode choice and the resultant impacts of strategies on reducing GHG emissions have been studied extensively. To this end, de Nazelle et al. estimated a 400 tons per day CO2 emissions reduction using the MOBILE6 emission factor model when other commute modes, instead of driving, are used for trips less than three miles (de Nazelle et al. 2010). Other researchers studied the benefits in public health when using more active transportation modes such as biking or walking. In this respect, Maizlish et al. discovered that an 18-minute extension in daily commute time using biking or walking reduces diabetes and colon and lung cancer by 14% and 5%, respectively, while minimizing GHG emissions by at least 9% (Maizlish et al. 2013).

2.2.3 Commute Mode Choice Incentive Programs

Full or partial subsidization of workplace parking spaces, along with the absence of alternative transportation incentive programs, is one of the primary reasons for high modal share of drive-alone. There seems to be a growing tendency to design and implement incentivized policies and programs to encourage commuters to change their commute behavior. These policies and programs include 1) parking cash-out, 2) employee parking pricing, 3) ridesharing and carpool matching, 4) emergency rides home, 5) teleworking, 6) employer-paid transit/vanpool benefits, 7) shuttles from transit stations, 8) and secure bicycle parking, showers and/or lockers.

In the parking cash-out program, the commuters can either continue using the employer-paid/subsidized parking space or get the equivalent cash out of the parking space as an additional taxable income. It is reported that the parking cash-out program can reduce the drive-alone commute mode by 17%, followed by 39% and 50% increases in bike/walk and public transportation usage, respectively (Shoup 1997). However, the parking cash-out program does not account for the commuters' benefit losses in terms of time, cost, convenience, and carbon footprint when calculating the equivalent cash-out parking space.

2.2.4 Business Commute Mode Choice Evaluation Tools

The existing tools to assess the costs and savings with respect to commuters and employers under different GHG emission control policies are limited. These tools are the CUTR_AVR model (University of South Florida 1998), Business Benefits Calculator (Center for Urban Transportation Research 2002), and Commuter Choice Decision Support System (Federal Highway Administration 2003). For example, the Commuter Choice Decision Support System, supported by DOTs and the EPA, is an interactive tool capable of assessing workplace conditions. It helps employers decide on establishing a better work environment that reduces drive-alone modal share. However, the aforementioned tools offer only limited guidelines regardless of the employees' preferences in terms of commute time or cost; therefore, the optimality of the outcomes is not clear. Moreover, incentives are often calculated regardless of the individual's contribution to GHG emissions while commute preferences in terms of travel time, cost, and convenience are often not taken into account. To address these shortcomings, the authors of the present study have previously proposed a framework for collecting and incorporating commute preferences to optimize commute plans in terms of GHG and air pollution emissions as well as commute time (Abdallah et al. 2017; Clevenger et al. 2016).

2.3 Research Objectives and Methods

This section presents the development of a novel optimization system designed to identify optimal trade-offs between two important transportation objectives of minimizing GHG and air pollution emissions and total travel time while meeting business commuter preferences and offering conveniences. The developed optimization system is designed to generate detailed solutions that identify optimal commute plans for each commuter while motivating commuters through monetary incentives supported by employers to cover extensions in commute duration.

The developed optimization system consists of a travel survey, a GIS model, and a multi-objective optimization model. The travel survey is designed to collect individuals' commute information, such as origin and destination addresses, arrival and departure times to and from work, and original commute methods. The GIS model is then used to calculate GHG emissions, travel time, and travel cost for every possible commute mode, including drive-alone using existing vehicle, use of public transportation, biking, walking, and carpooling with other commuters within the business. The multi-objective optimization model is designed to identify tradeoffs among optimization objectives to simultaneously minimize total GHG and air pollution emissions, total travel time, and total commute time. A case study of a group of students at the University of Colorado Denver is used to verify the performance of the developed system and demonstrate its use. The following sections describe the development of the GIS and optimization model and their application to the case study.

2.4 Geographical Information System

A GIS model is developed to calculate various travel attributes of all possible commute options, such as time, cost, distance, and GHG emissions and air pollution for every commuter in a business. This GIS model is designed to use transportation data collected from business commuters, including commuters' home and destination addresses, modes of commute, and departure and arrival times, to calculate the aforementioned attributes. The GIS model is coded to automatically calculate all trip attributes for all commuters in a business based on commuters' input data.

A set of coefficients were used to calculate travel cost, GHG emissions, and air pollution for every commute mode as a function of travel distance. GHG and air pollution emissions were calculated in the GIS model using the following coefficients: 294.6 g/mile, 1.643 g/mile, and 0.039 g/mile to calculate CO2, NOX, and VOC emissions for public transportation, respectively. Similarly, the coefficients 368.4 g/mile, 0.693 g/mile, and 1.034 g/mile were used to estimate CO2, NOX, and VOC emissions for driving, respectively. Equivalent social costs were calculated from emission values. Equivalent social cost of carbon is reported as $40 per metric ton (Environmental Protection Agency 2014). Similarly, the equivalent social cost per metric ton for nitrogen oxide and volatile organic compounds emissions are $10.293×10-3 and $2.392×10-3, respectively (Victoria Transport Policy Institute 2013). The travel cost is calculated in the GIS model based on $0.59/mi rate accounting for fuel and maintenance cost5s.

2.5 Optimization Model

The optimization model is developed in two main phases: 1) formulation phase, which defines decision variables and formulates objective functions and constraints; and 2) implementation phase, which uses the weighted mixed integer programming to execute the computations of finding the trade-offs between the total commute time and total social cost of GHG emissions and air pollutions. The following sections describe these development phases.

2.5.1 Formulation Phase

The decision variables are designed to model all possible commute options for each commuter using two type of decision variables. $X_{i,j}$ is used to model five types of commute alternatives, including, drive alone, use of public transportation, biking, walking, and carpooling picked up by another commuter where i represents a business commuter and ranges from 1 to number of commuters (M) and j represents the type of transportation mode and ranges from 1 to 5, as shown in Table 2.1. $C_{k,l}$ is used to model all carpooling options of two commuters where commuter k picks up commuter l and drives to destination, as shown in Table 2.1. Similarly $C_{k,l,m}$ is used to model all carpooling options of three commuters where commuter k picks up commuters l and m ($k, l,$ and m range from 1 to M and $k \neq l \neq m$). Binary decision variables were used in $X_{i,j}, C_{k,l}, C_{k,l,m}$, and $C_{k,l,m,n}$ where a value of 1 indicates choosing a commute option.
The objective functions are designed to quantify and minimize 1) total equivalent social cost of GHG and air pollution emissions and 2) total travel time. The total equivalent social cost in the model can be minimized by reducing the selection of drive alone options, where it is convenient to commuters and based on the model constraints. The total travel time can be calculated by summing up the commute durations of all commuters based on the selected commute options. The total travel time can be minimized generally by increasing the selection of drive alone options among the business commuters.

Table 2.6 Decision Variables

Commuter number	Travel modes								
	Drive alone	Public transportation	Biking	Walking	Carpool picked up	Carpool: Two commuters			
						Pick up commuter			
						1	2	$\cdots$	M
$i = 1$	$X_{1,1}$	$X_{1,2}$	$X_{1,3}$	$X_{1,4}$	$X_{1,5}$	n/a	$C_{1,2}$	$\cdots$	$C_{1,M}$
$i = 2$	$X_{2,1}$	$X_{2,2}$	$X_{2,3}$	$X_{2,4}$	$X_{2,5}$	$C_{2,1}$	n/a	$\cdots$	$C_{2,M}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$i = M$	$X_{M,1}$	$X_{M,2}$	$X_{M,3}$	$X_{M,4}$	$X_{M,5}$	$C_{M,1}$	$C_{M,2}$	$\cdots$	n/a

To ensure the practicality of the generated solutions, two types of constraints, logic and convenience, were implemented in the optimization model. The logic constraints are used in the model to ensure practicality of the modeled problem. For example, a commuter cannot drive in the afternoon if he/she has not driven in the morning. The convenience constraints were grouped in four sets: 1) commuter constraint, 2) carpool constraint, 3) commute-duration tolerance constraint, and 4) incentive constraint. The commuter constraint allows only commute modes that are preferred and accessible to the commuters. The carpool constraint limits the number of picked up commuters per carpooling mode to two, for a total of three passengers in a car (including the driver). Commute-duration tolerance constraint satisfies commuter preferences in terms of extensions in travel time and, accordingly, only commute options that do not extend the travel time beyond the commuter tolerance are considered as feasible commute options in the model. Lastly, the incentive constraint ensures that the total monetary incentives for all commuters will not exceed the business incentives budget.

2.5.2 Implementation Phase

The developed optimization model is implemented in three steps: 1) collecting input data from a GIS model to the optimization model, 2) executing the model computations using mixed integer linear programming solver in Matlab®2016b (intlinprog), and 3) organizing the model results in tabular and report format.

The calculated commute attributes for each commute option by the GIS model are fed into the optimization model, including equivalent social cost of GHG and air pollution emissions, travel time, travel distance, travel cost, and burned calories for each commute option. The optimization model then executes the model computations using weighted mixed integer programming to identify optimal trade-offs between the two transportation objectives while satisfying the model constraints. Weighted mixed integer programming was used in the model as it guarantees optimality of the identified solutions with short computational time. The Pareto-optimal trade-offs were identified by simultaneously minimizing total equivalent social cost of GHG and air pollution emissions and total commute time. The weighted sum of the normalized objective functions was used with various combinations of relative importance weights to generate the Pareto-optimal solutions. To this end, importance weight varies from zero to 1 with 0.01 increments where the summation of importance weights of the objective functions is equal to 1. The objective functions were normalized with an index ranging from 0 to 1, where 0 represents the minimum possible value of the objective function and 1 represents the highest possible value of the objective function. The weighted average of combining the two optimization objectives is used to solve each unique combination of the importance weights and identify optimal trade-offs. The final step of the model implementation is used to organize the model results and provide recommendations for each commuter in a business, including recommended commute method, reduction in GHG and air pollution emissions, savings in commute time and cost, monetary incentives, and burned calories.

2.6 Case Study

To evaluate the performance of the developed optimization model and illustrate its new capabilities, a case study of 24 students at the University of Colorado Denver was used. The students' commute information was collected through an online tool designed by the authors to collect data in two university representative days on home and destination addresses, arrival and departure times to/from the university in morning and afternoon, commute methods, and transportation options that students have access to. Additionally, students were asked to report their preferred transportation modes to/from the university. The details on the survey questions and analysis of collected data can be found in a previous publication by the authors (Clevenger et al. 2016). The collected data are used in the GIS model to calculate trip attributes for all possible commute options, as listed in Table 2.2, for samples of four commute options.

Table 2.7 Commute Information of the Case Study

Commuter number	Drive-alone		Public transportation		Biking		Walking	
	T (minutes)	D (miles)	T (minutes)	D (miles)	T (minutes)	D (miles)	T (minutes)	D (miles)
Commuter 1	10	5.2	34	4.4	39	6.6	76	3.7
Commuter 2	8	2.8	24	2.5	21	2.9	47	2.3
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Commuter 23	8	1.7	71	11.4	15	1.8	36	1.7
Commuter 24	8	3.6	47	4.1	22	3.7	59	2.8

The output of the GIS model was used as input to the optimization model. The optimization model was then used to identify optimal trade-offs between the two optimization objectives, as shown in Figure 2.1, for different time tolerances ranging from 15 minutes to 35 minutes in morning and afternoon commutes. It should be noted that the commuter tolerance is defined in the model as the extension in the commute trip duration as compared with the reported student commute behavior. The total equivalent social cost of GHG and air pollution emissions based on the reported commute behavior of students is calculated as \$5.78, as shown in Figure 2.1. The maximum equivalent social cost of GHG and air pollution emissions varies from \$4.31 to \$5.90.

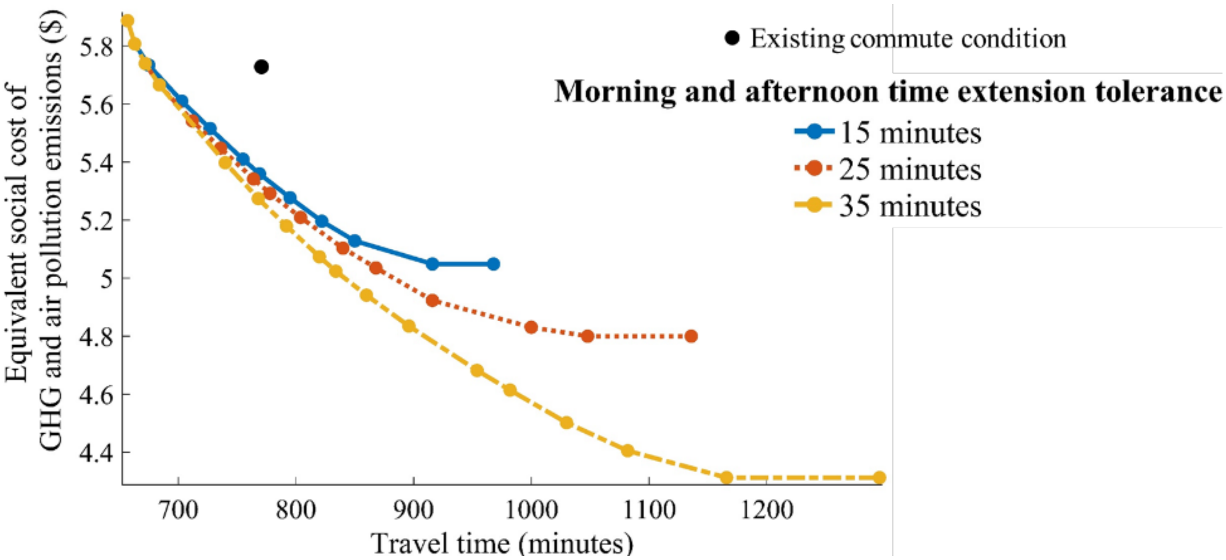


Figure 2.5 Pareto-optimal solutions for different time tolerances

The optimization model is designed to show the frequency of daily travel modes for the generated trade-off solutions, as shown in Figure 2.2, for five optimal solutions in the morning commute with commuter tolerance of 35 minutes. Each solution is associated with different weights for the travel time, w_1, and equivalent social cost of GHG and air pollution emissions, w_2. Solution #1 only minimized the total travel time ($w_1 = 1, w_2 = 0$) resulting in 19 commuters using drive-alone mode, four commuters using carpooling mode, and one commuter using biking mode. In contrast, when w_2 was set to 1.0, solution #22, only three commuters were recommended to use drive-alone mode to maintain commuter tolerance and minimize total GHG and air pollution emissions.

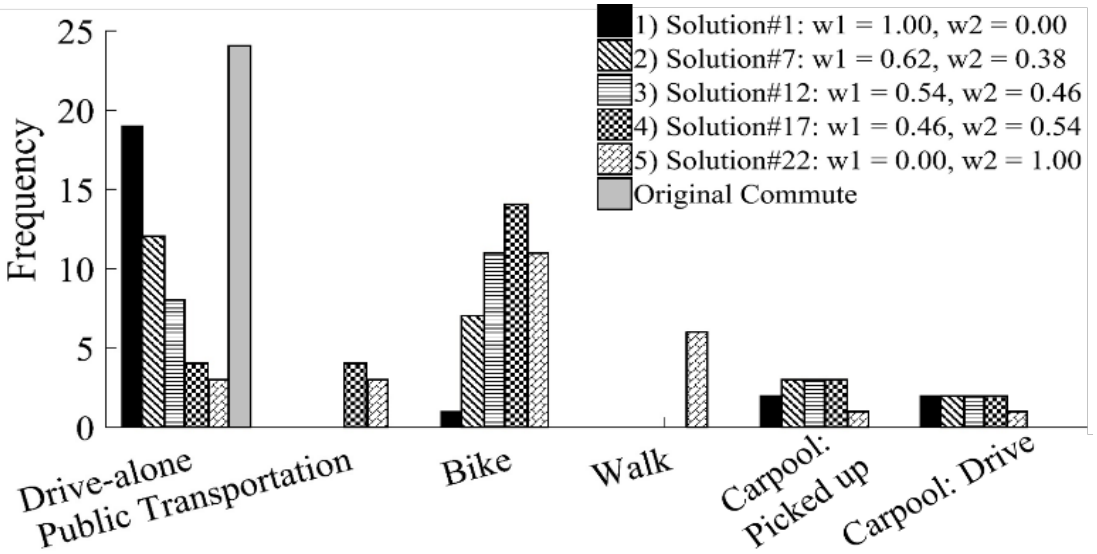


Figure 2.6 Frequency of travel modes

2.7 Discussion

Business transportation plans are frequently non-optimized to address negative environmental impacts, relying mainly on personnel convenience, time, and cost. The developed optimization system is designed to identify optimal commute plans for business commuters to simultaneously minimize GHG and air pollution emissions as well as total travel time while maintaining commuter preferences and convenience. The results of the model suggest that the developed optimization system can actively contribute to the goal of minimizing transportation related emissions and improve its efficiency. The generated optimal solutions show that the drive-alone modal share can be reduced from 79% to 13%. Simultaneously, the equivalent social cost of GHG and air pollution emissions can be reduced by 25%.

The results of the optimization system show that the reduction of GHG and air pollution emissions is dependent on commuter tolerance. For example, a 15-minute time extension tolerance can reduce GHG and air pollution emissions by only 13%, while a 35-minute commuter tolerance can achieve a 25% reduction. Furthermore, the optimization system is designed to compensate commuters due to inconvenience of extension in their commute trips using monetary incentives. For the identified optimal solutions, monetary incentives (total for all commuters) range from $0 to $185 per day, where the monetary incentives increase with higher reduction in negative environmental impacts. Finally, the developed optimization system is capable of providing commuters with promising recommendations that can influence their commute behavior and serve to achieve national objectives, such as reducing transportation related emissions.

2.8 Summary and Conclusions

This section presented the development of an optimization system that is capable of identifying optimal commute plans for commuters sharing a destination to simultaneously minimize GHG and air pollution emissions as well as total travel time. The optimization system consists of a travel survey, GIS model, and optimization model. The GIS model is used to calculate a number of trip attributes, including GHG and air pollution emissions, travel time and cost, travel distance, and burned calories for every possible commute mode. The optimization model is then used to identify the optimal commute mode for each commuter to achieve the aforementioned objectives while maintaining commuter convenience using tolerance to increase trip duration. A real world case study of a group of students at the University of Colorado Denver was used to verify the performance of the developed optimization system. The results indicated that a 25% reduction of GHG and air pollution emissions can be achieved in the studied student community. The authors are currently working on expanding the capabilities of the developed optimization system to consider additional optimization objectives, such as to minimize travel cost, energy use, and road congestion, and maximize burned calories. Furthermore, the authors will expand the capabilities of the GIS model to model the dynamics of the transportation system to account for traffic and the impact of weather on traffic. Finally, the authors will integrate the developed optimization system with current emission reduction policies offered by employers and DOTs, such as tax incentives and employer-paid transit passes, to generate more practical and promising solutions.

3. TIME-COST-ENVIRONMENT TRADE-OFF ANALYSIS FOR BUSINESS COMMUTING SYSTEMS

3.1 Introduction

The U.S. Environmental Protection Agency (EPA) reported in 2014 that greenhouse gas (GHG) emissions from the transportation sector is 26% of total national GHG emissions, second only to the electricity sector (Environmental Protection Agency 2013; U.S. EPA Office of Policy 2015). Over half of the emissions from the transportation sector are generated from passenger cars and light-duty trucks, such as sport utility vehicles, pickup trucks, and minivans. Many local, regional, national, and international agencies are actively studying opportunities to mitigate traffic congestion and reduce transportation related emissions. Several guidelines that support these studies and initiatives are currently available from several departments of transportation (DOTs). The existing DOT strategies rely mainly on 1) multimodal transportation systems, 2) mixed land-use and transit-oriented developments, and 3) design of active transportation friendly environments. While these strategies have contributed to the reduction of transportation related emissions and traffic congestion, additional research and innovative models are needed to further reduce transportation emissions as well as time and costs based on individualized action plans.

3.2 Literature Review

Commuters' mode choices and resultant impacts have received particular attention in the travel behavior literature. Since commute trips represent a significant percentage of morning and evening peak traffic, previous research has focused on understanding reasons behind commuter mode choice behavior, and identifying ways to decrease impacts of morning and evening commutes, primarily by reducing the share of drive-alone commutes. Outcomes of these research efforts have resulted in the development of many policies and programs. Accordingly, another part of the literature focuses on the development and assessment of the subsequent effectiveness of these programs. The following subsections provide brief breakdown of the existing literature.

3.2.1 Motivation for Commute Modal Shares

Drive-alone commute has been the primary mode of transportation in the United States for many decades, and the trend has been increasing. In 1980 and 2010, the modal share of drive-alone commute was 64.3% and 76.6%, respectively (American Association of State Highway and Transportation Officials 2013; A. Rossetti and S. Eversole 1993). Several factors appear to contribute to the high modal share of drive-alone commutes in the United States. While the relative convenience of the automobile in comparison to other modes is an understandable factor, it does not explain the higher share of drive-alone commutes when compared with societies in other developed states, such as Europe and Asia. Several other factors contribute to high drive-alone commuting, such as urban sprawl, relatively lower gas taxes and prices, lower overall (or perceived) quality of public transportation systems, and drive-alone commute subsidies.

Free or highly subsidized employee parking, compounded by the absence of equivalent subsidization for alternative modes of transportation, is believed to be one of the main reasons for the high percentage of drive-alone commutes in the United States (Shoup 2005). Several efforts and policies are being developed to increase modal shares of non-drive-alone commutes. Examples of these policies include the 1990 Clean Air Act provision that required employers with more than 100 employees located in ozone nonattainment areas to develop policies that would result in a 25% increase in their employees' commute auto occupancy above the area-wide baseline average (Black 2010; Meyer et al. 1999). Other common groups of programs include those that seek to increase percentages of telecommuting and employee parking cash-out programs where employees can opt to receive the value of a parking space as additional income and arrange their own means of commute transportation. The impacts of these policies, however, remain minimal. In 2015, the National Compensation Survey revealed that most employers offer their employees free parking; yet, only 7% offer subsidies for alternative modes of transportation (National Compensation Survey 2015).

It appears that the generalized nature of these policies represents significant limitations. For example, parking cash-out programs offer all employees the same, flat compensation regardless of their commute footprint. However, it is not uncommon for a single employee with a long commute to create a footprint equivalent to the combined footprint of several employees with shorter commutes. It may be more efficient, therefore, to convince this single employee to switch to an alternative mode of travel by offering a higher compensation than that offered to employees with shorter commute footprints. Similarly, since different employees have different mode preferences, businesses that offer mode-specific compensations (such as tax-free transit vouchers) may be able achieve higher impacts by individualizing their alternative transportation policies and associated incentives.

3.2.2 Commuter Mode Choice Behavior

Many factors contribute to commuter mode choices. Examples of these include traveler-specific factors, such as age, gender, income, and value of time; mode-specific factors, such as travel time and cost; trip-specific factors, such as trip chaining stops, and urban characteristics of origin and destination; business-related factors, such as existence of free parking and incentives for alternative transportation modes; and environmental factors, such as temperature and precipitation.

Examples of this group of literature include the work of Heinen et al., who used longitudinal data for 633 part-time bicycle commuters to investigate day-to-day decisions to commute by bicycles. Their results indicated that workers needing to wear business attire, transport goods, use a car during office hours, commute in the dark, commute facing higher wind speed, commute for a longer duration in rain, or have longer commute distances are less likely to commute by bicycle (Heinen et al. 2011). Chatman used the 1995 Nationwide Personal Transportation Survey (the predecessor name of the National Household Travel Survey, [NHTS]) to investigate the effect of density and mixed land use at the workplace on commute mode choice. He employed a joint logit-Tobit model and found that employment density at the workplace to be associated with a lower likelihood of automobile commuting (Chatman 2003). Bhat and Sardesai used stated and revealed preference data from a web-based commuter survey in Austin. They applied a mixed logit framework, and their results emphasized the effect of commute and midday stop-making on mode choices. Additionally, their results indicated that travel time reliability is an important factor influencing commute mode choices (Bhat and Sardesai 2006).

3.2.3 Impacts of Commuter Mode Choices

Examples of research efforts focusing on impacts of businesses' alternative transportation programs include the work of Hamre and Buehler. They applied multinomial logistic regression to reveal preference data of 4,630 commuters in the D.C. region, and found that employees who are offered transit benefits, showers or lockers, or bike parking, and had no free parking were more likely to use public transit, walk, or cycle to work. They also found that the existence of free parking seemed to offset the likelihood of this increase (Hamre and Buehler 2014). Similarly, Yang et al. conducted phone interviews with 1,338 commuters. These researchers used multivariate logistic regression models to explore the impacts of home and worksite environments and worksite support and policies on commuter mode choices. Their study uncovered significant associations among 1) walking time from home to transit stops and using worksite incentives for public transit, and commuting by public transit, 2) commuting distance and active commuting, and 3) the existence of free or low-cost recreation facilities around the worksite and using bike facilities to lock bikes at the worksite (Yang et al. 2015).

3.2.4 Tools for Business Alternative Transportation Programs

The literature is rich with research on commuter mode choice behavior; however, tools and applications that businesses can utilize to identify optimum policies and incentives and associated benefits are limited. Three available tools include the Commuter Choice Decision Support System, CUTR_AVR Model, and Business Benefits Calculator. The Commuter Choice Decision Support System is supported by the U.S. Department of Transportation (USDOT) and the EPA. It is designed to help employers determine the most appropriate types of commuter choice options for [their] worksite (U.S. Federal Highway Adminstration and U.S. Environmental Protection Agency n.d.). The CUTR_AVR Model, developed in 1999 by the Center for Urban Transportation Research (CUTR) at the University of South Florida, is "based on a large, real-world data set" and uses an artificial neural network to predict mode share and average vehicle ridership by inputting attributes of the employer-based TDM program" (Center for Urban Transportation Research 1999). The Business Benefits Calculator, developed by the EPA, is a "Web-based Calculator that enables an employer considering Best Workplaces for Commuters^{SM} to estimate the financial, environmental, traffic-related, and other benefits of joining the program" (Damsted 2006).

All three of these tools provide businesses with generalized recommendations for commuting policies and estimates on benefits (e.g., reductions in GHG emissions). They base their recommendations and estimates on aggregate measures of business employee commute data, rather than individualized commute information and individual-specific incentives that are suitable for individual commuters. Accordingly, this proposal addresses this particular limitation and significantly extends previous research efforts.

3.3 Research Objective

The main objective of this research is to develop an optimization system capable of simultaneously minimizing GHG and air pollution emissions as well as commute time and cost to businesses. Information regarding individuals' commute origins and destination, departure and arrival times as well as modes of transportation serves as the basis of the optimization system. The commute information is input into a GIS, which generates data about route and commute mode alternatives and corresponding emissions. The output data from the GIS are fed into a multi-objective optimization model to identify optimal commute plans for businesses and minimize negative environmental impacts as well as commute time and cost while maintaining commuter convenience. The optimization model is developed in two main phases: 1) formulation phase, which formulates the model decision variables, objective functions, and constraints; and 2) implementation phase, which performs the model computations using linear programming and specifies the model input and output data. A case study of student community at California State University at Fresno is analyzed and optimized using the developed system to verify its performance and illustrate its capabilities.

3.4 Commute Attribute Calculations

Inputs of the GIS model were collected using a simple travel survey. The travel survey collected information about the commute trip of 21 undergraduate students at California State University, Fresno on two consecutive days during the 2015 spring semester. The surveyed information included their commute trip origins and destinations, including all intermediate stops during the commute, departure and arrival times, their chosen mode of travel, and their willingness to use alternative modes of transportation.

Additional information and analysis of the survey results can be found in earlier publications (Clevenger et al. 2016; Tawfik et al. 2016). In order to quantify the footprint of the students' commute trips, the survey information was input into ESRI's ArcGIS and modeled using ESRI's Model Builder and the Network Analyst extension.

Building the ArcGIS multimodal transportation model involved a number of steps. First, GIS files for Fresno's different transportation networks (e.g., streets, bus lines, and bus stops) were obtained from the local Metropolitan Planning Organization (Fresno Council of Governments, Fresno COG). Second, these transportation networks were modified to ensure the connectivity between different elements across the different networks (e.g., connectivity between the streets and bus stops or between the bus stops and bus lines). Third, a multimodal network dataset was built to allow for the estimation of the trip characteristics (travel time and travel distance) and footprint attribute values (GHG and air pollution emissions, energy demand, and travel cost) of any trip within the study area. Calculations of the different mode-specific footprint attribute estimates were based on average parameter values that are included in Table 3.1.

Table 3.8 Values of Parameters Utilized in Calculations of Footprint Attribute Estimates

Attribute **Mode**	**Travel Time**	**Travel Distance**	**CO2 Emissions**	**NOx Emissions**	**VOC Emissions**	**Travel Cost**
Walk	$\frac{Distance}{3\ mph}$	Trip Origin to Destination	0.0	0.000	0.000	0.0
Bike	$\frac{Distance}{10\ mph}$	Trip Origin to Destination	0.0	0.000	0.000	0.0
Bus	$\frac{Distance}{30\ mph}$	Trip Origin to Destination	294.6 g/p-mi*	1.643 g/p-mi*	0.039 g/p-mi*	0.0
Car	$\sum \frac{Link\ Lengths}{Speed\ Limits}$	Trip Origin to Destination	368.4 g/mi	0.693 g/mi	1.034 g/mi	59.2 ¢/mi

* p-mi is passenger mile (assuming 25% bus occupancy)

Once the multimodal network dataset was created, the students' trip origins and destinations were geocoded into the GIS model. Next, models were created to simulate every student's commute trip using every possible travel mode (walk, bike, bus, car, and carpool), and calculate the trip footprint associated with every student-mode combination. The simulation code was created using ESRI's ModelBuilder and Python code. Further elaboration of the GIS model is included in a previous publication (Tawfik et al. 2016).

3.5 Optimization Model

3.5.1 Formulation

The optimization model's decision variables are designed to model all commuter transportation alternatives that impact GHG emissions, air pollution, commute time, and cost. These transportation alternatives include driving existing vehicle, driving new vehicle, using public transit and walking, using public transit and biking, walking, biking, and carpooling with every commuter separately (HOV 2), as shown in Figure 3.1. A binary decision variable is used to model each of the commute alternatives representing the primary mode of transport a commuter utilizes to travel from the origin of the commute trip to the final destination. The optimization model considers only one route for each transportation alternative, based on the GIS model, which represents the shortest travel time from the origin of the commute trip to the final destination.

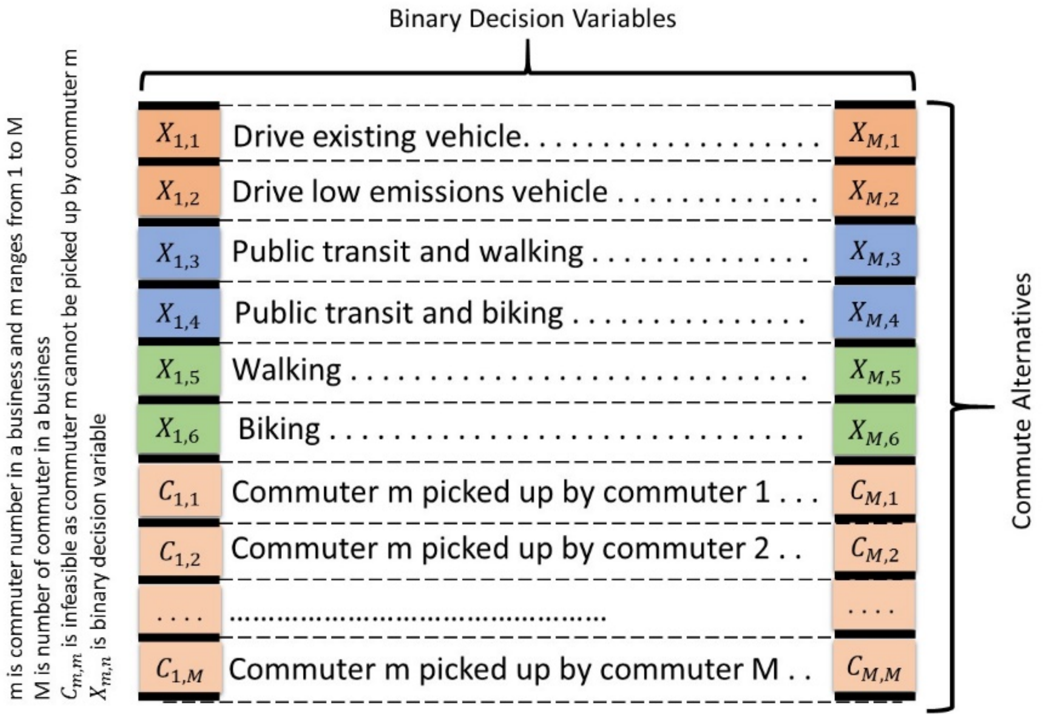


Figure 3.7 Optimization model decision variables

The objective functions of the optimization model are designed to quantify and minimize 1) GHG and air pollution emissions, 2) total commute time for a number of commuters who travel to/from a shared destination/origin, and 3) total commute cost for a number of commuters who travel to/from a shared destination/origin. Three objective functions are used to minimize the aforementioned negative environmental impacts and total commute time. GHG and air pollution emissions are qualified and combined based on 1) CO2, NOx, and VOCx emissions, 2) monetary values of GHG and air pollution emissions, and 3) selected commute alternatives. Total commute time of a business is qualified and minimized in the model based on the selected commute alternatives and their commute time from the GIS model. Similarly, total commute cost of a business is quantified and minimized in the model based on the selected commute alternatives and their costs from the GIS model.

The developed model integrates a number of constraints to ensure the practicality of the generated solutions, including commuter constraint, carpool constraint, and tolerance constraint. The commuter constraint is integrated in the model to select only one commute alternative for each commuter. For example, the optimization model can select commuter #2 to use public transportation and walking to get from the trip origin to destination. The carpool constraint is integrated in the model to allow two commuters to commute from the origin of their commute trip to the specified destination. The model is designed to allow one commuter to pick up another commuter and drive to the specified destination. Furthermore, when two commuters are commuting together, they cannot carpool with other commuters. A tolerance constraint is integrated in the model to limit the recommended commute alternatives of the model based on the flexibility of the commuter and to maintain convenience. For example, the model will only recommend a commute alternative that does not extend the commute time more than a specified commuter tolerance (in minutes). In addition, the developed model allows only two commuters to carpool together if the difference in their arrival time does not exceed a specified commuter tolerance (in minutes).

3.5.2 Implementation Phase

The developed multi-objective optimization model is implemented in four main steps: 1) specify the model input data from the GIS model, 2) execute the model computations using weighted mixed-integer programing, 3) generate trade-off solutions among the objectives of the optimization model, and 4) generate recommendations for business commuters.

The developed system is designed to receive commute data of all feasible commute alternatives for each commuter from the GIS. Commute data are designed to include commute time and cost, travel distance, environmental impacts in terms of carbon emissions, air pollution of nitrogen oxide and volatile organic compounds, and fuel consumption for each transportation mode of each commuter as well as carpooling in the business. Furthermore, the optimization model requires additional commuter data such as arrival time in the morning, departure time in the afternoon, parking cost, commuter hourly rate, and existing commute method for each commuter to transport to their destination in the morning and afternoon.

The optimization computations are executed in the model using weighted mixed-integer programming due to its capability to guarantee a global optimal solution of business commuters in a short computational time, and generate trade-off solutions among the three optimization objectives. The optimization model is designed to generate trade-off solutions among 1) minimizing total negative environmental impacts, 2) minimizing total commute time of business commuters, and 3) minimizing total commute cost of business commuters. These trade-off solutions represent those not dominated by any other solution with respect to the aforementioned three optimization objectives. The Pareto optimal solutions can be generated using unique combinations of relative importance weights for the aforementioned three optimization objectives. For example, a trade-off solution can be generated by setting the total equivalent cost of emissions weight to 100% and 0% to the other two optimization objectives. Similarly, two other trade-off solutions can be generated by setting total commute time weight to 100% with 0% to the other two objectives, and setting total commute cost weight to 100% with 0% to the other two objectives. Additional trade-off solutions can be generated by setting unique weights for the three optimization objectives. It should be noted that the optimization objectives need to be normalized while identifying the trade-off solutions. Finally, detailed results for each trade-off solution are provided by the developed optimization model. An action report is generated and includes individualized information on the recommended commute method for each commuter, expected addition/reduction in commute time, cost, and emissions, departure and arrival times, and expected savings.

3.6 Case Study

A case study of students at California State University at Fresno is analyzed to evaluate the system performance and illustrate its new capabilities. The case study data were collected using an online survey developed by the authors. The collected data represent real-world commute behavior of 21 engineering students as they commuted to and from California State University, Fresno campus on a representative school day. Collected data included departure and arrival times, transportation mode choice, and commute origin and destination. The departure and arrival time and primary transportation mode for student commute in the morning and afternoon are summarized and listed in Table 3.2.

The collected data were then input into the GIS to identify various commute attributes. Based on the integrated City of Fresno transportation system data, the GIS generated attributes of carbon emissions, nitrogen oxide emissions, volatile organic compounds, and commute trip duration and cost for each commute alternative in Fresno. The generated emissions were then converted to social costs based on emission factors discussed in the model formulation section. A sample of the generated data for one of the commuters is summarized and listed in Table 3.3.

Table 3.9 Departure and Arrival Time and Primary Transportation Mode for Students' Commute

	Morning Commute			Afternoon Commute		
Commuter	Departure time	Transportation Mode	Arrival time	Departure time	Transportation Mode	Arrival time
1	9:46 AM	Drive car	9:55 AM	2:01 PM	Drive car	2:10 PM
2	9:01 AM	Drive car	9:05 AM	5:56 PM	Drive car	6:00 PM
3	8:23 AM	Ride bike	8:25 AM	9:58 AM	Ride bike	10:00 AM
4	8:16 AM	Drive car	8:20 AM	6:25 PM	Drive car	6:30 PM
5	12:07 PM	Drive car	12:23 PM	3:54 PM	Drive car	4:10 PM
6	8:39 AM	Drive car	8:46 AM	10:57 AM	Drive car	11:00 AM
7	8:11 AM	Walk	8:12 AM	2:59 PM	Walk	3:00 PM
8	8:11 AM	Drive car	8:15 AM	8:11 PM	Drive car	8:15 PM
9	7:34 AM	Carpool	7:43 AM	6:22 PM	Carpool	6:30 PM
10	8:52 AM	Drive car	9:00 AM	11:53 AM	Drive car	12:00 PM
11	7:37 AM	Ride bike	7:40 AM	3:58 PM	Ride bike	4:00 PM
12	8:05 AM	Carpool	8:15 AM	10:51 PM	Carpool	11:00 PM
13	7:35 AM	Drive car	7:40 AM	7:36 AM	Drive car	7:40 AM
14	7:57 AM	Drive car	8:01 AM	9:56 AM	Drive car	10:00 AM
15	6:10 PM	Drive car	6:14 PM	7:56 PM	Drive car	8:00 PM
16	8:51 AM	Drive car	9:02 AM	1:55 PM	Drive car	2:00 PM
17	9:59 AM	Walk	10:00 AM	12:08 PM	Walk	12:10 PM
18	4:30 PM	walk	4:32 PM	9:28 PM	Walk	9:30 PM
19	9:43 AM	Drive car	9:55 AM	9:53 PM	Drive car	10:05 PM
20	10:59 AM	walk	11:00 AM	4:59 PM	walk	5:00 PM
21	8:08 AM	Drive car	8:20 AM	4:48 PM	Drive car	5:00 PM

Table 3.10 Sample of Commuter 1 Trip Attribute Values for All Possible Commuting Alternatives in Fresno

Commute Options		Vehicle/bus/ train time	Walk/bike skateboard	Total travel time	Carpool commute time to destination	Travel distance	Travel distance for carpooling after pickup	Emissions	carpool emissions after pickup	Commute cost	Carpool commute cost
Existing vehicle		1.8	0.0	1.8	0.0	0.9	0.0	0.0	0.0	1.0	0.0
Public transit 1		1.0	8.2	9.1	0.0	0.9	0.0	0.0	0.0	0.0	0.0
Public transit 2		1.0	3.3	4.3	0.0	0.9	0.0	0.0	0.0	0.0	0.0
Bike		0.0	5.6	5.6	0.0	0.9	0.0	0.0	0.0	0.0	0.0
Walk		0.0	17.4	17.4	0.0	0.9	0.0	0.0	0.0	0.0	0.0
Carpool options	2.1	0.0	2.1	3.0	0.9	1.8	0.0	0.0	1.8	1.1	1.1
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6
	7.8	0.0	7.8	8.5	4.5	4.1	0.2	0.0	6.8	2.4	2.4
	3.6	0.0	3.6	4.0	2.9	2.4	0.1	0.0	4.2	1.4	1.4
	14.0	0.0	14.0	15.8	8.8	9.7	0.3	0.0	14.1	5.7	5.7
	5.8	0.0	5.8	6.6	5.2	5.1	0.2	0.0	8.0	3.0	3.0
	0.8	0.0	0.8	1.0	0.5	0.4	0.0	0.0	0.8	0.2	0.2
	6.5	0.0	6.5	8.2	5.1	6.0	0.2	0.0	8.4	3.6	3.6
	7.5	0.0	7.5	7.8	6.6	6.0	0.2	0.0	9.9	3.5	3.5
	3.1	0.0	3.1	3.6	2.0	1.9	0.1	0.0	3.1	1.1	1.1
	1.5	0.0	1.5	2.8	1.0	1.3	0.0	0.0	1.7	0.8	0.8
	8.1	0.0	8.1	9.8	6.1	7.0	0.2	0.0	9.9	4.1	4.1
	3.3	0.0	3.3	4.4	2.0	3.2	0.1	0.0	3.8	1.9	1.9
	3.0	0.0	3.0	3.2	2.0	1.9	0.1	0.0	3.1	1.1	1.1
	10.4	0.0	10.4	10.1	7.1	6.3	0.2	0.0	10.6	3.7	3.7
	1.2	0.0	1.2	0.5	0.6	0.4	0.0	0.0	0.8	0.2	0.2
	3.5	0.0	3.5	3.7	2.0	1.9	0.1	0.0	3.1	1.1	1.1
	1.0	0.0	1.0	2.0	0.5	0.9	0.0	0.0	1.0	0.5	0.5
	9.6	0.0	9.6	11.4	9.4	10.3	0.4	0.0	15.0	6.1	6.1
	8.5	0.0	8.5	1.0	5.0	0.4	0.1	0.0	5.4	0.2	0.2
	17.8	0.0	17.8	11.8	12.6	7.6	0.4	0.0	17.0	4.5	4.5

Based on the collected data of the student community, the optimization system calculated total equivalent social cost at $4.61, total commute time at 382 minutes, and total commute cost at $205 as shown as an existing scenario in Figure 3.2 and Figure 3.3. The optimization model was then used to optimize the commute plan for the student community at Fresno by identifying the optimal selection of commute alternatives that generate optimal trade-offs among the three optimization objectives: 1) minimizing equivalent social cost of negative environmental impacts, 2) minimizing total commute time, and 3) minimizing total commute cost. A commuter tolerance of 25 minutes for departure and arrival times was used in optimizing the students' commute plan to limit the increase in commute time for each student to no more than 25 minutes.

The Pareto optimal solutions identified by the model for negative environmental impacts and total commute time are shown in Figure 3.2. Two extreme solutions were identified with minimum possible total commute time, as shown in solution (a) in Figure 3.2, and minimum possible negative environmental impacts, as shown in solution (b) in Figure 3.2. Similarly, the Pareto optimal solutions identified by the model for total commute cost and total commute time are shown in Figure 3.3. A new extreme solution is identified for minimum possible commute cost, as shown in solution (c) in Figure 3.3. It should be noted that solution (a) is the same in both Figure 3.2 and Figure 3.3, as they constitute a 3D space of the three optimization objectives. Between the identified extreme solutions, the optimization model identified several trade-off solutions, as shown in Figure 3.3 and Figure 3.3. Many of the identified solutions outperform the existing scenario in terms of the three optimization objectives. For example, solution (d) outperforms the existing scenario in terms of negative environmental impacts (31% reduction) and total commute time (21% reduction), as shown in Figure 3.2. Similarly, solution (e) outperforms existing students' commute in terms of total commute time (21% reduction) and cost (52% reduction), as shown in Figure 3.3. This highlights opportunities for identifying optimal business commute plans that not only maintain commuter convenience, but also incentivizes commuters based on savings in commute time and cost and reductions in their daily negative environmental impacts.

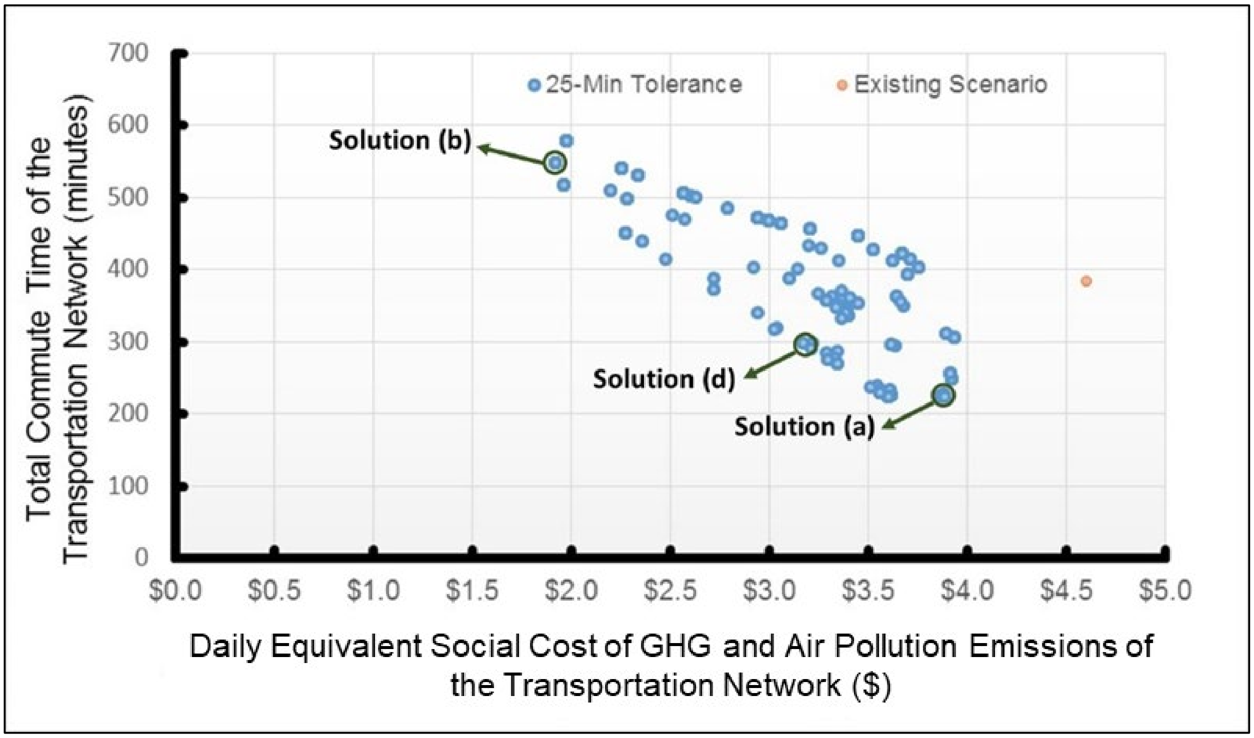


Figure 3.8 Time-cost-environment trade-off solutions for student community at Fresno

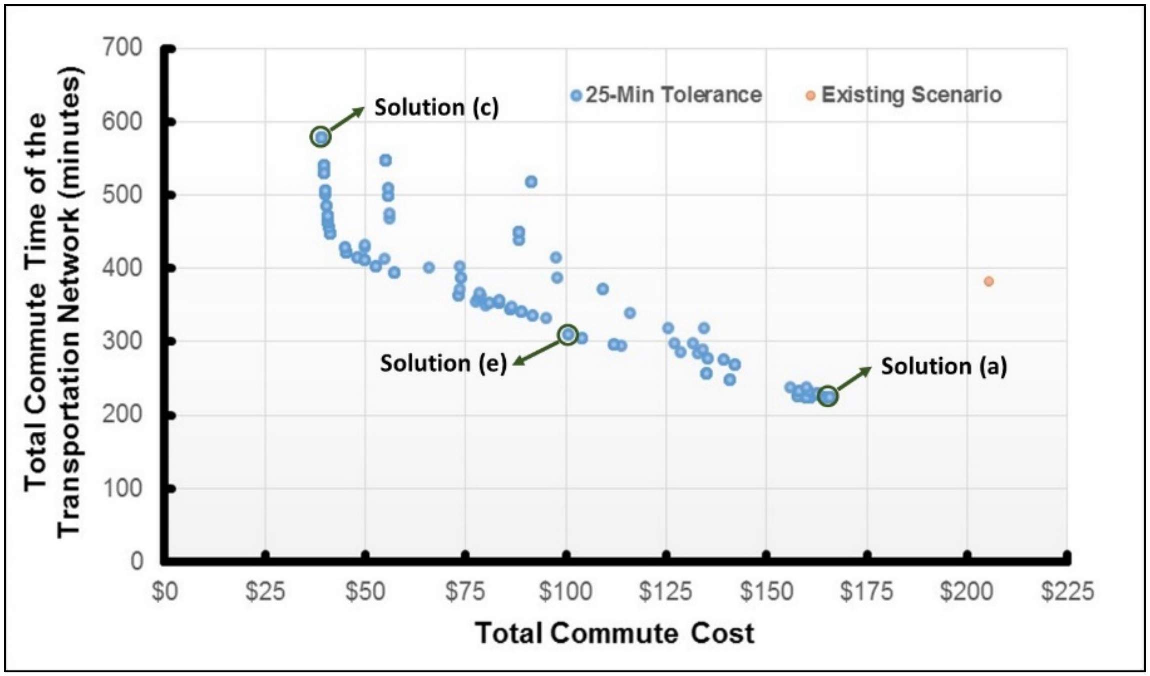


Figure 3.9 Time-cost-environment trade-off solutions for student community at Fresno

3.7 Summary and Conclusions

More than half of the emissions reported by the EPA from the transportation sector are generated from passenger cars and light-duty trucks. A significant portion of these emissions are caused by single occupant (drive-alone) automobile trips. Furthermore, business transportation plans are always non-optimized, relying mainly on personal convenience, time, and cost rather than environmental impacts and savings. This section presents the development of an optimization system capable of identifying the optimal selection of individualized business commute alternatives in order to minimize GHG and air pollution emissions, commute time and cost. The optimization system is integrated with GIS to quantify various commute attributes, such as trip time, distance, cost, and GHG and air pollution emissions for each possible commute alternative of each commuter. The output of the GIS is fed into an optimization model to minimize environmental impacts and commute time and cost. The optimization model is developed in two phases, which are formulation phase and implementation phase. The first phase focused on identifying the model decision variables to model all the commute alternatives for each commuter in a business. In addition, this phase focused on formulating the objective function to minimize the following: 1) total negative environmental impacts of a business, 2) total commute time, and 3) total commute cost. The model integrated a number of constraints to maintain commuter tolerance, commute logic, and carpool for two commuters. The second phase focused on executing the model computations to identify the optimal trade-offs among the three optimization objectives. Furthermore, this phase focused on identifying the model input data and recommendations for minimizing commute environmental impacts, time, and cost.

A case study was analyzed to evaluate the performance of the developed optimization model and demonstrate its new capabilities. Commute data from 21 students at California State University at Fresno were collected using an online survey then analyzed. The optimization model was able to identify time-cost-environmental trade-offs for the student community and provide recommendations that maintain the commuter tolerance and achieve the optimization objectives. The recommendations of the model showed promising expectations for implementation based on savings in the commute time and cost and potential for reducing negative environmental impacts. Future expansion of the model will analyze additional objectives, such as burned calories as health benefits. Furthermore, future expansion of the system will include dynamics of the transportation networks to provide practical solutions based on traffic congestion and route choices, along with and benefits of cap and trade and other carbon tax incentives.

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