ABSTRACT

DEVELOPING STATIC AND DYNAMIC MULTIMODAL TRANSPORTATION SYSTEM MODELS TO ESTIMATE INDIVIDUAL COMMUTER FOOTPRINTS USING ARCGIS, GOOGLE MAPS AND HERE 360

According to the U.S. Greenhouse Gas (GHG) Emissions and Sinks (2015), 27% of GHG emissions in the U.S. are produced by the Transportation sector, second only to the Electric Power Industry with 29%. A vast majority of these emissions are associated with single occupant (Drive-alone) automobile trips. While many policies exist for incentivizing alternative transportation modes, especially for commuting trips, only a few tools are available for estimating the potential benefits. Furthermore, the potential benefits are estimated using aggregate models and assumptions of commute behavior and existing transportation systems. Accordingly, to improve the accuracy of these estimates and potential impact of these policies, this research focuses on developing models to estimate footprints of individual commuters using real-world multimodal transportation systems.

Two different multimodal transportation system modeling approaches were developed and compared: 1. static models were developed using ESRI's ArcGIS 10.5 and its Network Analyst extension and Model Builder programming language, and 2. dynamic models were developed by the implementation of Google Maps and Here360 APIs in R Studio. Comparisons of the results of the static and dynamic models were further analyzed under two conditions: free flow and congested traffic. The developed multimodal transportation systems included six travel choices: Drive-alone, Bicycle, Walking, Bicycle-bus, Walking-bus and Carpool. The developed models computed individualized commuter estimates for

six travel measures: travel time, distance and cost, and CO₂, VOC, and NO_x emissions. A real-world case study was developed for commuters in Fresno, CA. A mixture of real-life and synthetic data comprising 218 commuters was used in the study.

Conclusions of this research include valuable insights about merits and limitations of the static and dynamic modeling approaches. Additionally, the results include multiple comparisons between the travel measure estimates of the two modeling approaches using different travel modes, and under the two traffic conditions. Outcomes of this research could prove valuable in transforming the existing approaches for estimating impacts of policies on alternative transportation incentives.

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DEVELOPING STATIC AND DYNAMIC MULTIMODAL
TRANSPORTATION SYSTEM MODELS TO ESTIMATE
INDIVIDUAL COMMUTER FOOTPRINTS USING
ARCGIS, GOOGLE MAPS AND HERE 360

by

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CHAPTER 1: INTRODUCTION

The 21st century holds many transportation-related challenges such as traffic congestion, air pollution, greenhouse gas emissions, and increasing energy and infrastructure costs. Transportation engineers are working tirelessly on overcoming and reducing these challenges. Until recently, the construction of new highways was thought to be an effective solution. Today, however, the development of integrated multimodal transportation systems holds more promise since it decreases the share of the personal automobile. Most challenges are especially prevalent during peak traffic hours in which commuter trips are playing a significant role and therefore receive most of the attention.

The majority of commute trips are single occupant (drive-alone) automobile trips. Within the last 30 years, drive-alone commutes have increased from 64.3% to 76.6% (American Association of State Highway and Transportation Officials, 2013; Rossetti & Eversole, 1993). One of the reasons so many travelers choose to commute alone is convenience. However, other factors include urban sprawl, lower gas taxes and dependent prices, lower overall quality of public transportation systems, and drive-alone commute subsidies. These factors explain the higher drive-alone mode share in the US compared to other developed countries in Europe and Asia. In order to decrease the number of drive-alone commutes, development of efficient planning and utilization of other transportation modes and policies to increase modal shares of active transportation, ridesharing, and transit systems is necessary.

Many policies such as the 1990 Clean Air Act have been developed to increase modal share of active transportation and transit systems. The Clean Air Act required companies, which have more than 100 employees and are located in

ozone nonattainment areas, to introduce policies that have the goal of increasing 25% of their employees' auto occupancy rates to be above the area-wide baseline auto occupancy average (Black, 2010; Gómez-Ibáñez, Tye, & Winston, 2011). Other programs that aim to increase modal shares of alternative transportation (other than the car) include telecommuting and parking cash-out programs, which allow employees to receive the value of parking spaces as additional income. However, it appears that most of these policies and programs have had only minimal impact. The National Compensation Survey in 2015 showed that most companies offer free parking for their employees and only 7% offer subsidies for alternative transportation modes (National Compensation Survey, 2015).

One of the major limitations of these policies is that they are not personalized; compensations and incentives depend on an estimate of the total companies' footprint rather than on individual commute footprints. Since a single employee with a long commute may have the same footprint as the combined footprint of several employees with shorter commutes, it would probably be more efficient if an employee with the longer commute received higher compensation for using alternative transportation modes than employees with a shorter one.

Currently, there are only a limited number of tools that estimate a company's total commute footprint, recommend alternative transportation programs, and assess the benefit of these programs. However, all those tools are limited to the output of total estimates of all employees and not individualized to each employee.

Hence, this research focuses on improving the detailedness of these calculations and potential impacts of recommended policies by developing models to estimate the footprint of individual commuters using real-world multimodal transportation systems. The outcomes of this research would include valuable

insights about merits and limitations of different modeling approaches and help transform the existing approaches for estimating impacts of policies on alternative transportation incentives.

This research focuses on the development and comparison of two different multimodal transportation system modeling approaches: 1. Static models were developed using ESRI's ArcGIS 10.5 and its Network Analyst extension and Model Builder programming language, and 2. Dynamic models were developed by the implementation of Google Maps and Here 360 APIs in R Studio. Comparisons of the results of the static and dynamic models were further analyzed under two conditions: free flow and congested traffic. The developed multimodal transportation systems included six travel choices: drive-alone, bicycle, walking, bicycle-bus, walking-bus, and carpool. The developed models computed individualized commuter estimates for six travel measures: travel time, distance, and cost, and CO₂, VOC, and NO_x emissions. A real-world case study was developed for commuters in Fresno, CA. A mixture of real-life and synthetic data comprising 218 commuters was used in the study.

The next chapters are organized in the following manner: Chapter 2 provides a review of existing literature and tools, chapter 3 presents and discusses the methodology developed and adopted in this research, chapter 4 analyzes the results, and chapter 5 summarizes and concludes this work.

CHAPTER 2: LITERATURE REVIEW

This chapter is organized in the following manner. Existing literature on commute choice will be presented and two tools for providing guidance to companies for the development of alternative transportation modes and the reduction of drive-alone commute will be explained in more detail.

2.1 Existing Literature

This section presents existing literature on reasons for travelers' commute mode choice and how companies' alternative transportation programs impact commute mode choice. Commuters' mode choices have received much attention in the research of travel behavior. While part of the literature focuses on finding the reasons for travelers' commute mode choice behavior, other parts focus on the development of ways to decrease the impact of morning and evening commute traffic on the environment. There has been a significant amount of research done in the area of commute trips, specifically the drive-alone commute. In the United States in 2009, 76.1% of commuters chose to drive alone and only 5% chose public transportation (U.S. Department of Commerce, 2011). As a result of that research, programs and policies with the hope to reduce drive-alone commuters were developed.

Many different factors influence commuters' mode choices. These factors are commuter-specific (e.g., age, income and gender); mode-specific (e.g., travel time and cost); company-related (e.g., the presence of free parking and incentives for the use of alternative transportation); environmental (e.g., precipitation and temperature); and trip-specific (e.g., destination and origin characteristics and number of trip chain stops).

A few examples of literature for the above described factors are listed in the following paragraph. Using the 1995 Nationwide Personal Transportation Survey, Chatman (2003) analyzed the effect of density and mixed land use at the workplace on employees' mode choice and personal commercial vehicle miles traveled (VMT). The research suggested that a higher employment density is associated with a lower likelihood of employee automobile use, and a higher workplace density is associated with the reduction of VMT (Chatman, 2003). A second example is the research of Heinen, Maat, and Wee (2011), which looked at 633 part-time bicycle commuters and the determining factors to use a bicycle for commuting. Day-to-day decisions were analyzed and the research suggests that workers having to wear business attire, transport goods, use a car during office hours, commute in the dark, ride longer distances, and experience a higher wind speed or a longer duration of rain are less likely to commute by bicycle (Heinen et al., 2011). Research done by Bhat and Sardesai (2006) suggested that weekly and daily commutes and midday stop-making influence mode choice. The analysis was done using a web-based commuter survey in Austin, Texas; it also emphasized travel time reliability as an important factor on commute mode choices (Bhat & Sardesai, 2006).

Other research focused on the impacts of companies' alternative transportation programs. Yang et al. (2015) used a multivariate logistic regression model to analyze the relationship between home and worksite neighborhood environments, worksite support and policies, and employees' commuting modes. The research was done using a telephone survey completed by 1,338 participants. The following associations were the main findings of their analysis: nearby home transit stops or employer-provided free or discounted public transit passes and commute with public transit; low worksite nearby cost or free recreation facilities

and active commuting; availability of bike facilities at workplace and active commuting; negative association between commute distance and active commuting (Yang et al., 2015). Similarly, Hamre and Buehler (2014) looked at the relationship between employer benefits for free car parking, public transportation, walking, and cycling. The study consisted of 4,630 regular commuters and multinomial logistic regression models were used for the analysis. The research showed that if free parking was available, more commuters chose the car, whereas the availability of showers/lockers, public transportation benefits, bike parking, and the lack of free parking increased the commuters' use of alternative transportation modes (Hamre & Buehler, 2014). Much research has been done on commuter mode choice behavior and its impacts on companies, but limited tools for employers to choose the right transportation program are available.

2.2 Available Tools

Further researched has shown that more and more state and federal programs have been developed with the goal of reducing the commute modal share of driving-alone and increasing the share of alternative transportation modes. Tools for employers to determine and apply optimum transportation benefits are limited. The following two tools are currently available for businesses to reduce drive-alone and encourage the use of alternative transportation modes: Commuter Choice, and the CUTR_AVR Model.

2.2.1 Commuter Choice

Commuter Choice helps companies create customized solutions to employees' daily commute challenges. It is supported by the U.S. Department of Transportation (USDOT) and the Environmental Protection Agency (EPA) and helps employers connect with local service providers to implement relevant

commuter choice programs. Transit and van services, tax benefits assistance, telework setup, worksite programs, and commuter services can be found on their website for local and nationwide coverage. The following guides can help to find the right program for employees. The next sections include detailed information about three commuter choice programs: Commuter Choice Decision Support System, COMMUTER, and the Business Benefits Calculator.

2.2.1.1 Commuter Choice Decision Support System. The Commuter Choice Decision Support System is one guide to find recommended commuter choice programs. It is an interactive guidance tool that takes about 10 min to complete. Three different types of question groups are asked, including employer motivation, employer and worksite characteristics, and management support. Examples of questions can be found in Table 1. The output of this tool provides a broad range of incentives, which are each given a different number of points, with the highest thought to be the most effective option for implementation. The four different options for incentives are mode choice (transit, carpool, vanpool, bike/walk, parking management); time choice (flextime and alternative schedules); location choice (telework, live near your work, on-site employee services, worksite locations and design); and route choice (real-time commuter services, and advanced route planning).

2.2.1.2 COMMUTER. The EPA has also published a commuter choice model, a spreadsheet-based software program called COMMUTER. It evaluates travel and emission impacts of employer-based travel demand management strategies. The traditional forecasting method is the 4-step transportation model, which is a very long and complicated process. The COMMUTER model is based on the Federal Highway Administration's Travel Demand Management Evaluation

Table 1

Input Requirements and Examples of Questions of the Commuter Choice Decision Support System

Employer Motivations

- Employee Issues: Interest to increase the employee productivity and reduce tardiness?
- Facility Needs: Interest to reduce the demand for parking?
- Costs: Interest in reducing operating costs?
- Public Relations: Interest in enhancing the corporate image?

Worksite Characteristics

- Location: rural/urban; Level of transit service; Pedestrian and bicycle friendly; does congestion cause delays for employees?
- Parking: Free parking for employees? Is the parking site leased or owned?
- Facilities and Services: Are there lockers, showers, storage facilities available? Are there nearby services for employees available during lunch such as food and banks?
- Your Employees: What is the number of Employees working at the site? Estimate how your employees get to work each day: Drive Alone, Transit, Carpool, etc. How far do most employees live from work?
- Your Organization: What type of business is your organization involved in? Which of the following best describes the work hours at this site for the majority of employees?

Management Attitudes

- How important are commuting issues to the organization's management? Would management consider purchasing equipment for new services and provide financial incentives to employees?
-

Model (FWHA TDM Model), developed in 1993. The COMMUTER model is separated into three steps:

1. Establish a baseline supplying essential information on local conditions (area size, setting, analysis scope, average trip length, employment base, existing mode split, vehicle occupancy, peak period duration, speeds).
2. Analyze selected scenario (up to four different strategies can be applied: employer TDM Support, alternative work schedules, travel time improvements, and travel cost changes).
3. Calculate vehicle miles traveled (VMT) for peak and off-peak travel periods; estimate change in volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO₂), particulate matter (PM_{2.5}), and six air toxins.

Model outputs include the following:

1. Baseline and final mode share for each selected mode
2. Percentage of trips moved from peak to off-peak period
3. Baseline and final daily VMT and vehicle trips for peak and off-peak
4. Changes in total daily emissions

2.2.1.3 Business Benefits Calculator. One of the other resources available is the Commuter Choice Business Benefits Calculator. The Business Benefit Calculator is a third tool for businesses to reduce drive-alone and encourage the use of alternative modes. Employer inputs for this model include the location and type of location, information about the organization, and that organization's taxes. Also, the number of employees, average salary, tax rates, existing travel patterns and parking situation are included in this model. The second section asks for the benefits the employer would be interested in including (e.g., parking cash out,

employer-paid transit/vanpool benefits, telework, shuttles, secure bicycle parking, showers and lockers). The output of this tool is the estimated employee program participation and estimated employer costs and savings, including incentive costs, administrative costs, equipment costs, value of incentives to employees, employees gas and auto maintenance cost savings, and employee parking cost savings. Figure 1 presents a flowchart of steps required in the Benefits Calculator.

Figure 1. Flowchart of steps required in the Benefits Calculator.

To estimate the participation of each program, several calculations are made. The number of employees participating in telecommuting programs is calculated directly from the input provided by the user on the program selection page, using the percent of employees telecommuting full-time and part-time and

the total number of employees at the work site. The estimated participation of employees in other programs is computed using the EPA commuter model. Look-up tables, generated by the commuter model run with several combinations of programs and locations, are used for the selection of trip rate changes for selected programs. Values in the look-up tables represent the trip rate change with the implementation of a specific program. Since participation varies with location, the estimated participation values can be adjusted manually by the user. High and low values reflect a reasonable range, depending on variations such as size, traffic congestion, and types of transit (Herzog & Grant, 2002).

The following different costs and benefits are represented at the end of the model: direct financial effects, potential parking and office space cost savings, recruitments, retention, and productivity effects, and community benefits. Each of these are calculated with a different default and from the user provided values. Table 2 shows a breakdown of all outputs relevant to the employer, employee and the community.

One of the main concerns of this research is the estimation of commuter travel miles and its level of greenhouse gas emission. The following paragraph breaks down the calculations of these attributes by the Benefits Calculator.

Community Benefits:

1. Commute vehicle trip reduction is calculated by multiplying the reduction in daily drivers by two trips per day and by 240 work days per year;
2. Vehicle miles traveled (VMT) reduction: estimated by multiplication of vehicle trips reduced by and average commute trip length of 11.8 mi (Hu & Young, 1999), differential trip reductions when switching to vanpooling, carpooling vs. walking and bicycling are not accounted for;

Table 2

Output of Benefits Calculator

 Direct Financial Effects:

- Administrative Costs
- Facility and Equipment Costs
- Transit and Vanpool Benefits: Employer Costs and Employee Value
- Employee Pretax Deduction for Transit and Vanpool Expenses:
Employer Cost Savings and Employee Value
- Parking Cash-Out: Employer Incentive Costs and Employee Value

Potential Parking and Office Space Cost Savings:

- Parking Cost Savings
- Office Space Cost Savings

Recruitments, Retention, and Productivity Effects:

- Recruitment and Retention Effects
- Productivity Benefits

Community Benefits:

- Reduced vehicle travel
 - Reduced urban air pollutant emissions
 - Reduced greenhouse gas emissions
-

Source: Herzog, E., & Grant, M. (2002). Commuter Choice Benefits Calculator: Web-based tool for estimating costs and benefits of commuter programs. *Transportation Research Record: Journal of the Transportation Research Board*, 1781, 32-39. doi:10.3141/1781-05

3. Energy consumption reduction: VMT divided by average vehicle fuel economy of 20.4 mi per gallon;
4. Emission reduction: VMT multiplied by average vehicle emission factors from EPA's MOBILE and PART5 models.

Limitations of this program include the lack of individualized incentives or calculations of reduced CO₂ emissions and vehicles miles traveled. Also, many default values are used for the calculation of these attributes, which results in a generalized estimation of outputs. The interactive guidance tool and Business Calculator are just starts in the commuter choice system. More employer resources are listed on the Commuter Choice website; unfortunately most of the guides and detailed information on how to implement recommended commuter programs have been discontinued and can no longer be accessed.

2.2.2 CUTR_AVR Model

The CUTR_AVR Model was developed in 1999 by the Center of Urban Transportation Research (CUTR) at the University of South Florida. Changes in average vehicle ridership (AVR) resulting from employer-based transportation demand management programs are being predicted using an artificial neural network. Based on a 7,000-employer trip reduction plan from three metropolitan areas in Arizona and California, the CUTR_AVR Model is particularly suited for a single employer with 100 or more employees at site or on multiple sites.

Inputs for the model include existing mode share, number of employees, and average vehicle ridership. The first software screen asks for general worksite information such as name, address, plan start, number of employees, local area population, and size of local area. The next page requires employee commute information such as number of employees driving alone, 2-4+ carpool, buspool,

transit, bicycle, walking, telecommute, on vacation, and have a one-way commute time over 40 min. The last input is the incentive plans placed during the time under study (1-year periods). It has the option of five plans: higher cost of driving, any type of guaranteed ride home, in-house or regional ridematching system, alternative mode use subsidies, and compressed work week programs. The output of this software is the estimated average vehicle ridership (AVR) and vehicles per 100 employees with and without the implementation of the previously selected plans (Winters, Cleland, Burris, Perez, & Pietrzyk, 1998). Figure 2 shows the input, model evaluation, and output of the CUTR_AVR model.

Figure 2. Flowchart of steps of CURT_AVR tool.

This tool is limited to only five specific TDM programs and different levels (partial implementation of a program) cannot be evaluated. Additionally, different financial or time-based incentives cannot be managed and Vehicle Miles Traveled (VMT) and emission reductions are not calculated (USDOT). Also, when trying to use the software, it was not possible to download it from the given website.

2.3 Research Objective

All of the previously reviewed and presented tools provide businesses with generalized recommendations for commuting polices and estimates of benefits. All

calculations are based on aggregate measures of business employee commute data, instead of modeling footprints of individual commuters. Individualized commute incentives might be more suitable for business and result in a lower greenhouse gas footprint. Also, some of the above explained tools are no longer available to use and websites have been discontinued.

Accordingly, the objective of this research is to develop a new tool capable of quantifying footprints of individual commuters. To achieve this objective the following four steps were implemented:

1. Develop an algorithm, a model capable of quantifying individual commuter footprint in real-life multimodal transportation systems;
2. Implement the developed model in three different platforms (ArcGIS, Google Maps and Here 360);
3. Compare the capabilities and limitations of the three platforms; and
4. Adopt a real-world case study to test and examine the functionality of the developed models and platforms.

This research has the potential to set the foundation for software to significantly improve previous research efforts. The following chapter presents the methodology adopted in this research.

CHAPTER 3: METHODOLOGY

Two different multimodal transportation systems were developed. The static model was developed using Esri's ArcGIS network analysis extension and the model builder programming language, and the dynamic model was developed using Google Maps and Here 360 APIs (Application Programming Interfaces) implemented into R Studio. The models were further analyzed under two conditions: free flow and congested traffic. The developed transport systems include six travel modes: drive-alone, bicycle, walking, bicycle-bus, walking-bus, and carpool.

This chapter is organized in the following manner: First, equations of the adopted general statics are described. The next part explains how the ArcGIS model and its Network Analysis and Model Builder extensions operate and how they were developed. That part also includes a description of how the data points of commute origins used for this research were created. The next part focuses on the operation and development of Google Maps and Here 360 APIs. The last part shows how these models were analyzed and compared.

3.1 General Statistics

Three different descriptive statistics were used for the analysis: mean, variance, and standard deviation. The mean is the average of a set of numbers. The variance describes the average of the squared difference from the mean. The standard deviation is a description of the range of the set of data. All three equations can be seen in Table 3.

Table 3

Equations for Mean, Variance, and Standard Deviation

Mean	Variance	Standard deviation
$\bar{X} = \frac{\sum_{i=1}^N x_i}{N}$	$S^2 = \frac{\sum_{i=1}^N (x - \bar{x})^2}{N - 1}$	$S = \sqrt{\frac{\sum_{i=1}^N (x - \bar{x})^2}{N}}$

Where: $\bar{X}$ = mean

S^2 = Variance

S = Standard Deviation

N = number of items in sample

X_i = value of observation i

3.2 ArcGIS 10.5

ArcGIS is a Geographic Information System (GIS). It is used for processing and compiling geographic data, creating and analyzing maps, and using the geographic information in a great range of application and processing tools. The two main tools used for this analysis were the Network Analyst, which is an ArcGIS extension and solves complex routing problems (Esri, 2017a), and the Model Builder, which is a visual application for creating and managing models by stringing together a sequence of several different geoprocessing tools (Esri, 2016b). The following sections of this chapter include the model inputs, connection of all network elements, creation of the commute origins data points, building the network analyst and building and running the models in the Model Builder.

3.2.1 Model Input

The first step for building the model was the development of the network dataset. The network was made of the Fresno County Road Network, four

different transit systems, and the commute origins data points. All shapefiles and network elements had to be gathered. Table 4 shows all network elements.

Table 4

<i>Description of the Shapefiles used in the ArcGIS Multimodal Network Model</i>	
Shapefile Name	Description
Fresno County Road Network	All Fresno County Streets with information such as Speed limit, direction, street function class, name, etc.
Fresno Area Express (FAX) transit lines and stops	FAX bus lines and stops including bus line length
Fresno County Rural Transit Agency (FCRTA) transit lines and stops	FCRTA bus lines and stops including bus line length
Clovis Roundup Transit lines and stops	Clovis Roundup Transit bus lines and stops including bus line length
Bus Rapid Transit (BRT) lines and stops	BRT bus lines and stops including bus line length
Commute Origins Data Points	218 data points made up of a mixture of real-life and synthetic data points representing origins of the commute trips

All above listed elements were added to the network. For a correct analysis, it was important that all shapefiles were converted into the same geographic coordinate system and projection. For this analysis the projected coordinate system “NAD 1983 California IV (feet)” and the geographic coordinate system “GCS_North_American_1983” were used.

For further data management and editing, a geodatabase was created and all shapefiles were added to it. The Fresno County Road Network, provided by the Fresno County of Governments, was the first shapefile implemented into the network. The “streets” shapefile consists of over 100,000 network links; to avoid network errors, it was important to test the streets network by itself first. Unfortunately, several errors occurred when trying to build the network with the Fresno County streets file. The errors were most likely a result of the attribute “functional class,” as several street links had no input for this attribute. These streets were cross-referenced with Google Maps, and it was seen that these streets did not exist there. Therefore it was concluded that, since no functional class information was included and they did not exist in Google Maps, these streets did not exist and could be deleted from the network.

The function class of a road could be used to determine its speed limit. Trip distances could be calculated directly from the geographic characteristics of street segments. However, to calculate trip time, it was important to have information about both road distances and speed limits. Fortunately, the utilized shapefile entailed speed limits for all links and did not have to be calculated separately. In case of missing information on speed limits, Table 5 can be used.

3.2.2 Connection of Network Elements

This section describes the connection of all network elements. To correctly calculate a multimodal trip from point A to point B, all network elements had to be connected to each other. For example, a multimodal transit trip includes a person walking (or biking) on street segments, getting to the bus stop, and traveling on the bus line. Therefore, streets have to be connected to transit stops, and transit stops have to be connected to bus lines. To ensure these connections, bus stops have to

Table 5

Functional Classes and Corresponding Speed Limits

Functional Class	Road Name	Speed Limit
1	Interstate e.g. I-5	70 mph
2	Freeway or Expressway e.g. SR 41	65 mph
3	Principle Arterial e.g. Herndon Ave	50 mph
4	Minor Arterial e.g. Bullard Ave	40 mph
5	Major Collector e.g. Gettysburg Ave	35 mph
6	Minor Collector e.g. Rd 36	30 mph
7	Local Roads e.g. San Ramon Ave	20 mph

Source: Caltrans (Cartographer). (2016). California Road System (CRS) Map Retrieved from http://www.dot.ca.gov/hq/tsip/hseb/crs_maps/

perfectly coincide on streets and bus lines. The “snap” tool from the editing toolbox was used. As stated by ArcGIS documentation, the “snap” tool “moves points or vertices to coincide exactly with the vertices, edges, or end points of other features” (Esri, 2017b). The snap environment parameter determines the snap rules; vertices of the input layer can be snapped onto vertices, edges, and endpoints of multiple layers or feature classes. The following rules were used for this network:

1. Snap transit stops on street network EDGE: ensures that the vertices of transit stops coincide with the edges of the street network links, which results in an overlap between the transit stops and street segments
2. Snap transit routes on transit stops END: ensures that the vertices of transit links coincide with transit stops, which results in an overlap between the transit lines and transit stops.

The “snap” tool only provides the overlay of network elements. While the different elements may appear to overlap, they are usually not completely overlapping. Complete overlapping is required for connectivity between different transportation elements. Therefore, for full connection, a topology has to be created using ArcCatalog. According to ArcMap a “topology is the arrangement that defines how point, line, and polygon feature share coincident geometry” (Esri, 2016a). For this analysis, the topology ensured that transit lines, transit stops, and street segments share common geometry. The first step in creating a topology is to choose all feature classes that will participate. For this research, this included the Fresno County streets and all four transit networks and their corresponding transit stops. Following that, the topology rules were set to establish the spatial relationships between features and how their geometry was shared. The following rules were used for this case study:

1. All transit lines “must be covered by feature class of” Fresno County streets. This ensured that the lines from the transit system were covered by the boundary of the Fresno County street network and their geometry coincided (Figure 3 part a).
2. All transit stops “point must be covered by line” of Fresno County streets. This rule ensured that all transit stops were covered by segments of the Fresno County streets network and their geometry coincided (Figure 3 part b).

These two rules ensured that a route could be created using the transit and road system together. The transit stops were now connected to both the transit lines and the road network to guarantee proper transfer between different travel modes. After all rules were set, the topology was saved and validated.

a. Topology rule description line “Must be covered by feature class of”.

b. Topology rule description point “Must be covered by line.”

Figure 3. Topology rule descriptions

3.2.3 Data Points

This section describes the creation of all commuter origin data points used in this research. This case study consists of a mixture of real-life and synthetic data comprising 218 commuters.

1. 23 Real-life commuters: These data were collected using a travel survey that documented real-world commute behavior for engineering students at California State University, Fresno. The commute data were recorded on a single school day in spring 2015. The data included transportation mode choice, arrival and departure times, commute origin and destination (Fresno State). Due to the small size of the surveyed data, additional synthetic data points were generated using a simulation algorithm.

2. 195 synthetic commuters: Synthetic commuters were added to the real-life commuters to have a larger data set and make outcomes of this research more reliable. The following are details about the adopted algorithm for the creating of the synthetic points.
 - a. 500 random origins were created using “Create Random Points” with the ArcGIS Data Management tool; the geographic constraints were the Fresno County “streets” shapefile (i.e., these points were generated within the boundary of Fresno County).
 - b. Using the latitude and longitude coordinates of every point, the Euclidean distance from each point to Fresno State was calculated using the field calculator.
 - c. It was assumed that 80% of all commuters are commuting a distance less than or equal to 10 mi to Fresno State and 20% of all commuters are traveling longer than 10 mi. This radius is just an assumption and can be adjusted to the circumstances at any time. Using the “buffer” tool from the proximity toolset of ArcGIS, a radius of 10 mi around Fresno State was created and all random points were sorted by “near,” meaning within the radius, or “far,” meaning outside the radius.
 - d. Using a random number generator, Rnd() within the field calculator, 80% of all points within the 10 mi radius and 20% outside the radius were accepted and all other points rejected. This resulted in the creation of 195 random commute origin points. Figure 4 depicts the process of creating the 195 synthetic points. In reality, the origin point locations might not be random; they might instead be concentrated in residential and similar land use areas, but for the focus of this research, random locations were sufficient. All data points are shown in Figure 5.

Figure 4. Flowchart of synthetic random point creation.

Figure 5. Map of Fresno County street network with 218 commuter data points.

3.2.4 Multimodal Network Analyst

This section lists all steps of the development of the multimodal network analyst. Esri's ArcGIS Network Analyst Extension was used to build the transportation network dataset. This step enables the calculation of possible routes from one location to another using multimodal transportation systems. The following steps include the development of the multimodal network analyst.

1. All previously used network system elements, including Fresno County streets, transit routes, and transit stops, were added to the analyst. Only added elements were used for further analysis.
2. Connectivity: Determined which edge and junction elements coincided geometrically. Two separate connectivity groups were created; this was

done to model multimodal transportation systems. Transit stops formed the links between both connectivity groups. This guaranteed that transit lines connected to street segments through transit stops.

- a. Fresno County Streets: Group 1
 - b. Transit Routes: Group 2
 - c. Transit Stops: Groups 1 and 2
3. Attributes: Controlled traversability over the network (e.g., direction of travel, and restricted streets) and allowed calculation of desired travel measures (e.g., travel time, distance and costs; air pollution and different GHG emissions, and calories). Following is a list of the attributes utilized in this work:
- a. COST attributes: measuring and modeling impedances
 - i. Travel distance: measured as a function the geography of the traveled segments (drive-alone, walking, bicycle, bicycle-bus, walking-bus)
 - ii. Travel time: using attribute parameters presented in Table 7
 - iii. CO₂, VOCs, NO_x emission, cost for modes “car alone” and “bus” using attribute parameters presented in Table 7.
 - iv. Calories burned and CO₂FoodPrint for modes “walking” and “bicycle” using attribute parameters presented in Table 7
 - b. RESTRICTIONS attributes: controlled traversability over the network
 - i. ONEWAY: One-way street segments (i.e., freeway ramps).
Restriction evaluators assigned values for the attributes; those were either assigned from a field within the shapefile or calculated through the field calculator. Table 6 shows the evaluator for the restriction attributes.

- ii. FREEWAY: Modes “transit,” “walking,” and “bicycle” were restricted to use freeways and freeway ramps. Restriction evaluator: If the functional class of Fresno County streets was “1,” then route was restricted.

Table 6

Network Analyst Restriction ONEWAY Evaluators

Direction of Link	Restriction
LinkToFrom : (T) one way	NOT Restricted = False
(F) two way	NOT Restricted = False
LinkFromTo: (T) one way	Restricted = True
(F) two way	NOT Restricted = False

Table 7

Attribute Parameter for ArcGIS Network Analyst

Attribute Mode	Travel Time	Travel Distance	CO2 Emissions	NOx Emissions	VOCs Emissions	Travel Cost	Calo ries
Bus	$\frac{Distance_{(1)}}{30\text{ mph}}$	Trip Origin to Destination	294.6 g/p-mi* ^(1,2)	1.643 g/p-mi* ^(1,2)	0.039 g/p-mi* ^(1,2)	0.0	
Car	$\sum \frac{Link\ Length}{Speed\ Limit.}$	Trip Origin to Destination	368.4 g/mi ^(2,3)	0.693 g/mi ^(2,3)	1.034 g/mi ^(2,3)	59.2 ¢/mi ⁽⁴⁾	
Walk	$\frac{Distance_{(6)}}{2.8\text{ mph}}$	Trip Origin to Destination	1.589 g/cal ⁽⁸⁾				4.10 kcal/ min (5)
Bike	$\frac{Distance_{(7)}}{10\text{ mph}}$	Trip Origin to Destination	1.589 g/cal ⁽⁸⁾				4.68 kcal/ min (5)

* p-mi is passenger mile and gge is gasoline gallon equivalent

¹(U.S. Department of Energy Alternative Fuel Data Center, n.d.); ²(US EPA Office of Transportation and Air Quality, 2008); ³(Transportation and Air Quality, 2008); ⁴(Delucchi & Lipman, 2001); ⁵(Department of Public Health State Of Wisconsin, 2005); ⁶(Here, 2017); ⁷(American Association of State Highway and Transportation Officials, 2010); ⁸(Gössling, Garrod, Aall, Hille, & Peeters, 2011)

3.2.5 Model Builder

This section details the developed models using the ArcGIS Model Builder programming language. Esri's ArcGIS Model Builder was used to develop two different models. The Model Builder helps to string sequences of geoprocessing tools together, feeding outputs from one tool as an input to the next tool.

The first model calculates possible routes from one location to another for all different modes (except carpooling). Figure 6 part a shows an example model for the mode "car-alone" with used tools ("yellow"), input ("blue"), and output ("green"). To ensure realistic routes and corresponding attributes for every mode, different impedance attributes and restrictions within the "make route layer" tool were set. With respect to the modeled mode, the impedance attribute was always set to the total trip time. This ensured that the determined route was the one with the minimum travel time (rather than the shortest distance). After a successful model run, results were stored in the attribute table of the created layer.

The second model captured characteristics of carpooling trips. Several adjustments had to be made. To run the model once for all commuters, an iterator was added. For a given origin (driver, which also the first traveler), the iterator ran through the pool of all possible first passengers (second traveller), and calculated all associated trip attributes for each. The output of this model was a route layer for every driver-passenger combination. The carpool model was run for only a sample of the 218 commuters, because no differences in overall results between the carpool and drive-alone modes for ArcGIS, Google Maps, and Here 360 could be seen. Figure 6 part b shows an example of the ArcGIS Carpool model.

a. Drive-alone ArcGIS model.

b. Carpool ArcGIS model.

Figure 6. Drive-alone and carpool ArcGIS model.

3.3 R Studio

This section includes detailed information about the analysis of dynamic models using Google Maps and Here 360 APIs (Application Programming Interfaces), which were used and implemented in R Studio. APIs are subroutines and protocols for the development of application software. By implementing APIs into R Studio, the communication between Google Maps or Here 360 and R Studio was developed. Google Maps and Here 360 are web mapping services which allow the user to see satellite imagery and receive detailed information of real-time traffic conditions and route planning.

3.3.1 Construction of Google Maps and Here 360 URLs

To receive data from Google Maps or Here 360, URLs had to be constructed using the following seven steps. Access to Google Maps or Here 360 APIs can be received through the HTTP interface, which provides access to and receives data from either Google Maps or Here 360. The requests are sent with a constructed URL string with several different parameters, including origin, destination, waypoints, mode, time, and access key. The following list explains how to construct successful Google Maps and Here 360 URLs.

1. Understanding Directions API, Distance Matrix API, and Routing API:
 Directions API provides the calculation of direction between locations, Distance Matrix API provides travel distance and time for matrix of origins and destinations, and Routing APIs calculate routes for multiple waypoints. Table 8 presents a description of the necessary information of these APIs.
2. Activate the API and get API keys: Many different plans are available when using the Google Maps API. For the purpose of this research the standard free “Web services” Plan was chosen. It provides up to 2,500

requests per day. The Directions API and Distance Matrix API were the two main APIs used for this analysis. For the implementation of Here API a 90 day free trial was used. It includes 100k transactions per month and had no daily limitation. It includes all standard and advanced features. The Routing API provided all necessary information for this evaluation.

3. Install R studio packages “httr” and “ggmap.” “httr” sends the information entered in R Studio to the requested API server. “ggmap” visualizes spatial data and models (including routing) from Google Maps and Here 360
4. Import commuter addresses: For this step, the 218 addresses created by ArcGIS were used but had to be converted into a readable format for R Studio. This included Longitude and Latitude coordinates separated by “%2C” instead of a comma.
5. Construct URLs using mainly “for” loops and “if” statements. This part is the most important step of the process. These loops run through the constructed URLs and request services such as routing, direction, or distance for the commuter addresses and returns and prints desired outputs such as travel distance and time.
6. Set Departure Time: Google Maps APIs use Unix epoch time (which is the number of seconds elapsed since January 1, 1970). On the other hand, in Here 360, an actual date and time is used. Google Maps can only process travel times in the future, whereas Here 360 can process trips in the past.
7. Set Attribute parameter: The same attribute parameters for the calculation of GHG emissions, cost, and calories as for the ArcGIS analysis were used and can be found in Table 7. The default transit trip includes only Walking and transit, i.e. no Bicycle-bus mode exists for either of the two APIs.

Therefore, the Walking-bus mode was used to determine the distance to and

from transit stops. Then, this distance, combined with a biking speed of 10 mph was utilized to calculate the Bike-Transit times. In addition, each mode was analyzed using the fastest trip attribute (rather than the shortest trip).

Figure 7 shows a flowchart of the main steps for construct Google Maps and Here 360 URLs.

Figure 7. Flowchart of Google Maps and Here 360 URL construction.

Table 8 provides details of the used Distance Matrix API, Direction API, and Routing API.

3.3.2 Specification for Here360

Here 360 has additional attribute specifications that are further explained here.

1. **Public Transportation:** Transit routing calculates routes using known online timetable information. Walking Radius and Walking Speed can be adjusted using “walkRadius” and “walkSpeed” parameters. The default maximum Walking Radius to a transit stop is 3000 m. Adjustments can be made from 0 to 6000 m. The default Walking speed is 1.25 m/s which can be changed anywhere from 0.5 to 2 m/s.

Table 8

Definition, Modes, and Required Parameters for Distance Matrix, Direction, and Routing APIs

	Distance Matrix API	Direction API	Routing API
Def.	Provides travel distance and time for matrix of origins and destinations	Calculation of direction between locations	Calculation of routes for multiple waypoints
Modes used for	Drive-alone, Bicycle, Walking	Walking-bus, Bicycle-bus, Carpool	All
Required parameters	Origins: can be written as coordinates or text strings separated by the pipe character () Destinations: same as Origins Key: application's API key)	Origin: can be written as coordinates or text strings separated by the pipe character () Destination: same as Origin Key: application's API key)	App ID and APP Code: application API key Waypoint 0 and Waypoint 1: Coordinates only Mode: car, CarHOV, truck, pedestrian, bicycle, public transport
Optional parameters	Mode: defaults to driving units, departure time, transit mode, etc.	Mode: defaults to driving Waypoints, departure time, etc.	Departure, walkRadius, walkSpeed, routing type, etc.
Response	Status, origin addresses, destination addresses, duration, distance	Status, geocoded waypoints, routes with distance and duration, available travel modes, transit details, etc.	Meta Info, route with distance and time, summary, language

2. Bicycle: The Bicycle routing uses the pedestrian road network but makes adjustments based on each road's suitability for cycling.
3. Pedestrian: Pedestrian routing calculates routes based on the easiness for pedestrian to maneuver between links (disregarding traffic conditions). It can also be optimized using different Walking Speeds or avoid or promote specific roads or areas such as parks.

3.4 Comparison

Results of all models were compared in the following manner. Generated routes in all models were minimum travel time routes. Figure 8 depicts the different comparisons adopted in this work. Since speed limits were utilized to calculate travel times in ArcGIS, the ArcGIS models' routes reflect free flow traffic conditions – and could not model peak traffic. Accordingly, only the free flow traffic analysis was possible using the ArcGIS. On the other hand, the models developed with Google Maps and Here 360 are able to capture traffic conditions. Accordingly, peak and free-flow traffic conditions were evaluated. Three different types of comparison were made: 1. ArcGIS Static to Google Maps and Here 360 free-flow conditions, 2. Peak traffic to free-flow traffic in Google Maps and Here 360, and 3. differences within peak traffic in Google Maps and Here 360.

Figure 8. Model comparison.

Free flow traffic was assumed at a set departure time of Sunday 4 a.m., and peak (congested) traffic was assumed at a set departure time of Thursday 8 a.m. Since transportation challenges are prevalent during peak traffic, that period was further evaluated with departure times every 30 min starting at 7 a.m. to 9 a.m.

The following chapter presents the results of the models and provides details of limitations and advantages of each model.

CHAPTER 4: RESULTS

As presented in chapter 3, two different multimodal transportation systems were developed. The static model was developed using Esri's ArcGIS Network analysis extension and Model Builder programming language, and the dynamic models were developed using Google Maps and Here 360 APIs implemented into R Studio. The models were further analyzed under two conditions: free flow and congested traffic. The developed transport systems include six travel modes: drive-alone, bicycle, walking, bicycle-bus, walking-bus, and carpool.

This chapter is organized as follows: Free flow analysis will be the first comparison followed by the comparison of peak analysis and lastly all advantages and disadvantages of all three models will be listed.

4.1 Free Flow Analysis

This section includes summary of results for free flow analysis using all the models. First the free flow analysis for drive-alone, walking, and bicycle is presented followed by the free flow analysis for walking-bus and bicycle-bus.

4.1.1 Free Flow Analysis for Drive-alone, Walking, and Bicycle

The first comparison was made for three modes: drive-alone, bicycle, and walking using ArcGIS, and the free flow condition using Google Maps and Here 360. Figure 9 depicts the drive-alone commute of the ArcGIS Model. It shows the calculated routes for all 218 data points. The gray and black lines in the background show the Fresno County streets network.

Figure 9. ArcGIS drive-alone output map.

Figure 10 parts a through c present the descriptive statistics from the travel time of the three transportation modes using all three models. The orange point shows the average and the blue whiskers show the positive and negative standard deviation. It can be seen that Here 360 has the highest average travel time and bigger range of standard deviation for all three modes. The fastest routes were calculated by Google Maps for bicycle and walking, but ArcGIS had a quicker route for drive-alone which could be due to differences in the assigned speed limits. Also, Google Maps and Here 360 road networks have the latest updates regarding construction zones and other obstacles slowing down traffic. The network used for the development of the model in ArcGIS is presently used by the Fresno County Metropolitan Planning Organization but does not include real time data.

a. Descriptive statistical analysis for the free flow period for mode choice walking.

b. Descriptive statistical analysis for the free flow period for mode choice bicycle.

c. Descriptive statistical analysis for the free flow period for mode choice drive-alone.

Figure 10. Descriptive statistical analysis for free flow for three types of modes and three models.

Better visualization of the travel time averages for all three modes can be seen in Figure 11. (The average trip travel distances can be seen in Figure 17 in the Appendix.)

4.1.1.1 Drive-alone. This section includes the results of the free flow drive-alone analysis. The following figures show a 45-degree comparison of drive-alone commute travel times with Google Maps, Here 360, and ArcGIS (Figure 12 parts a through c). The black lines represent the 45-degree line and the blue line is the

Figure 11. Average travel time for modes drive-alone, walking, and bicycle using ArcGIS, Google Maps, and Here 360.

trendline of the data. The figures indicate that Here 360 estimates slightly longer travel times than Google Maps and ArcGIS. If the ratio between the y-axis and x-axis values is greater than 1, the points fall above the 45-degree lines, and below the line if the opposite. If the independent variable is larger than 1, then the values on the y-axis are bigger, whereas if the independent variable is smaller than 1, then the values on the x-axis are bigger. It can also be observed that there is only a small number of outliers in the results. Since CO₂, NO_x or VOCS emissions are all constant rate functions in travel time or distance, no additional figures were created – i.e., the same results would be produced.

a. 45 Degree comparison of travel times for Google Maps and Here 360 for drive-alone.

b. 45 Degree comparison of travel times for Google Maps and ArcGIS for drive-alone.

c. 45 Degree comparison of travel times for ArcGIS and Here 360 for drive-alone.

Figure 12. 45-degree comparison of travel times for drive-alone using three models.

Figure 13 is another analysis of drive-alone. Linear trend lines and their equations were used to evaluate the relationship between the percent difference of distance to traveled time using Here 360 compared to ArcGIS and Google Maps compared to ArcGIS. The percent difference of distance in Google Maps and Here 360 compared to the model in ArcGIS slightly decreased over time. For the percent difference of time over travel distance, it was observed that Here 360 has a more constant but high (average around 30%) percent difference of time over distance, whereas Google Maps decreases rapidly with increased travel distance; with short travel distances it is around 32% but decreases to less than 1% at around 100 km travel distance.

Figure 13. Percent difference of travel distance and travel time of Google Maps and Here 360 to ArcGIS as a function in travel time and travel distance, respectively.

Table 9 shows a summary of results for drive-alone. CO₂ emissions for drive-alone were calculated as a function in travel distance. On average, the longest distance was traveled using the Here 360 model, which results in the highest average CO₂ emission with 6388.23 g per trip compared to 6276.97 g and 6309.45 g for ArcGIS and Google Maps, respectively. Since NO_x, VOCs and cost are all functions in trip distance, similar results were found for those attributes.

4.1.1.2 Walking and bicycle. Walking and bicycling do not have any immediate emission; for these modes the number of calories needed to complete the trip was used to calculate the CO₂ food print. This reflects the CO₂ needed to produce the burned food calories. In this research, the used calories depended on the time of activity. Here 360 calculated on average the longest trip time, which resulted in the highest number of calories burned and CO₂ produced. Tables 14 and 15 in the Appendix show results for walking and bicycle.

Table 9

Summary of Results for Drive-Alone Models

Model	Avg. Trip Time (min)	Avg. Trip Distance (km)	Avg. CO ₂ (g/trip)	Avg. NO _x (g/trip)	Avg. VOCs (g/trip)	Avg. Cost (\$/trip)
ArcGIS	21.38	27.26	6276.97	11.81	17.62	10.09
Google Maps	24.51	27.41	6309.45	11.87	17.71	10.14
Here 360	26.21	27.74	6388.23	12.02	17.93	10.23

4.1.2 Walking-bus/Bicycle-bus

For the comparison of walking-bus or bicycle-bus modes, the static ArcGIS model and free-flow (Sunday 4 a.m.) Google Maps and Here 360 models were used. Although this is considered free-flow, it might influence the bus routes significantly. Here 360 uses real-time schedules for the route calculations. Since the routes were calculated for a Sunday morning, not all bus lines were in operation. One of the main differences between the ArcGIS model on one hand, and Here 360 and Google Maps on the other hand, was that in the latter models not all routes were calculated. Routes with a walking distance to the bus station longer than 3000m were not included in the output. Therefore, ArcGIS routes had to be sorted for the outputs of Here 360 and Google Maps in order to be able to compare the results correctly. Only 127 out of 218 routes were calculated by Here 360 and Google Maps when using the default walking to station radius of 3000m.

Figure 14 shows the average travel time and average travel distance for walking-bus for all three different models. It can be seen that Here 360 calculated

on average almost 800% longer bus travel times than Google Maps or ArcGIS. But when looking at the average bus distance, Here 360 calculated on average 63% shorter bus distances than Google Maps and 4% shorter than ArcGIS. The reason behind this is that Here 360 included wait times at bus stations in the calculations. The free flow analysis was modeled for Sunday at 4 a.m. Since Here 360 uses online time schedules for the route estimation, the bus travel time had such a significant difference to both other models because many of the bus lines service doesn't begin before 6 a.m. It is unclear which schedule Google Maps uses, but no schedules were implemented into the ArcGIS model.

In Here 360 it is possible to change the walking to station radius from 0 to 6000 m. When running the model with the maximum walking radius a total of 158 routes were calculated. It was observed that the average bus time increase by 58%.

4.2 Peak Analysis

This section details the peak period analysis for several different modes. The peak analysis was performed for Google Maps and Here 360 only, since ArcGIS is a static model and does not include traffic information. The goal was to find out if there are differences within the peak period. First the peak analysis for drive-alone, walking, and bicycle is presented followed by the peak analysis for walking-bus and bicycle-bus.

Figure 14. Average bus travel times and bus travel distance for free flow condition for the walking-bus mode for all three different models.

4.2.1 Peak Period Analysis for Drive-alone, Walking and Bicycle

This section includes the details for drive alone, walking, and bicycle analysis.

4.2.1.1 Drive-alone. For the drive-alone analysis the model was done for the morning peak of a Thursday starting at 7:00 a.m. and at 30 min intervals till 9:00 a.m. (i.e. at 7:00 a.m., 7:30 a.m., 8:00 a.m., 8:30 a.m., and 9:00 a.m.). Table 10 shows the average travel distance and average travel time of both models for the entire peak period. A slight difference in travel distance was seen for almost every 30 min. This is due to changes in travel routes. Here 360 and Google Maps have almost the same average travel distance but Here 360 estimated on average longer travel times.

Table 10

Average Travel Times and Travel Distances during the Peak Period for Drive-alone with Google Maps and Here 360

Model	Attribute	7:00	7:30	8:00	8:30	9:00
		a.m.	a.m.	a.m.	a.m.	a.m.
Google	Distance (km)	27.80	27.74	27.80	27.82	27.82
Maps	Time (min)	24.44	24.45	24.43	24.43	24.43
Here 360	Distance (km)	27.80	27.79	27.79	27.84	27.82
	Time (min)	26.88	27.10	27.21	27.21	27.21

4.2.1.2 Walking and bicycle. For the modes walking and bicycling no differences within the peak period were found. When comparing peak to off-peak traffic it was evaluated that Here 360 estimated a significant longer travel time for peak/off-peak for both bicycle and walking (up to 20% longer travel time peak period for bicycle) which also results in a 20% higher CO₂ footprint. During the analysis of walking with the Here 360 model, it was observed that the default walking speed was not 1.25 m/s, as indicated. The evaluation concluded that the default walking speed was around 1 m/s, instead. Fortunately, the walking speed could be changed manually from 0.5 to 2.0 m/s using the attribute “WalkingSpeed.” For proper comparison, the walking speed was adjusted to 1.25 m/s. Table 11 shows average travel times and travel distances during peak/off-peak periods.

4.2.2 Peak Period Analysis for Walking-bus/Bicycle-bus

The next comparison was made for the peak period of walking-bus and bicycle-Bus. The analysis was done for a Thursday 7:30 a.m. and 9:00 am. Figure

Table 11

Average Travel Times and Travel Distances during Peak /Off-Peak Periods for Bicycle and Walking with Google Maps and Here 360

Model	Attribute	Bicycle		Walking	
		Peak	Off-Peak	Peak	Off-Peak
Google Maps	Distance (km)	26.90	25.86	25.68	25.50
	Time (min)	88.60	88.17	314.77	312.61
Here 360	Distance (km)	26.05	25.86	25.81	25.62
	Time (min)	107.12	106.26	344.03	341.40

15 represents the average bus travel times and bus travel distances during the peak period for walking-bus mode for all ArcGIS, Google Maps, and Here 360. It can be seen that Here 360 has a 77% longer average bus trip time than Google Maps. The walking-bus peak analysis was done for Thursday 7:30 a.m., when most of the bus lines started with the transit service already. With comparison to the free flow analysis, the difference of Here 360 to Google Maps is much smaller during the peak analysis but Here 360 is still significantly higher than Google Maps. This supports the previously made statement that Here 360 includes wait times at bus stations in the estimation.

Table 12 shows the average number of transfers made for each trip during different peak/off-peak periods. It is observed that Here 360 has a lower average number of transfers for during off-peak and peak 9:00 a.m. period. All numbers range between 0 and 1, which indicates that on average a maximum of one bus transfer is necessary to complete the trip. The maximum number of transfers was five using the Google Maps model for the peak period at 9:00 a.m. It was also seen that with an increased total trip distance and trip time, a higher number of transfers for both Google Maps and Here 360 was estimated.

Figure 15. Average bus travel times and bus travel distance for peak condition for the Walking-bus mode for all three different models.

Table 12

Average Number of Transfer for Walking-bus During Off-Peak and Peak Period Using Google Maps and Here 360

Condition	Number of Transfers in Google Maps	Number of Transfers in Here 360
Free-flow	0.49	0.38
Peak 7:30 am	0.47	0.54
Peak 9:00 am	0.41	0.37

4.3 Carpool Analysis

The carpool Model Builder was developed in a similar manner to drive-alone: results of the static ArcGIS model were compared to the off-peak results of Google Maps and Here 360. Since there was a total of 218 commuters, the model would have been very extensive and time consuming to build in ArcGIS.

However, an example of five origins with a two-person carpool was run and evaluated in all three models. Although it is much easier to build a carpool model in Google Maps and Here 360, the same number of examples were run in those platforms to have a reliable comparison. A total of 1,085 trips was estimated and used for further analysis. Figure 16 shows the average first and second leg travel distances and travel times. As seen in the figure, the biggest difference is during the second leg distance with ArcGIS being 19% longer than Google Maps. Since the same road network and time to drive-alone was used a similar outcome is assumed, with ArcGIS having the shortest average travel time and a very similar travel distance for each model.

Figure 16. Example of average travel times and distances for Carpool using a selection of origins and passengers modeled with ArcGIS, Here 360 and Google Maps.

4.4 Advantages and Limitations of All Models

The previous sections describe most of the results in detail. Table 13 is a listing of all limitations and advantages of each model.

Table 13

Limitations and Advantages of Each Model

Model	Limitations	Advantages
ArcGIS	<ul style="list-style-type: none"> • Real time data requires significant additional information and effort • Requires acquiring shapefiles of desired transportation modes • Requires the creation of a Network Dataset. • Modeling of multimodal transportation systems requires additional steps for ensuring connectivity across the networks • Models take a significantly longer time to run 	<ul style="list-style-type: none"> • Is not limited by a maximum Walking distance to a bus stop • Transit model can be run for each transit option separately (i.e. bus, tram, light rail) • Modeler has full control on the transportation network, e.g. can add or remove transportation infrastructure and/or connections
Google Maps	<ul style="list-style-type: none"> • Transit routes with walk to station radius greater than 3000m cannot be calculated • Walk to station radius cannot be changed • Modeler uses Google Maps network, and does not have control over the transportation network. • Walking Speed cannot be adjusted • Unclear which transit time tables are used for estimation of trips • No Bicycle-Bus mode 	<ul style="list-style-type: none"> • Different transit modes available and can all be run separately: Bus, Subway, Train, Tram, Rail • Models requires less effort • Models run significantly faster than ArcGIS
Here 360	<ul style="list-style-type: none"> • Default Walking radius 3000m • Default Walking speed is 1.0 m/s which is different from what is listed on website (1.25m/s) • Can only have all public transportation together, not each transit option by itself • No Bicycle-Bus mode 	<ul style="list-style-type: none"> • Walk radius to transit station can be adjusted from 0 to 6000m • Walking speed can be adjusted from 0.5 to 2 m/s • Model requires less effort • Models run significantly faster than ArcGIS • Ped. Routing can be optimized for example routes going through specific areas such as parks) • Transit routing: calculates transit by using known online timetables information

CHAPTER 5: CONCLUSION AND FURTHER RESEARCH

This chapter presents the conclusions of this research. Transportation plays an important role in everyone's daily life. Almost 30% of greenhouse gas emissions are produced by the transportation sector. Emissions are just one major challenge transportation engineers have to overcome in the 21st century. Most of the challenges are prevalent during the peak traffic hours, in which commuter, mostly drive-alone, are the majority of trips. In the past decades, the modal share of drive-alone trips has increased to over 75%. Efforts to decrease and minimize drive-alone commuters for businesses have been primarily focusing on average aggregate commute measures instead of modeling footprints of individual commuters.

The objective of this research was to develop a new tool to quantify footprints of individual commuters using real-world multimodal transportation systems. This was done by first developing a model and implementing it in three different platforms; a multimodal transportation model was developed and implemented in ArcGIS 10.5, Here 360, and Google Maps. The next step was to compare each model's limitations and capabilities and examine their functionality. This step was completed using a case study with 218 commuters in Fresno County. The following paragraphs provide a summary of the modeling approach, results of the case study, and capabilities and limitations of the models.

Two different modeling approaches were developed and compared: 1. static models were developed using Esri's ArcGIS 10.5 and its Network Analyst extension and Model Builder programming language and 2. dynamic models were developed by the implementation of Google Maps and Here 360 APIs in R Studio. The results were analyzed under two conditions: free flow and congested traffic.

The analysis was completed for six different commute modes: drive-alone, bicycle, walking, walking-bus, bicycle-bus, and carpool. A combination of real and random data points (total of 218) was used for the analysis.

The evaluation showed that all three models are suitable for modeling footprints of individual commuters in multimodal transportation systems. Attributes such as CO₂, VOCs, and NO_x emissions were calculated for all individual commuters using different types of modes. It is possible to manually apply emission factors and change these accordingly. All three models have the potential to estimate individual emissions based not only on travel time and travel distance but could also be expanded to reflect the make and model of the car and different engine types.

Although all three models can be used for the analysis, there are differences in the results. ArcGIS was used for static analysis only, since it would be very time-consuming to build many different models. Google Maps and Here 360 are dynamic models and are suitable for every time of the day. Only a few small changes have to be made to calculate routes and corresponding attributes for different time periods. While Google Maps is more famous and popular around the world, learning and utilizing the API requires additional effort. However, Google Maps does not offer the range of API parameters as Here 360. Many more individual based changes and adjustments, such as walking speed and walking to station radius can be made using the Here 360 APIs.

One of the biggest limitations for Here 360 and Google Maps is that no bicycle-bus or even car-bus mode exists. It is assumed that transit routes are only connected to walking routes; however, for longer distances to stations, bicycles and cars are common transit access modes. In addition, Google Maps only calculates transit routes with a maximum walking to station radius of 3000 m.

Fortunately, that radius can be adjusted to a maximum of 6000 m in Here 360. The advantage of ArcGIS is that any route can be forced, disregarding its walking distance. As mentioned earlier, one of the biggest advantage of Google Maps and Here 360 to ArcGIS is the dynamic modeling. Real-time traffic conditions are included into route calculations. Also, Here 360 and Google Maps run significantly faster and require much less effort to build than ArcGIS.

To improve the results of the models and expand their capabilities, several research improvements and further analyses can be done. Examples of possible research extensions include: 1. using vehicle specific factors (for each make or model of car), instead of averages; 2. adding different types of car types such as hybrid and electric vehicles; 3. adding other modes of travel (e.g., light rail and metro); 4. analyzing differences between the models in other cities with higher levels of congestions; and 5. modeling and examining additional travel measures (e.g., PM2.5 and PM10).

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APPENDIX: SUMMARY TABLES OF MODEL OUTPUTS

Table 14

Summary of Results for Walking Models

Model	Avg. Trip Time (min)	Avg. Trip Distance (km)	Avg. Calories (kcal/trip)	Avg. CO ₂ FoodPrint (g/trip)
ArcGIS	339.16	25.47	1390.56	2209.59
Google Maps	312.61	25.49	1281.70	2036.62
Here 360	341.4	25.62	1399.74	2224.19

Table 15

Summary of Results for Bicycle Models

Model	Avg. Trip Time (min)	Avg. Trip Distance (km)	Avg. Calories (kcal/trip)	Avg. CO ₂ Food Print (g/trip)
ArcGIS	95.00	25.47	444.89	706.92
Google Maps	88.17	26.73	412.90	656.10
Here 360	106.28	25.86	497.71	790.86

Figure 17. Average travel distance for drive-alone, bicycle, and walking using ArcGIS, Google Maps, and Here 360.