ABSTRACT

Title of Thesis: REDUCING CONGESTION POST-COVID-19 THROUGH TELECOMMUTING AND HOV LANES

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The historic low traffic during the COVID-19 pandemic reignited interest in telecommuting as a low-cost effective Travel Demand Management (TDM) strategy. Telecommuting, introduced as a TDM in 1970, has been studied extensively but there has never been an opportunity of this magnitude to investigate its potential. As the percentage of teleworkers increased from five percent to over 50 percent in 2020, commuter traffic in the D.C.-Maryland-Virginia region was almost non-existent. We argue that increased telecommuting played a significant role in the traffic reduction during the pandemic, and that continued sustainable and equitable telecommuting coupled with implementing more High Occupancy Vehicle (HOV) lanes could significantly remove traffic bottlenecks. This study uses mobility data from the University of Maryland COVID-19 platform and traffic data from Maryland Department of Transportation to specify a regression model that estimates roadway performance in hypothetical telecommuting and HOV scenarios. The investigation showed that the reduced work-related trips were a major cause of the congestion reduction in 2020. With only 20 percent more of the population telecommuting than in 2019, there was a significant improvement in roadway congestion on almost all major roadways. We propose two low-cost sustainable transportation

strategies to maintain the reduced congestion post-COVID-19: promoting telecommuting and implementing HOV lanes. Policies through which the government and employers can support telecommuting are also recommended.

REDUCING CONGESTION POST-COVID-19 THROUGH TELECOMMUTING AND HOV LANES

by

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The COVID-19 pandemic reshaped the way we travel and has challenged planners and researchers to re-imagine transportation. I am proud to have addressed this timely issue in support of an environmentally and economically friendly future for transportation. I am grateful for all the encouragement and support I received during my Master's program.

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List of Abbreviations

ADT	Average Daily Trips
ATR	Automatic Traffic Recorders
CATTLab	Center for Advanced Transportation Technology Laboratory
CDC	Center for Disease Control
DMV	D.C., Maryland, and Virginia
DOE	Department of Energy
DOL	Department of Labour
DOT	Department of Transportation
EPA	Environmental Protection Agency
HCM	Highway Capacity Manual
HCS	Highway Capacity Software
HOV	High Occupancy Vehicle
LOS	Level of Service
MTI	Maryland Transportation Institute
NCS	National Compensation Survey
RITIS	Regional Integrated Transportation Information System
SAH	Staying at Home
TDM	Travel Demand Management
TRB	Transportation Research Board
UDC	User Delay Cost
VMT	Vehicle Miles Traveled
WFH	Working from Home

Chapter 1: Introduction

1.1 Background

The COVID-19 virus caused a world-wide pandemic in the year 2020, killing over 1.8 million people (Sanchez Rosa et al., 2021). With vaccines not yet available, the United States Centers for Disease Control and Prevention (CDC) recommended social distancing, self-quarantine, and working from home (WFH) from early February 2020 to prevent the spread of the virus (Liu et al., 2020). Mandates and CDC guidance caused most non-essential workers to shift to telecommuting, schools to switch to online learning model, and all non-essential businesses to either close temporarily or provide services virtually. This shift from in-person to virtual activities drastically affected the transportation industry as travel behaviors changed considerably. In absence of the peak-hour commute between home and office and vice versa, regular commuting jams almost completely disappeared (Hendrickson & Rilett, 2020), leading to declines in delay, fuel consumption and emissions (Du et al., 2020). The widespread adoption of telecommuting by most organizations was responsible for reducing traffic and congestion on the roads and may never have occurred had it not been for the pandemic.

Due to the mandatory stay-at-home orders issued in the states, counties and cities in the United States, the traffic volume was observed to reduce by 45-55 percent, with mobility reducing up to 90 percent in severely affected areas (Moreland et al., 2020). Recent studies found that a 15 percent reduction in traffic volume, comparing July 2019 to July 2020, eliminated almost all the recurrent traffic bottlenecks in the region (Lee et al., 2020). Prior to the pandemic, Maryland had the second worst one-way commute time in the USA with an average one-way trip to work of 32.9 minutes (Caldwel, 2020; Murillo, 2020; U.S. Census Bureau, 2018). In the state of Maryland, nitrogen oxide decreased by 15 percent, while carbon dioxide and carbon monoxide each decreased by 30 percent from the pre-pandemic levels (MDE, 2020).

In many ways, COVID-19 provided an unfortunate but imperative juncture to understand the impacts of telecommuting or WFH on transportation systems. In addition, it served as a real-world experiment for transportation researchers and policy makers to take note and investigate implementation of policies to reduce the travel demand and the number of vehicles on the roadways. Transportation Research Board (TRB) Executive Director Neil Pedersen has encouraged civil engineers and researchers to not only figure out ways to deal with the new sense of normal but to use this opportunity to re-imagine transportation (Jankauski, 2020). This thesis aims to re-imagine ways to reduce traffic congestion, improve safety and reduce emissions on roadways in the DMV through maintaining some travel behavior changes experienced during the COVID-19 pandemic. We investigate the effect of two such transportation policy measures post-pandemic: telecommuting and High Occupancy Vehicles (HOV) lanes for significantly reducing the post-pandemic traffic and alleviating congestion on selected roadways in Maryland. We argue that increased telecommuting played a significant role in the traffic reduction during the pandemic and that continued sustainable and equitable telecommuting coupled with implementing more HOV lanes could significantly remove bottlenecks in Maryland.

1.2 Problem Statement

For the past 20 years, transportation researchers and planners have been working on improving traffic conditions (Hendrickson & Rilett, 2020). Their efforts include increasing the capacity of roads (adding lanes, widening roads, or building interchanges), implementing road pricing, eco-routing, and optimizing traffic control devices (Du et al., 2020; TRB et al., 2016). The United States spends hundreds of billions of dollars on transportation infrastructure yearly, yet delays caused by traffic congestion alone cost over $160 billion per year, and motorists are forced to pay over $1,000 every year in wasted time and fuel (The White House, 2021). The effects of infrastructure improvements have not significantly reduced congestion (Du et al., 2020). We cannot build out of the infrastructure crisis; increasing capacity only induces demand (Schaefer, 2015). Interestingly, the most effective possible solution to this problem: decreasing the demand and the number of vehicles in the network has been the least investigated (Du et al., 2020).

This study explores two transportation strategies: telecommuting and HOV lanes to reduce demand and the number of vehicles on the road network, respectively. Rather than continuously expanding capacity, sinking resources into hard infrastructure that limits future opportunities, we argue that investing in low-cost strategies to reduce demand and improve the quality of life is a better strategy. Even though the scale of telecommuting during the COVID-19 pandemic is unprecedented, this presents an opportunity for transportation policymakers to learn from the change in transportation behaviors and propose policies in favor of resilient, sustainable, and socially equitable transportation.

1.3 Research Objectives

The objective of this study is to analyze two low-cost strategies to reduce travel and vehicle demand: telecommuting and HOV lanes respectively using the pandemic as a natural experiment. This paper also details policies to support equitable telecommuting. Specifically, this paper:

a) Demonstrates the nexus between telecommuting and reduction in congestion on roadways. To achieve this, traffic trends from previous years were compared to 2020 trends. The busiest highways in Maryland, particularly those connecting Maryland to DC and Virginia, were used as the study area. A regression model which had "working from home" as a variable was then used to determine the effect of telecommuting on the volume of traffic.

b) Investigates the effect of promoting telecommuting in reducing the traffic congestion on Maryland roadways. A Level of Service (LOS) analysis on the ten busiest highways at various telecommuting percentages was conducted to see how the changes in the percentage of people telecommuting would change roadway performance.

c) Investigates the effectiveness of the existing HOV lanes in the state of Maryland in reducing the peak hour traffic.

d) Evaluates the reduction in traffic congestion on the ten busiest highways in the study area due to the conversion of the left-most lane of the highways to an HOV-only lane.

e) Recommends policies to promote equitable telecommuting beyond COVID-19. The findings of this study add to the literature promoting telecommuting.

1.4 Research significance

The results from this study will be useful for transportation researchers and planners to identify significant factors leading to the reduction in traffic volumes in 2020, and the relative contribution of work and non-work-related trips for the same. This study will also investigate the relationship between telecommuting and reduction in traffic volumes and will present a model to evaluate the impact of telecommuting on traffic volumes based on real-world data. Due to the use of real-world traffic and mobility data during the pandemic, this evaluation should be as close to a real-world simulation as possible. Having a good understanding of accurate travel behavior such as during a pandemic can greatly assist the transportation policymakers in proposing new policies and allocating resources. The results of this study will also help the transportation planners address the rebound effect of telecommuting.

This research also evaluates the implementation of HOV lanes to alleviate congestion in Maryland during peak hours. We evaluate the feasibility of converting an existing freeway lane to an HOV-only lane during peak hours to improve the LOS. Even though the analysis in this thesis is restricted to the DMV region, transportation planners and researchers can apply the methodology and findings of this research to evaluate transportation policies in their regions, and to better allocate resources in support of different transportation planning applications. While more extensive research is needed on the costs and barriers of telecommuting and HOV lanes, this thesis provides a good working framework to reduce congestion particularly in the DMV region now and post-COVID-19.

1.5 Thesis Overview

This thesis report contains eight chapters. Chapter one provides an introduction to the impact of COVID-19 on the transportation sector due to telecommuting and outlines the research objectives, significance, and limitations. Chapter two introduces the literature review for the various travel demand policies being implemented and evaluated to address the problem of traffic congestion in the United States. Chapter three details the three main data sets used in this research, explaining the sources of the data and the definition of relevant variables. Chapter four describes the methodology used to analyze the various data sets, including the data visualization, the regression modeling, and the LOS analysis. Chapter five explores the COVID-19 platform and the traffic volume data. The results of the telecommuting and HOV analysis are described in chapter six. Chapter seven describes the recommended policies and strategies to support the practice of telecommuting beyond the pandemic. Lastly, chapter eight provides a summary of the paper and a commentary on the proposed direction of future research work.

Chapter 2: Literature Review

2.1 Impact of COVID-19 on traffic

It is crucial to begin this chapter by recounting what life was like before COVID-19. American workers spent an average of 54 minutes each day commuting to and from work (Mullen, 2020). The DMV region was particularly notorious for its levels of commuter congestion. Having the third-highest traffic delay and the fifth-longest queuing time in the nation, DMV drivers spent on average 102 hours each year in traffic delays, costing commuters about $2,015 and the region $4.6 billion in lost time and fuel (Kim, 2019; Schrank et al., 2019). The average commute time in DC is about 50 percent longer than the national average. Reducing commute hours saves money, time, and energy that could be better utilized. A study found that workers invest about 60 percent of the time saved from commuting on non-leisure activities, like paid work, chores, childcare, and home improvement and 35 percent of it on their primary jobs (Mullen, 2020).

COVID-19 led to a dramatic reduction in traffic demand producing noticeable declines in traffic delays, energy consumption, and emissions due to the government-issued SAH order and teleworking (Du et al., 2020; Lou et al., 2020). Figure 2-1 shows the changes in User Delay Costs (UDC) in million dollars for the state of Maryland from 2019 to 2021. Since the SAH order, the UDC dropped between 31 percent and 82 percent with an overall decrease in delay cost of $202M for the six-month period (TRB, 2021). The reduction in UDC continued through 2021 several months after the SAH order had been lifted.

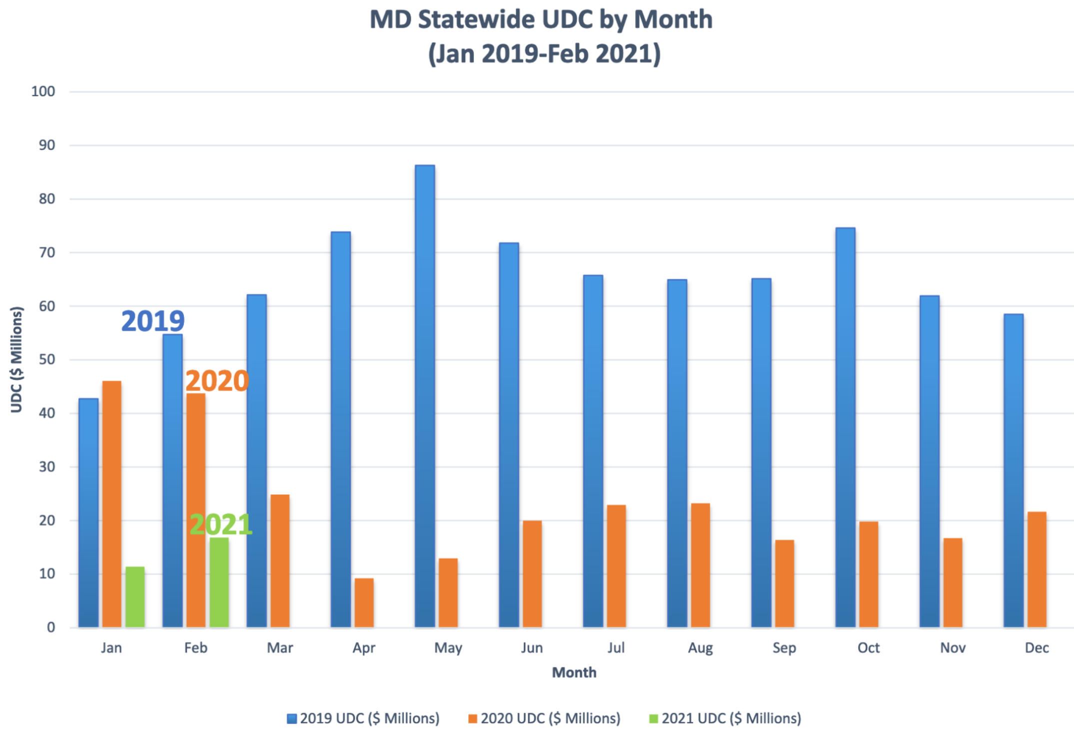

Figure 2-1: Maryland User Delay Costs (UDC) by Month. Source (TRB, 2021)

In an analysis to predict the reduction in traffic volume based on demand reduction in Los Angeles, their research model found that decreasing demand by approximately 15 percent to 20 percent resulted in a 50 percent reduction in delay (Du et al., 2020). A study by MTI also found that reducing travel demand by 15 percent in the morning peak period resulted in annual time savings from reduced congestion worth $918 million. Even after the reopening, there was still a 15 percent reduction in traffic volume observed in July 2020 compared to July 2019. This reduction was enough to eliminate almost all traffic bottlenecks in the region (Lee et al., 2020). Adopting learnings from the COVID-19 pandemic could potentially reduce congestion, improve safety, and reduce total energy consumption by 20 percent, or by 60 million gallons of fuel and 650,000 tons of Greenhouse Gas (GHG) annually (MTI, 2020).

2.2 Benefits of Telecommuting

Telecommuting dates as far back as the 1970s, when it was envisioned as a policy tool in a Travel Demand Management (TDM) toolkit to help decrease congestion, air pollution, and waste of resources(Oakman et al., 2020). Legislation and planning at many levels of government support telecommuting as a measure to benefit the public, employers, and employees and it is widely considered to be a way of solving mobility issues (Ravalet & Rérat, 2019; Su et al., 2021).

The 2010 Telecommuting Enhancement Act was aimed at helping employees enhance work-life effectiveness. It defined telecommuting as "a work flexibility arrangement under which an employee performs the duties and responsibilities of such employee's position, and other authorized activities, from an approved work site other than the location from which the employee would otherwise work" (US Congress, 2010). Telecommuting uses Information and Communication Technology (ICT) to replace the more traditional working at workplaces and traveling to work (Su et al., 2021). In other literature, telecommuting is popularly referred to as teleworking, remote work, and Working from Home (WFH). Telecommuting promises several benefits, such as:

a) Improved roadway and traffic performance

Choo and Mokhtarian's study suggests that telecommuting reduces VMT by less than one percent, with 94 percent confidence (Choo et al., 2005) and a supporting study found that neighborhood telecommuting centers reduce commute VMT by about 50 percent (Lin et al., 2006). A 2017 California-NHTS case study agrees that telecommuting has already had a positive impact on transportation with a lower number of trips and number of miles driving alone and less travel during peak hours (Su et al., 2021).

b) Better use of public transportation

The demand for public transportation significantly declined during the pandemic, but it was still needed for essential workers, and transit agencies must be prepared to continue such services even if telecommuting becomes a norm (Hendrickson & Rilett, 2020). Public transportation was still very relevant as during the pandemic. Those traveling longer distances were less likely to choose private transport relative to public/paratransit when compared to those traveling for shorter distances (Abdullah et al., 2020).

c) Improvements in freight movement

Interestingly, albeit the demand for transportation and logistics in certain sectors (e.g., e-commerce) surged during the pandemic, it barely offset the reduced transportation demand (Hendrickson & Rilett, 2020). Rather, movement of freight trucks was aided by reductions in traffic congestion on major roadways (Hendrickson & Rilett, 2020).

d) Environmental benefits

By leveraging Google and Apple mobility data, researchers found empirical evidence for a link between global vehicle transportation declines and the reduction of ambient NO_2 exposure during the pandemic (Venter et al., 2020). In Maryland, nitrogen oxides decreased around 15 percent, and carbon dioxide and carbon monoxide by 30 percent each from roughly mid-February to late May following the plummets in traffic (MDE, 2020).

It is easy to hypothesize that reducing emissions, especially through telecommuting, will reduce global warming and lead to healthier populations that will be better able to withstand the next pandemic (Hendrickson & Rilett, 2020). In addition, telecommuting encourages economically and socially sustainable alternatives to fossil fuel use in industries, transportation, and power plants, and cleaner fuels for use in households to support the pollutant declines we have observed during the global response to COVID-19 (Friedman, 2020; Hendrickson & Rilett, 2020; Sutter, n.d.; Venter et al., 2020).

e) Workplace benefits

Telecommuting is an excellent way for companies to reduce their carbon footprint and improve employees' general well-being. A range of positive benefits are associated with teleworking, including improved family and work integration, reductions in fatigue and improved productivity (Gajendran & Harrison, 2007). Telework is also associated with flexible working practices and a way for employees to improve their work-life balance (Onyemaechi et al., 2018). Additionally, hiring remotely creates access to a wider pool of talent geographically, which promotes diversity in the workplace and provides more opportunities for handicapped people (Lin et al., 2006). In terms of urban planning, it helps to reduce spatial concentration in urban areas and the need for expanded transport infrastructure as telecommuters are flexible to choose a home that is remote or farther from the workplace or not to relocate (Ravalet & Rérat, 2019).

f) Economic benefits

The COVID-19 pandemic has been an enormous global disruption with immense economic, environmental, and social impacts throughout the world (Hendrickson &

Rilett, 2020). Studies show $700 billion a year national savings if eligible workers would work half the time from home (Su et al., 2021). Additionally, in 2015, data shows that U.S. employers saved up to $44 billion with the existing almost 4 million telecommuters working half time or more (Radu, 2018).

Overall, telecommuting represents a way of limiting the environmental impacts of mobility and reducing infrastructure congestion (Ravalet & Rérat, 2019).

2.3 Barriers of telecommuting

Below are a few barriers associated with telecommuting;

a) Equity and accessibility

One of the major barriers to teleworking today is equity. Stanford economist Nicholas Bloom called the WFH economy a "ticking time bomb for inequality" (Wong, 2020). In terms of socioeconomic status, it is consistently demonstrated that the people with the highest incomes and highest levels of education are the most likely to telework (Melo & João de Abreu e Silva, 2018; Ravalet & Rérat, 2019). Studies indicate that the pandemic stay-at-home orders did not significantly reduce work-related trips for the very low-income group (personal income per capita < $30,000USD) and that upper income groups had more flexibility to reduce their work trips under SAH order (Lou et al., 2020).

In terms of accessibility, teleworking is infeasible in sectors which require the co-presence of production factors or work with customers (for example mailmen, cashiers, barbers) and most of these are lower income jobs (Aguilera et al., 2016; Ravalet & Rérat, 2019). A large population of those who can telework do not have adequate technology to support it. A study showed 35 percent of respondents have such poor internet at home – or no internet – that it prevents effective telecommuting (Wong, 2020).

Figure 2-2 below shows the percentage of people teleworking in 2019 by occupation, industry, and size of employer. Before the pandemic, mainly "knowledge workers" and people who do most of their work on computers had access to teleworking. Around a quarter of workers in "management, business and financial" occupations could access telework and only one percent of private sector workers in the bottom quarter of occupations (those with average hourly wages of less than $13.25) had access to telework (DeSilver Drew, 2020). However, we find in this study that approximately 50 percent of workers were teleworking by July 2020, a significant increase from 2019 (Maryland Transportation Institute, 2020).

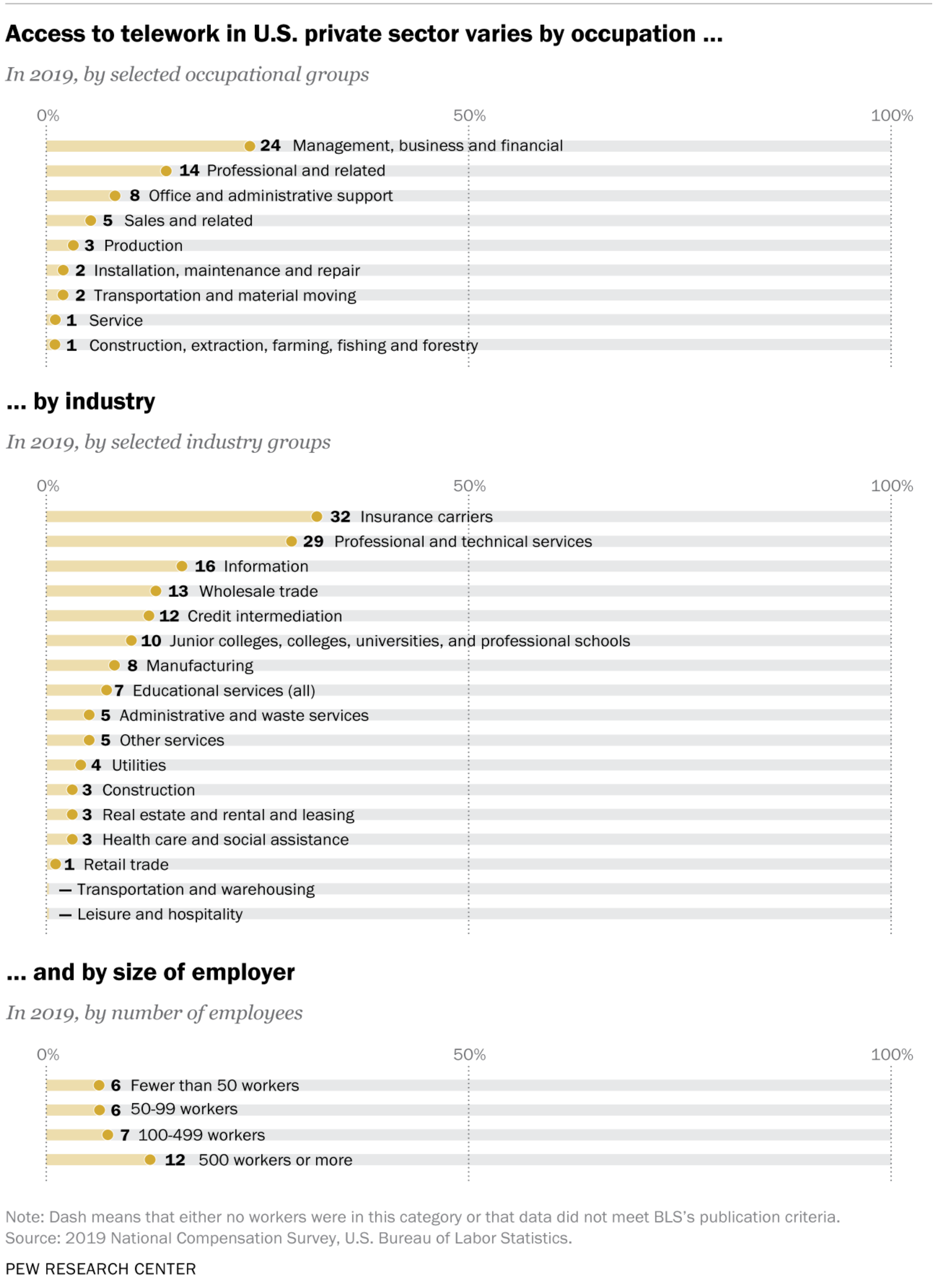

Figure 2-2: Access to telework in U.S. Private Sector (2019)

b) Workplace organization / work-life balance / mental health

The blurring of physical and organizational boundaries between work and home can also negatively affect mental and physical health due to extended hours, lack of or unclear delineation between work and home, and limited support from organizations (Allen et al., 2015; Oakman et al., 2020). Employees can feel isolated and disconnected from their managers and colleagues, and some feel as though they are 'on call 24/7'(Jaeseung Kim et al., 2020; Oakman et al., 2020). Systems that facilitate effective formal and informal coworker and manager support as well as clear expectations of working hours help teleworkers formally develop boundaries between work and family (Eddleston & Mulki, 2017). There are also concerns about labor laws and tax policies- legal and employment concerns around the balancing of worker privacy and safety rights with organizational data security.

c) Rebound effect

In economics, a rebound effect is an increase in consumption that partially or totally offsets the gains made by using a new technology (Ravalet & Rérat, 2019). There are concerns of the rebound effect of telework: telework could generate trips that would not take place if people spent a usual day in the workplace (Ravalet & Rérat, 2019). A study showed telecommuters that have at least one trip during their workday accrue more vehicle miles traveled and number of trips than their commuter counterparts. However, they travel less driving alone and tend to have more complex schedules visiting more locations and possibly utilizing the time saved by not travelling to work for other trips

(Ravalet & Rérat, 2019; Su et al., 2021). Some claim that households with telecommuters tend to have higher daily total VMT (Zhu & Mason, 2014).

Others argue that VMT are 53 percent to 77 percent lower on telecommuting days than on non-telecommuting days in the United States (Ravalet & Rérat, 2019; Walls & Safirova, 2005). And others say telecommuters do not obey uniform travel patterns, and substantial heterogeneity exists among individuals. But little is known about teleworking and, more specifically, its links with spatial mobilities and the potential rebound effects (Ravalet & Rérat, 2019; Su et al., 2021).

2.4 Benefits of High Occupancy Vehicle (HOV) lanes

Another approach adopted by the transportation policy makers to reduce the travel demand has been to encourage carpooling by implementing an exclusive High-occupancy Vehicle (HOV) lane on the highways. HOV, also known as carpool lanes, are restricted-use freeway lanes reserved for vehicles with more than a predetermined number of occupants (Kwon & Varaiya, 2008). HOV lanes typically do not get congested and are able to maintain the free-flow speed, even during peak hours (Boriboonsomsin & Barth, 2008). It is expected that due to the requirement of carpooling, it would result in the reduction of the number of vehicles using the HOV, making the commute faster than the non-HOV lanes (Kurzhanskiy & Varaiya, 2015). From a study conducted on the effectiveness of HOV lanes in Maryland, it is known that an HOV lane can carry 1.9 times more occupants than a non-HOV lane (Commuter Connections, 2017).

The advantages associated with HOVs include:

- Shared rides translate to lower traffic and commute times for everyone, safer driving conditions, reduced fuel consumption and tailpipe emissions, and reduced wear and tear of the freeways (Daganzo & Cassidy, 2008; Kurzhanskiy & Varaiya, 2015).
- HOV lanes can be converted to High Occupancy Toll (HOT) lanes which provide revenue for the transportation departments (Daganzo & Cassidy, 2008; Kurzhanskiy & Varaiya, 2015).
- Emergency vehicles are allowed to use the HOV lanes. Some states also permit free usage of the HOV lanes for electric vehicles and hybrid vehicles, and even motorcycles without meeting the requirement for the minimum number of occupants (Boriboonsomsin & Barth, 2008).
- The direction of the HOV lanes as well as the duration of operations can be fixed or variable (Kwon & Varaiya, 2008).

2.5 Barriers of HOV Lanes

There are several possible barriers to the successful implementation of HOV lanes in a region.

a) Implementation costs

The most important barrier to an HOV lane implementation is additional land requirements to create a new dedicated HOV lane (Kurzhanskiy & Varaiya, 2015). This barrier could be overcome partially by converting an existing general-purpose lane (usually the leftmost in the US) to an HOV-lane. If funding is available, the HOV lane could be either grade separated or barrier-separated from the general-purpose lanes. In addition, investment would be required to build infrastructure to provide direct access/egress for the HOV lanes. A part of the implementation costs can be recovered by converting the HOV lanes to High Occupancy Toll (HOT) lanes, but this may cause increased public opposition (Fuhs & Obenberger, 2002).

b) Reduced freeway capacity

Another possible barrier for the implementation of the HOV-lanes is reduced capacity of the freeway depending on the operational hours of the HOV lanes. Enforcing the operation of HOV-lanes beyond the peak hours may result in underutilization of these lanes with respect to general-purpose lanes, thus reducing the traffic flow on the freeway (Kurzhanskiy & Varaiya, 2015).

c) Other barriers

Other barriers include public perceptions, legality, and ensuring the safety of all motorists and emergency vehicles.

Chapter 3: Data Collection

We used three main datasets to evaluate the effectiveness of proposed policies on reducing traffic congestion in Maryland. These are (a) the COVID-19 mobility impact data, (b) the Automated Traffic Recorder (ATR) volume data, and (c) the lane-wise traffic and occupancy data from Regional Integrated Transportation Information System (RITIS). These data sets were used individually and in combination with each other to derive trends and to produce the final results. There were also limitations with the available data which are detailed later in the chapter.

3.1 COVID-19 Mobility Platform

The University of Maryland COVID-19 Impact Analysis platform used for this study provided data on mobility for all counties and states in the United States. The data were compiled by the MTI and CATT Lab using privacy-protected data from mobile devices, government agencies, healthcare systems, and other sources. Metrics used were validated using computational algorithms and have been peer-reviewed by an external expert panel funded by the U.S.DOT Federal Highway Administration (Maryland Transportation Institute, 2020).

January 1st, 2020, to December 31st, 2020, data from the platform gives an insight into the travel behavior of people during different significant policy changes and at the different re-opening stages. Data are available at the county, state, and national level in the United States. The entire dataset contains about 36 variables from three categories: “Mobility and Social Distancing”, “COVID and Health”, and “Economic Impact”. However, most health variables were not used in this study because our interest is not health related. Table 3-1 summarizes the selected variables used throughout this study. To view all available variables, visit data.covid.umd.edu.

Table 3-1: COVID-19 Impact Analysis Platform variables (Maryland Transportation Institute, 2020)

Variables	Description
Trips/person	Average number of all trips taken per person per day.
Work trips/person	Number of work trips per person per day (where a “work trip” is defined as going to or coming home from work location).
Non-work trips/person	Number of non-work trips per person per day. Additional information on trip purpose (grocery, park, restaurant, etc.) is available, but not currently shown on the platform.
Unemployment claims/1000	New weekly unemployment insurance claims/1000 workers. Source: Department of Labor.
% Working From Home(WFH)	Percentage of workforce working from home based on UMD models. Calculated by MTI based on changes in work trips and unemployment claims.
% Staying home	Percentage of residents staying at home (i.e., no trips with a non-home trip end more than one mile away from home).
% Out-of-county trips	Percentage of all trips that cross county borders.
% Hispanic Americans	Percentage of Hispanic Americans. Source: Census Bureau.
Population density	Population density. Source: Census Bureau.
Employment density	Employment density. Source: Smart Location Database.

3.2 Automated Traffic Recorder (ATR)

Volume data collected from ATRs were used to analyze the trends across the DMV region and specify the regression model that is discussed in future chapters. ATRs are automatic vehicle counters which contain sensors that are installed directly into each lane of pavement to take continuous counts of vehicles (FHWA, 2016). The Maryland DOT provided ATR counts for 19 locations for the years 2019 and 2020. These were the locations where ATRs had been previously placed and the complete data was already available. However, only sixteen detectors were studied as those did not have missing data. Nine of the detectors were on interstates, five were on Maryland owned freeways, and two were on US federal roads. The detectors captured traffic in both directions and some interstates such as IS-495, IS-95, and IS-270 had multiple detectors. Table 3-2 and Figure 3-1: Mapping of ATR Locations

provides information about where the ATRs are located.

Table 3-2: ATR Location Description

LOCATION_ID	ID_PREFIX	ID_RTE_NO	FUNC_CLASS	LOCATION_DESCRIPTION
P0066	IS	195	1-Interstate	IS 195 - .59 Mile North of MD 295 (ATR#66)
P0024	IS	595	1-Interstate	US 50/IS 595 - 1.34 Miles West of MD 424 (ATR#24)
P0038	MD	100	2-Freeways and Expressways	MD 100 - .45 Mile West of Oakwood Rd (ATR#38)
P0025	MD	295	2-Freeways and Expressways	MD 295(NB) - .81 South of MD 100 (ATR#25 Includes ATR#81)
P0003	MD	17	7-Local	MD 17 - 1.05 Miles North of US 40AL (ATR#03)
P0068	US	15	3-Principal Arterial	US 15 - 1.16 Miles North of Basford Rd (ATR#68)
P0039	IS	95	1-Interstate	IS 95 - .08 Mile South of MD 103 (ATR#39 Includes ATR#97SB)
P0069	MD	32	2-Freeways and Expressways	MD 32 - .78 Mile North of IS 95 (ATR#69)
P0060	IS	270	1-Interstate	IS 270 - .47 Mile South of Middlebrook Rd (ATR#60)
P0004	IS	270	1-Interstate	IS 270 - 2.0 Miles South of MD 121 (ATR#04)
P0040	IS	495	1-Interstate	IS 495 - 50ft East of Persimmon Tree Rd Overpass (ATR#40 includes ATR#102OL)
P0041	IS	495	1-Interstate	IS 495 - .82 Mile West of MD 650 (ATR#41 includes ATR#100OL)
P0043	IS	95	1-Interstate	IS 95 - 1.02 Miles South of MD 214 (ATR#43 Included with ATR#98SB)
P0055	IS	95	1-Interstate	IS 95 - .05 Mile North of Good Luck Rd (ATR#55)
P0006	MD	4	4-Minor Arterial	MD 4 - .54 Mile North of Patuxent River Bridge (ATR#06)
P0061	US	50	2-Freeways and Expressways	US 50 - .75 Mile West of MD 202 (ATR#61)

Figure 3-1: Mapping of ATR Locations

3.3 Regional Integrated Transportation Information System (RITIS)

RITIS is an automated data sharing repository created and maintained by the Center for Advanced Transportation Technology Laboratory (CATT lab) at the University of Maryland. RITIS collates and combines data from various regional transportation and emergency operations centers on a private, secure cloud and provides several performance measures, dashboard, and visual analytics tools to disseminate information among agencies and to the public for situational awareness, incident response and planning, and decision making (CATT Lab, 2020). RITIS helps transportation planners by reducing the cost of planning activities by information-sharing between various agencies. Figure 3-2 shows the RITIS data collation and dissemination process.

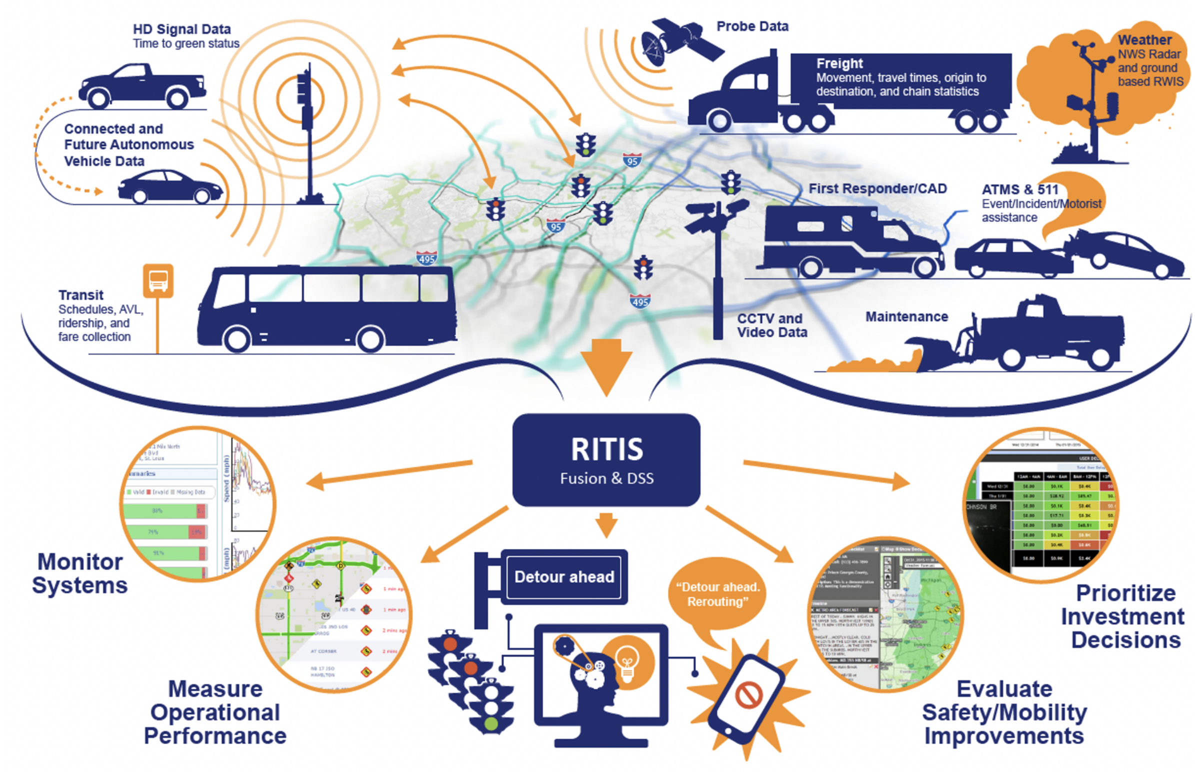

Figure 3-2: RITIS data collation and dissemination process (CATT Lab, 2020).

The traffic and occupancy data for the managed lanes (HOV's) in Maryland was obtained from RITIS to evaluate the effectiveness of the HOV's. The data were downloaded for the month of January 2016 as MDOT did not support their traffic detectors beyond 2016. There are two HOV facilities in the State of Maryland. The first one is along I-270 in Montgomery County and the second one is along US-50 in Prince George's County. The traffic count data and the total number of occupants for the HOV and the general-purpose lanes for I-270 in Maryland was available at every 5 minutes duration for the entire month of January 2016.

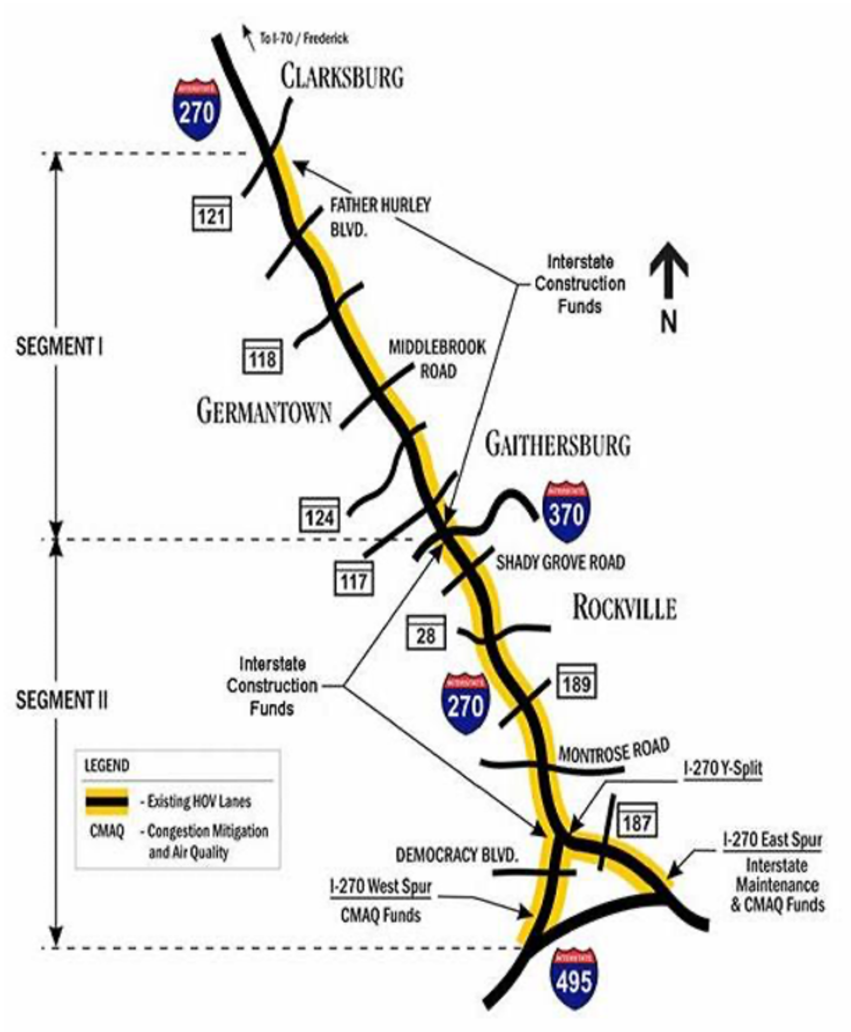

Figure 3-3: I-270 HOV lane (MDOT SHA, 2020)

Figure 3-3 shows the HOV lanes on I-270. For the US 50, one HOV lane is provided in each direction along with multiple general-purpose lanes from Route 301 to the Beltway (I-495). The HOV lanes on the US 50 require two or more occupants and are in operation at all times. No data was available for the HOV lane usage on US 50 from RITIS.

The HOV lane enforcement in Maryland is carried out by the Maryland State Police and the local law enforcement. The first HOV violation and any subsequent HOV violations carry a $90 fine and one point against the driver's license. For an HOV violation resulting in a crash, three points are subjected to the driver's license.

3.4 Data limitations

The challenges and limitations with the available data are detailed below:

- Limited collection period - The COVID-19 portal began collecting mobility data January 1, 2020. This makes it challenging to compare the 2020 mobility and travel trends with those of previous years. Additionally, at the time of the release of this paper, the pandemic is still ongoing and travel trends continue to change.
- No individual/personal mobility data - The data did not account for individual travel behavior. This made it difficult to study the travel patterns of those who did telework vs those who did not.
- No hourly mobility data - The mobility data provided was grouped by day for each county, state or nation level. No hourly mobility data were available. Nonetheless, the research was able to supplement this with hourly data from the volume data, but this is a general representation of the trends and cannot be directly compared to the mobility data.
- Limited locations - Due to the limited number of detectors already in place certain key areas could not be studied. For future work ATR data from another DOT such as VDOT and DDOT could also be utilized.

Chapter 4: Methodology

This chapter provides a brief overview of the methods used to address the research objectives of this study.

4.1 Data Visualization

Visuals were made using R programming language to understand the trends, outliers, and patterns of the data discussed in the previous chapter. For the Covid-19 mobility data, a package called lubridate was used to separate the dates into months, days, and weekdays for a better analysis. Tidyverse and dplyr packages were used in R to filter, sort, select and group the relevant data entries. Formattable and ggplot2 packages were then used to produce the relevant tables and graphs. Detectors "P0021", "P0089", and "P0067" were not used for the volume analysis as there were some missing values for those detectors in the data. The data visualizations presented in the results chapters provide information on the relationships between the variables and help to understand the trends during the pandemic and trends over time.

4.2 Regression Analysis

A regression model was specified to predict the hourly vehicle volume (dependent variable) by merging the ATR data for 2020 and the COVID-19 impact analysis platform data. In the regression equation below, **Y** is the prediction of the dependent variable, X are the selected independent variables, and *B* are the coefficients or slopes of the independent variables, describing the size of the effect the independent variables are having on your dependent variable. The intercept, B_0, is the value *Y* is predicted to have when all the independent variables are equal to zero.

$$\mathbf{Y} = \boldsymbol{B_0} + \boldsymbol{B_1 X_1} + \boldsymbol{B_2 X_2} + \boldsymbol{B_n X_n}$$

Seven independent variables: "% Staying home", "Employment density", "Out of county trips", "% Hispanic Americans", "Unemployment claims/1000", "Population density", and "%WFH" were represented in the final equation. The final model had the highest R-squared and all variables had significant p-value. Only data for the last 9 months of 2020 between 7am-7pm were used as the last 9 months was when the first spikes in WFH in 2020 began.

4.2.1 Heteroskedasticity test

First, we tested the variables for correlation and multicollinearity using the variance inflation factor (VIF) in the "car" package in R-software and found it not to be an issue. In order to satisfy the assumptions associated with regression and to be able to trust the results obtained from the regression model, the residuals should have a constant variance, else we encounter a condition called heteroskedasticity (Hayes, 2020). This violates a key ordinary least square assumption, $var(yi)=var(ei)=\sigma 2$, of constant variance. The Breusch-Pagan test was used in R-software to check for and correct the heteroskedasticity in the model. Breusch-Pagan test involves using a variance function and a $\chi 2$-test to test the null hypothesis that heteroskedasticity is not present (i.e. homoskedastic) against the alternative hypothesis that heteroskedasticity is present (Yobero, 2016). The test statistic for the Breusch-Pagan test can be obtained by multiplying the *R*-squared of the estimated variance function by the number of observations (*N*). If the null hypothesis is true, the sample size has a $\chi 2$ distribution (Yobero, 2016). This test was done in R using the lmtest package and calling the bptest function for the fitted model. If the p-value is less than the level of significance (in this case if the p-value is less than α=0.05), the null hypothesis can be rejected. Since p = 2.2e-16 < 0.05 in our analysis, we can reject the null hypothesis at a 95 percent confidence level.

The test results indicated that heteroskedasticity is present. We instead use the generalized least squares (gls) estimator, which is (the best linear unbiased estimator) depending on the unknown $\sigma 2i$. This improved the $R^2$to 0.73 (from 0.64) and reduced the errors making it homoscedastic. All p-values were less than 0.05, indicating that the coefficients are significant at the 95 percent confidence level. The standard error of 42 is a measure of the precision of the model. F-stat gives you the probability that the model explains the data better than the overall average (Rawlings et al., 1998).

Our final specification model is shown in

Table 4-1. The independent variables, "% out-of-county trips" and "employment density", had a direct relationship with the hourly vehicle volume traffic. There is an inverse relationship between independent variables: "% Staying home", "% Hispanic Americans", "Unemployment claims/1000", "Population density", and "%WFH" and the hourly vehicle volume. The "% Staying home" inversely affected the hourly vehicle volume as the people at home did not make trips. Regions with higher percentage of

Hispanic Americans could have had an inverse relationship with the dependent variable as African and Hispanic Americans are especially likely to use public transportation on a regular basis and are less likely to have access to an automobile (Anderson, 2016; FHWA, 2010). Population density also had an inverse relationship with the dependent variable possibly because dense populations have better access to public transportation reducing the need for vehicle trips (FHWA, 2010). The "Unemployment claims/1000" could have had an inverse relationship as those who were out of work may have also stayed at home receiving employment benefits or finding alternate work, and the "%WFH" could have had an inverse relationship with hourly vehicle traffic volume as those working from home made less work-related vehicle trips. Our final regression model in

Table 4-1was used to test the effect of WFH on traffic volumes for different scenarios.

Table 4-1: Final Regression Model

Volume Regression Model

Regression Statistics	
R Square	0.733
Adjusted R Square	0.733
Residual Standard Error	42.68
Observations	79730

ANOVA	*df*	*F-static*	*Signif. F*
Regression	7	3.13E+04	0

Independent Variables	*Coefficients*	*Std. Error*	*t Stat*	*P-value*
Intercept	8771.1177	290.3584	30.208	<2e-16
% Staying home	-54.3705	0.9656	-56.307	<2e-17
% Out-of-county trips	23.4946	1.7427	13.482	<2e-18
% Hispanic Americans	-175.4307	5.5242	-31.757	<2e-19
Unemployment claims/1000	-37.4102	1.3451	-27.812	<2e-20
Employment density	116.4045	3.2017	36.357	<2e-22
Population density	-59.5751	1.7173	-34.690	<2e-23
% Working From Home (WFH)	-10.6441	1.2442	-8.555	8.64E-11

4.3 Modeling Scenarios

As the percentage of teleworkers increased from five percent to over 50 percent in 2020, we decided to conduct a sensitivity analysis to investigate the relationship in traffic and the percentage of teleworkers. The telecommuting percentage was increased in equal intervals of 10 percent over the base condition (in 2019) to set up four sensitivity scenarios with one scenario to investigate HOV lane implementation. The five scenarios were studied in this analysis:

- Scenario 1: %WFH was set at 10 percent above base condition
- Scenario 2: %WFH was set at 20 percent above base condition
- Scenario 3: %WFH was set at 30 percent above base condition

- Scenario 4: %WFH was set at 40 percent above base condition
- Scenario 5: Converting a lane of freeways to HOV lane.

In Scenarios one, two, three, and four, we used the model to predict the hourly vehicle volume by changing the "%WFH" variable in the model for each scenario. The 2019 conditions served as the base condition. In Scenario five, the effectiveness of the HOV lanes on the I-270 in Maryland is investigated by comparing the average occupancy of vehicles in the HOV lanes versus general-purpose lanes during the HOV lane operation. This ratio of average occupancy (HOV vs general-purpose lanes) is used to redistribute traffic on the other freeways (other than I-270) and the LOS is recalculated with the revised traffic.

For each scenario, a Level of Service (LOS) analysis was done to determine the roadway performance on the ten busiest highways. LOS is a qualitative mechanism used to determine how well a transportation facility is operating from a traveler's perspective. LOS has a letter designation from A to F, with LOS A representing the best operating conditions, and LOS F the worst. The Table 4-2 shows the metric for assigning LOS.

Table 4-2: Road and Intersection Level-Of-Service (LOS) (Zuniga-Garcia et al., 2018)

LOS	Freeway (assuming 70 mph design speed)	Arterial (assuming typical 40 mph free flow speed)	Signalized Intersections (average controlled delay per vehicle)	Traffic Flow Characteristics
A	Greater than 60 mph Average spacing: 22 car-lengths	Greater than 35 mph	Less than 10 seconds; most vehicles do not stop at all	Virtually free flow; completely unimpeded Volume/Capacity (V/C) ratio less than of equal to .60
B	57 to 60 mph Average spacing: 13 car-lengths	28 to 35 mph	10.1 to 20 seconds; more vehicles stop than LOS A	Stable flow with slight delays; reasonably unimpeded Volume/Capacity (V/C) ratio .61 to .70
C	54 to 57 mph Average spacing: 9 car-lengths	22 to 28 mph	20.1 to 35 seconds; individual cycle failures may begin to appear	Stable flow with delays; less freedom to maneuver Volume/Capacity (V/C) ratio .71 to .80
D	46 to 54 mph Average spacing: 6 car-lengths	17 to 22 mph	35.1 to 55 seconds; individual cycle failures are noticeable	High Density, but stable flow Volume/Capacity (V/C) ratio .81 to .90
E	30 to 46 mph Average spacing: 4 car-lengths	13 to 17 mph	55.1 to 80 seconds; individual cycle failures are frequent; poor progression	Operating conditions at or near capacity; unstable flow Volume/Capacity (V/C) ratio .91 to 1.00
F	Less than 30 mph Average spacing: Bumper to bumper	Less than 13 mph	More than 80 seconds; not acceptable for most drivers	Forced flow, breakdown conditions Volume/Capacity (V/C) ratio greater than 1.00
>F	Demand exceeds roadway capacity, limiting volume that can be carried and forcing excess demand onto parallel routes and extending the peak period.			Volume/Capacity (V/C) ratios of greater than 1.10

The Highway Capacity Software (HCS10) was used to calculate the LOS based on the volumes in each scenario. Additional information such as the speed limits, road type, number of lanes, lane widths, availability of shoulders and medians etc. were also imputed into HCS10 based on Highway Capacity Manual (HCM). Using this method, we were able to estimate how different teleworking percentages affect the performance of roadways.

Chapter 5: Exploratory Data Analysis

The data visualizations in this chapter help demonstrate a nexus between telecommuting and the reduction in traffic congestion between 2019 and 2020. Since changes in travel behavior was affected by different policies and events undertaken to prevent the spread of COVID-19, it is important to highlight some of the key events of 2020 that will aid in contextualizing the results. The first reports and subsequent outbreak of the COVID-19 were in December 2019 (Liu et al., 2020). According to the CDC, the first USA case was in January 2020. However, the DMV region reported its first cases in early March. On March 30th, all three regions in DMV (DC, Maryland, and Virginia) had issued executive stay at home orders. These orders prohibited large gatherings and events, closed senior centers and all non-essential businesses and other establishments, and additionally required all persons to stay at home (Commonwealth of Virginia, 2020; Government of the District of Columbia, 2020; State of Maryland, 2020). In Washington D.C. and Maryland, this order carried a possible sentence of up to one year in prison and/or a fine of up to $5,000 (Government of the District of Columbia, 2020; State of Maryland, 2020).

March 30th is an important date in the analysis; it marks the beginning of most of the trend changes between 2019 and 2020. Through the months of May and June, the DMV regions adopt varying reopening plans which lead to variations in mobility trends. Table 5-1 highlights the timeline of these policies and key events discussed above.

Table 5-1: Highlights of COVID-19 Timeline in DMV

Date(2020)	Covid-19 related events in DMV
	Maryland
5-Mar	Governor Hogan declares a state of emergency after first 3 confirmed positive cases
16-Mar	Executive order to closes schools and public places
23-Mar	Governor Hogan orders nonessential businesses to close
30-Mar	Maryland issues executive stay-home order
15-May	Phase One of reopening: retail businesses in the state could reopen at 50% capacity, as well as barbershops and hair salons. Restaurants, movie theaters and gyms remained closed
	The two largest in counties in Maryland(Montgomery and Prince George's) and some local jurisdictions delayed their Phase One opening
5-Jun	Phase Two of reopening: There were multiple stages in June (Maryland.gov)
27-Aug	All schools were authorized to reopen
1-Sep	Phase Three of reopening: Indoor dining increased from 50% to 75% beginning on Sept. 21
	Virginia
7-Mar	Virginia recorded it's first COVID-19 case
23-Mar	Schools closed for the rest of the year
30-Mar	Virginia issued executive stay-home order (EO55)
15-May	Phase One re-opening for many parts of the state excluding Northern Virginia, including Arlington, Fairfax, Vienna, and Alexandria.
29-May	Phase One re-opening for rest of Virginia ie. Northern Virginia, Richmond and Accomack county
5-Jun	Phase Two of the reopening in parts of Virginia. Indoor seating at 50% capacity to parties of up to 50 people. All retail businesses are permitted to reopen at 50% capacity. Gyms can reopen at 30% capacity. Richmond and Northern Virginia remain in Phase 1
12-Jun	Phase Two for all of Virginia
1-Jul	Phase Three reopening plan
11-Sep	Executive order to move Hampton Roads area of Virginia back into Phase Three of reopening.
14-Dec	Governor Ralph Northam announced a statewide curfew from midnight to 5 a.m.
	Washington D.C
7-Mar	First known coronavirus case
13-Mar	Order banning gatherings of 250 people or more. Nonessential businesses ordered to close.
24-Mar	Over a dozen rail stations closed indefinitely.
30-Mar	Executive stay-home order
9-Apr	Order requiring grocery stores to limit the number of customers inside stores. D.C. region's first mask mandate.
29-May	Phase One reopening: restaurants were allowed to reopen for outdoor dining, and nonessential retailers were allowed to reopen for curbside pickup.
22-Jun	Phase Two reopening: indoor dining at 50% capacity, indoor shopping at nonessential businesses, and the reopening of parks and gyms with safety restrictions.
25-Aug	DC remains in a modified Phase 2 as of late December 2020.

5.1 Traffic Volumes Trends

In 2020, the average US driver spent 26 hours in traffic which is only a quarter of the 99 hours spent in traffic jams by the average US driver in 2019 (Gitlin, 2021). This reduction in travel demand was both due to fear of contracting the virus and governments imposing preventive measures such as closures of schools, offices, businesses, restaurants, travel borders, etc. The startling change of events led to a reduction in gas prices and even a surplus of crude oil, to the extent that there weren't enough places to store it. For the first time in history, crude oil prices per barrel dropped below zero going from $18 to -$38 (Ambrose, 2020).

Comparing 2019 to 2020 average monthly volumes in Figure 5-1, 2020 January and February volumes are higher than 2019 by four and two percent, respectively. This is typical as prior to 2020 there had been a yearly increase in traffic volume. Passenger car travel has increased steadily around one to two percent per year during the past several years prior to COVID-19 (Ewoldsen, 2021). In March, Maryland recorded its first COVID-19 case (Fulginiti, 2021). The state gradually began imposing regulatory policies which resulted in a reduction of traffic volumes. The steady decline continues and reaches its trough in April at less than 50 percent of what it was the previous year. On average there was an -18.9 percent change in volume between 2019 and 2020. As the lockdown policies begin to loosen up in May and June, there is an increase in traffic volume, but it has not yet surpassed the volumes of 2019.

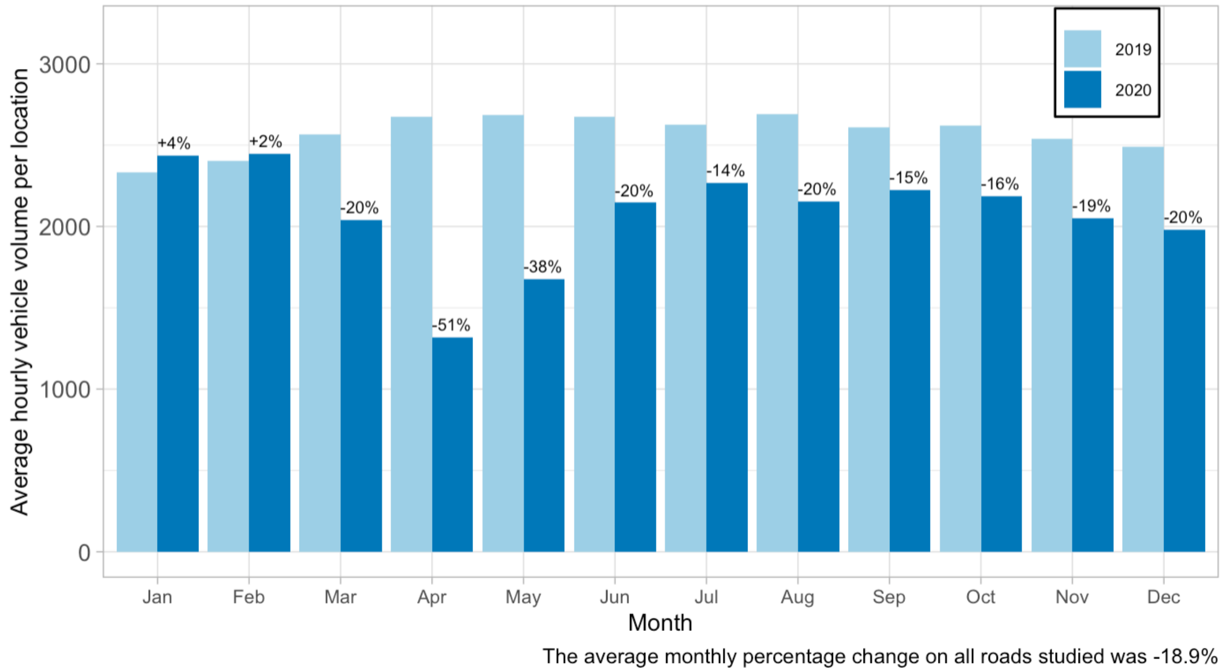

Figure 5-1: Monthly Volumes Percentage Change

In Figure 5-2 we see the same trend across all road types. The three road type categories were: Interstates, Maryland local roadways, and U.S. federal highways. On the interstates, there was a drop of over 500 vehicles per hour when comparing the 2019 and 2020 data. On Maryland and U.S. highways there was also a significant drop in vehicle volume that remained through 2020. This establishes that the traffic reduction was observed across all road types.

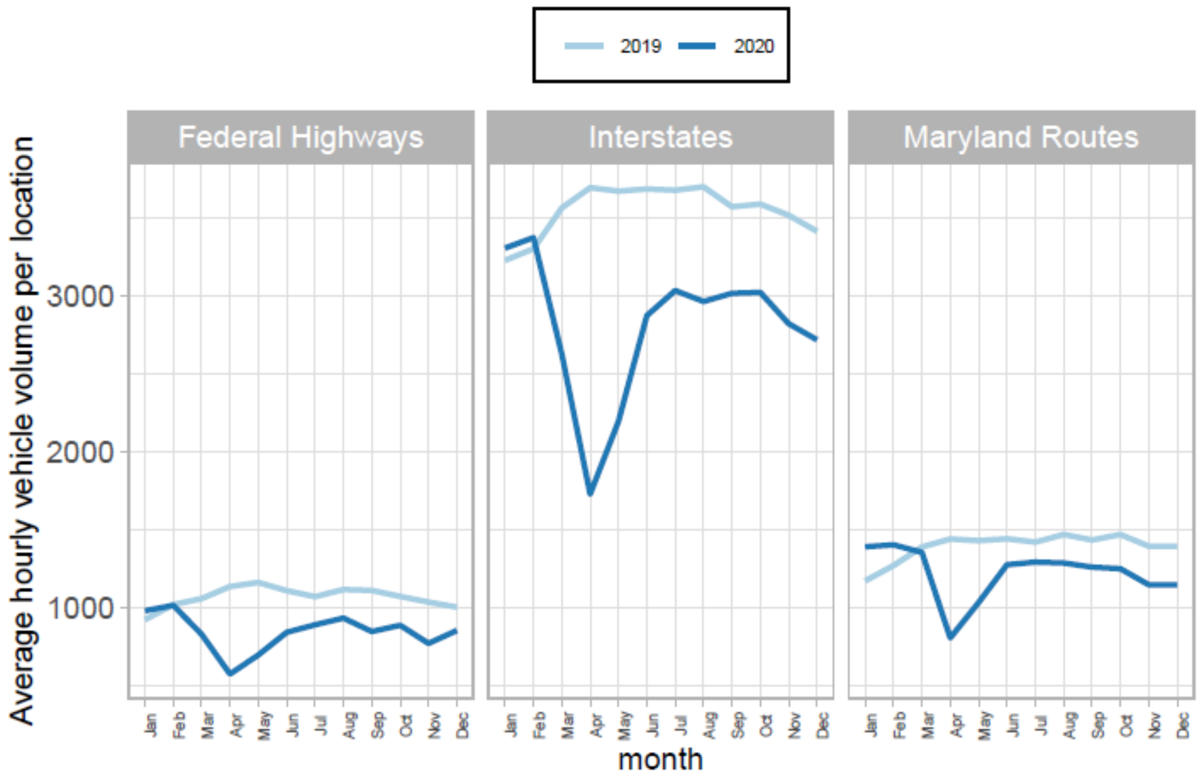

Figure 5-2: Monthly Volumes by Year, Road Type

5.2 2020 Mobility Trends

The data from COVID-19 platform was used to visualize the mobility trends of people in the DMV in 2020. In the months of January and February, pre-SAH order, the average daily trips per person are very similar and range from 3.25 to 3.5 trips in Maryland, Virginia, and for comparison the USA. Washington D.C., however, had a higher mobility pattern of about 4 to 4.5 daily trips per person in the months of January and February. In March, there is a dramatic decline in daily trips as schools and public transportation stations begin to close. All regions studied have their lowest point shortly after March 30th due to the executive SAH orders. The average daily trips per person in Maryland was the lowest in DMV with less than 2.5 daily trips per person. In Washington D.C. and Virginia, the lowest average daily trips were about 2.7 trips per person.

Although the first reopening phase did not begin until May, a greater number of trips were seen throughout the DMV. Around April 13th, researchers found more Americans venturing out against coronavirus stay-at-home orders (Katherine Shaver, 2020). The exhaustion associated with the new restrictive lifestyle adopted to slow the spread of COVID-19 was termed quarantine fatigue (Marques, 2020). In Maryland and Virginia, the first reopening was on May 15th whereas Washington D.C. did not begin reopening until May 29th. It is important to note that as of the end of 2020 Washington D.C. was still in phase two of its reopening, which is why average daily trips were still below pre-lockdown levels. Virginia had post-SAH order average trips that were slightly higher than the pre-SAH order trips at certain times. Figure 5-3 presents the average daily trips (ADT) per person in DMV and USA in 2020.

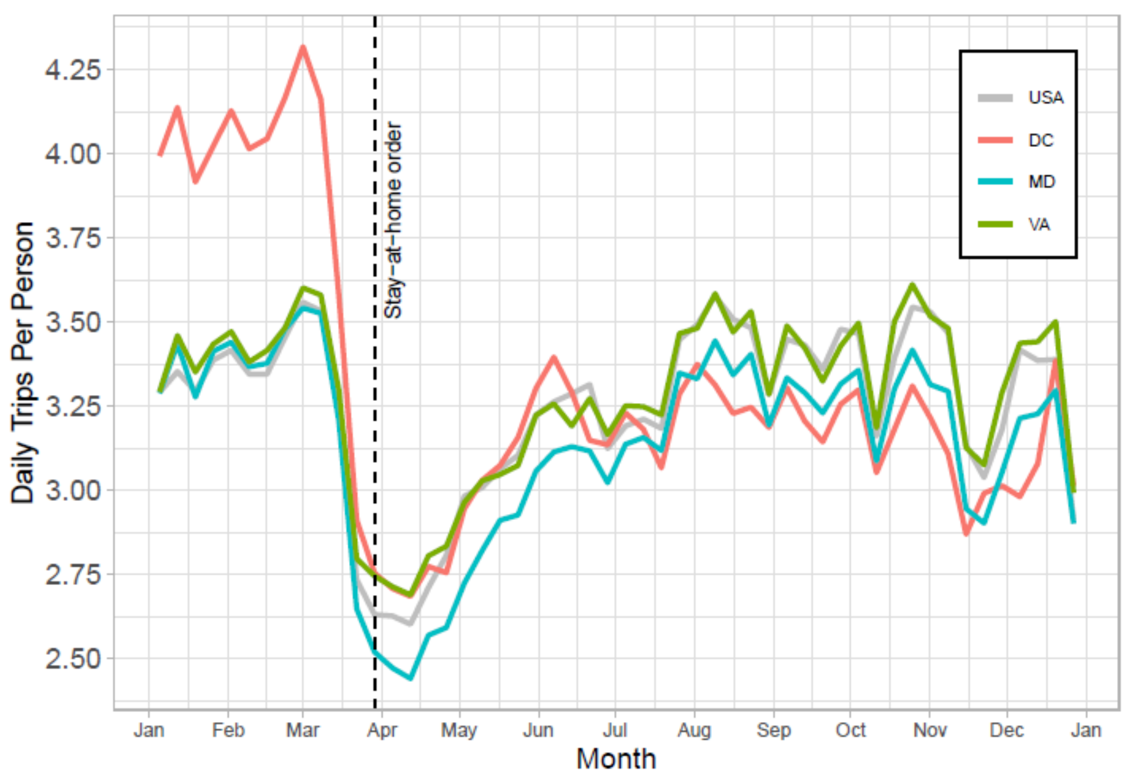

Figure 5-3: Average Daily Trips Per Person (2020)

Figure 5-4 shows daily trips by trip type. The non-work-related trips trend is similar to the daily trip trends in Figure 5-3. In all regions, there were more non-work-related trips than work-related trips. The work-related trips remained low and did not increase or fluctuate much after the SAH order. In Maryland and Virginia, there have been less than 0.5 work trips per day per person since the stay-at-home order, which is similar to the USA average. In Washington D.C., the work-related trips are slightly higher than other DMV regions. Washington D.C. is the only region in which the non-work trips remained significantly lower after the SAH order. Recall Washington D.C. was still in phase two of reopening at the end of 2020.

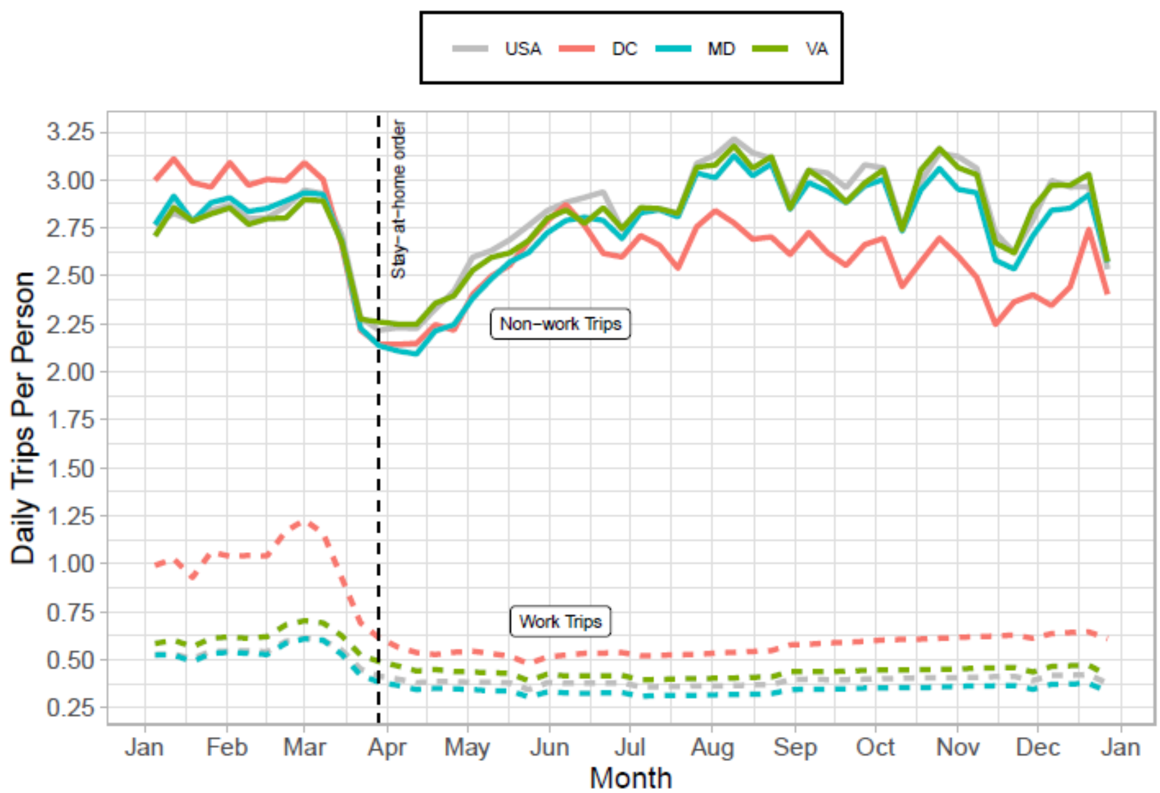

Figure 5-4: Work vs Non-Work Trips (2020)

Comparing Figure 5-2 and Figure 5-4, we notice that even though the non-work trips increased, highway volumes in 2020 were still lower than in 2019; this indicates that, as expected, work trips are a major factor in highway congestion. However, there are other reasons besides teleworking that account for the reduction in volumes such as the closure of non-essential businesses, loss of jobs, and fear of contracting the deadly virus.

An important shift observed in the work culture during COVID-19 is the widespread adoption of teleworking by most organizations. Notable companies such as Google, Microsoft Uber, American Express, and Airbnb extended work-from-home policy and plans to accommodate remote work indefinitely while improving their remote work policies (Joey Hadden et al., 2020).

Prior to the pandemic, less than 5 percent of Maryland workforce was working from home. Figure 5-5 shows the numbers rose to almost 50 percent of the Maryland workforce participating in telecommuting. In Washington D.C., almost 60 percent of residents were teleworking as of July 2020. In the last few months of 2020, there was a drop in the number of people teleworking, however, this is still almost ten times higher than the pre-SAH averages. Washington D.C. region had the highest percentage of people WFH in the DMV region followed by Maryland and then Virginia. This may be partially due to Washington D.C. federal government offices. Although the DMV region had a higher percentage of teleworkers than the USA, the temporal trends are similar across all regions.

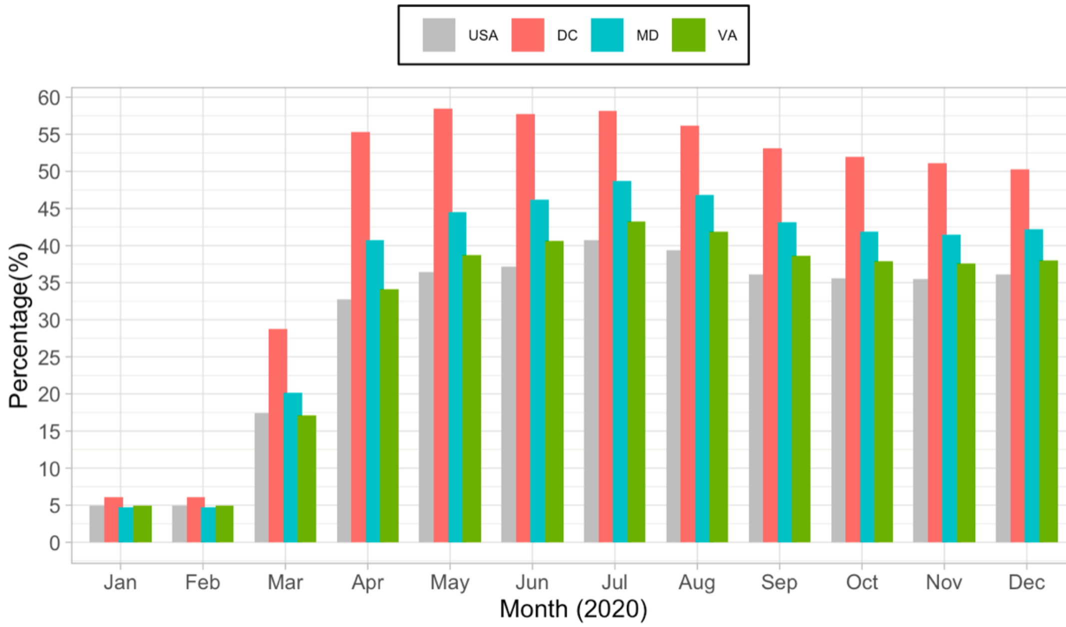

Figure 5-5: Percentage Working from Home in DMV

Figure 5-6 shows the average hourly vehicle volume in 2019 vs that of 2020 for the locations studied. The 2020 volumes were lower than 2019 in every hour. The AM and PM peak hours in both years were eight to nine am and three to five pm, respectively. During the AM peak hours there was upwards of 20 percent reduction in volume and during PM peak hours there was over 10 percent reduction in the volume of traffic.

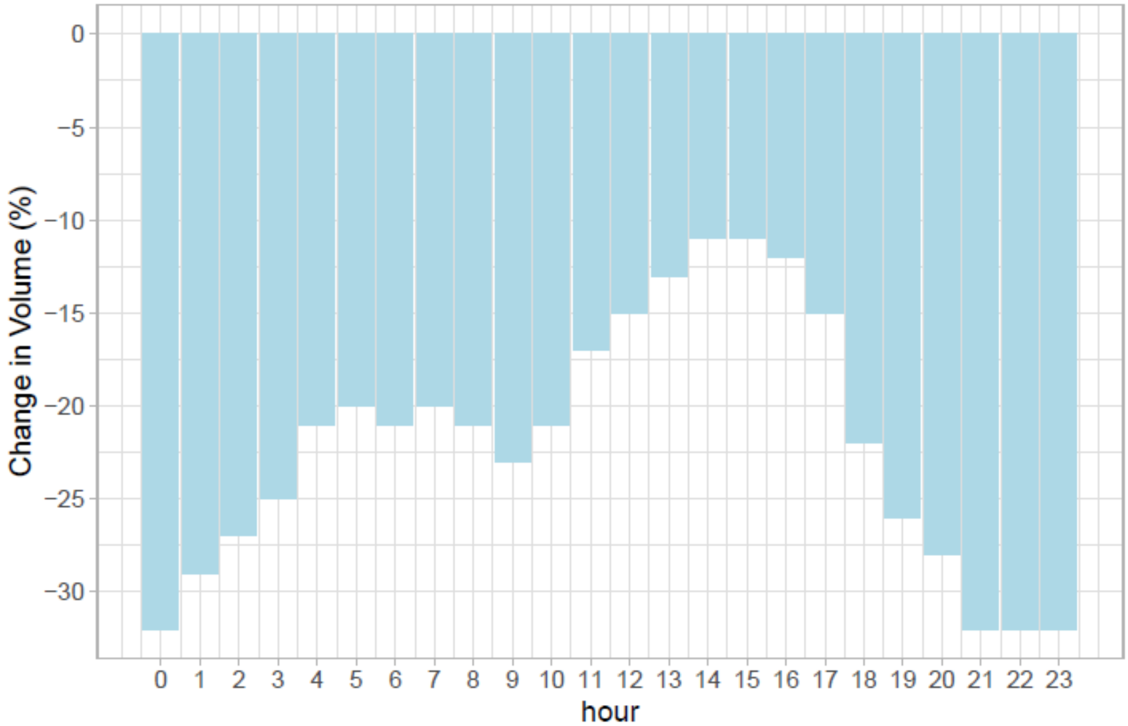

Figure 5-6: 2019 vs 2020 Change in Average Hourly Traffic Volume

In Figure 5-7, only the hourly volumes for the interstates are presented. There is a higher reduction in hourly traffic volumes on the interstates. On average traffic volume dropped by 28.4 percent. However, at certain hours the traffic volume dropped up to 40 percent. The peak hours remained the same but there were very significant traffic reductions of about 30 percent during AM peak hours and almost 20 percent during the PM peak hours. Overall, there was a higher drop in peak hour in the mornings than in the evening hours.

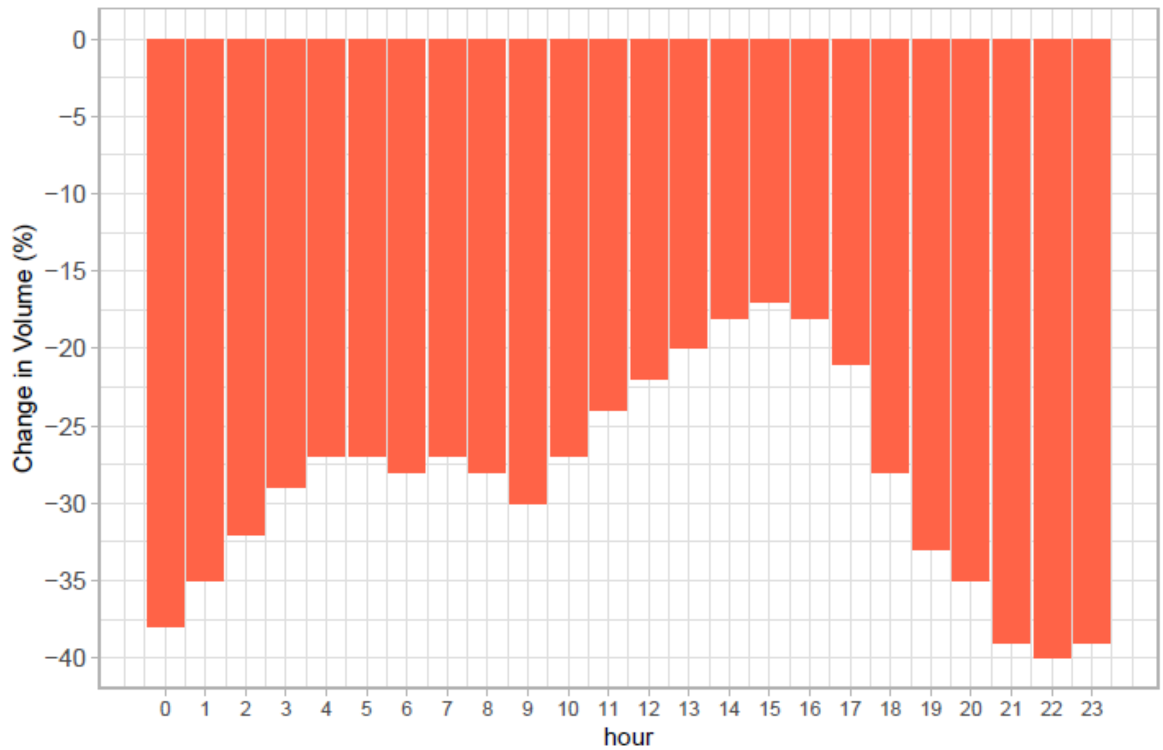

Figure 5-7: 2019 vs 2020 Change in Average Hourly Interstate Traffic Volume

Chapter 6: Results

6.1 Telecommuting

We use our final regression model to determine the traffic volume on each roadway for each of our telework scenarios. The estimated traffic volumes were used to calculate the LOS for the congestion hotspots in HCS10 software. Figure 6-1 shows the LOS color scale, A LOS of B, C, D, and E are colored green, yellow, orange, and red respectively. There were no locations with a LOS of A indicating free-flow traffic nor a LOS of F indicating a traffic jam in this study. Table 6-1 shows the LOS for the top 10 busiest ATR locations in 2019, between 7AM and 7 PM, for each direction. This is the base condition onto which other scenarios are compared.

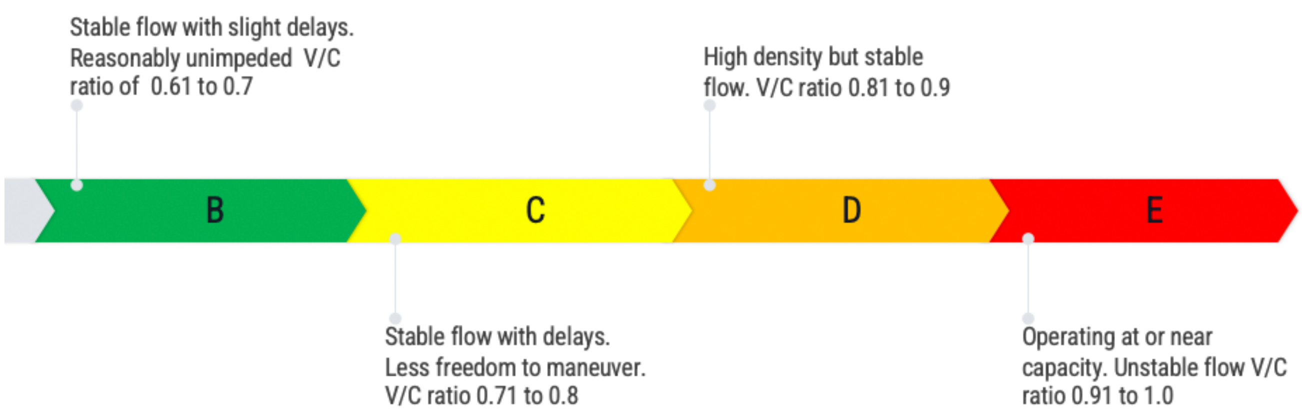

Figure 6-1: Level of Service Color Scale

Table 6-1: Baseline LOS for the top 10 busiest ATR traffic volume locations

ATR	P0040		P0043		P0041		P0055		P0039		P0060		P0004		P0069		P0024		P0025	
Direction	E	W	N	S	E	W	N	S	N	S	N	S	N	S	N	S	E	W	E	W
7 AM – 8 AM																				
8 AM – 9 AM																				
9 AM – 10 AM																				
10 AM – 11 AM																				
11 AM – 12 PM																				
12 PM – 1 PM																				
1 PM – 2 PM																				
2 PM – 3 PM																				
3 PM – 4 PM																				
4 PM – 5 PM																				
5 PM – 6 PM																				
6 PM – 7 PM																				

Most detectors in Prince George's County (P0043 and P0055) and Montgomery County (P0004, P0060, P0040 , and P0041) performed at LOS D. Detector P0040 on IS-495, in particular, was a location of concern with a LOS of E representing unstable flow near capacity during the hours of 2 to 3 pm in 2019. Detectors in Anne Arundel (P0024 and P0025) and Howard County (P0069 and P0039) performed better.

Mappings of the worst AM and PM peak periods of the 10 busiest roads in Maryland are used to depict the LOS for the roadways during either the morning or evening peak hours. In Figure 6-2, the base condition shows that during the AM peak hours, the locations on the periphery of Washington D.C. all have LOS D. As we move away from Washington D.C., all other locations have better LOS conditions except for one location (P0039).

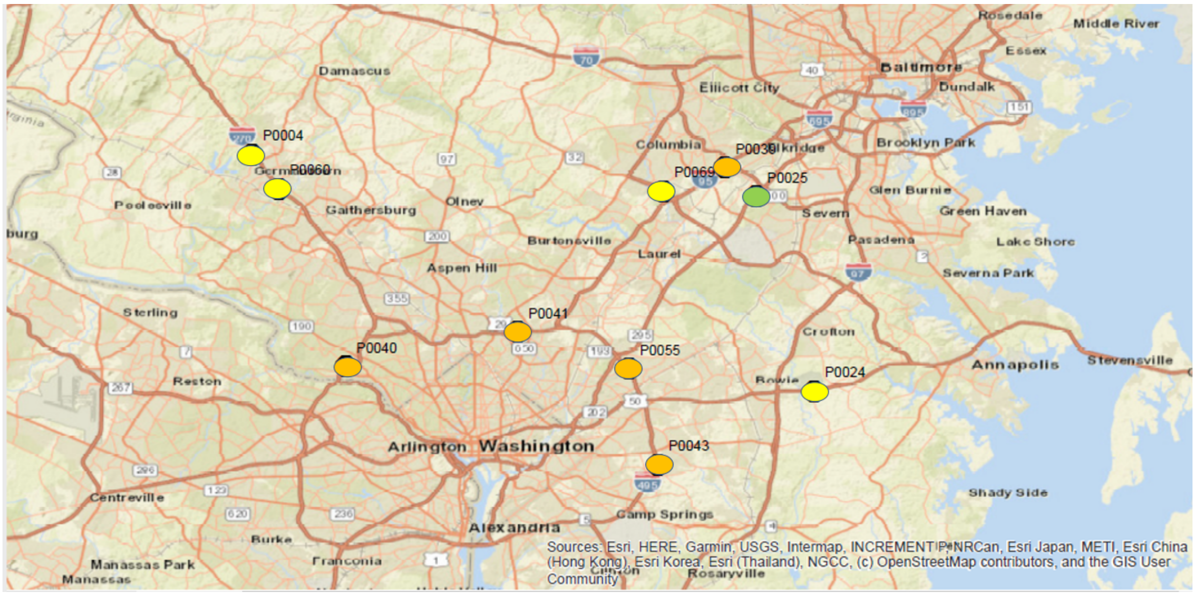

Figure 6-2: Baseline: AM Peak Hours for Maryland

Figure 6-3 shows the baseline PM peak periods. The roadways around the Washington D.C. area witness heavy traffic congestion during the evening peak hours. One of the locations also registers an LOS E, indicating that the traffic in the area is heavily congested. Similar to as witnessed with the AM peak analysis, the LOS for the areas away from Washington D.C. are less congested.

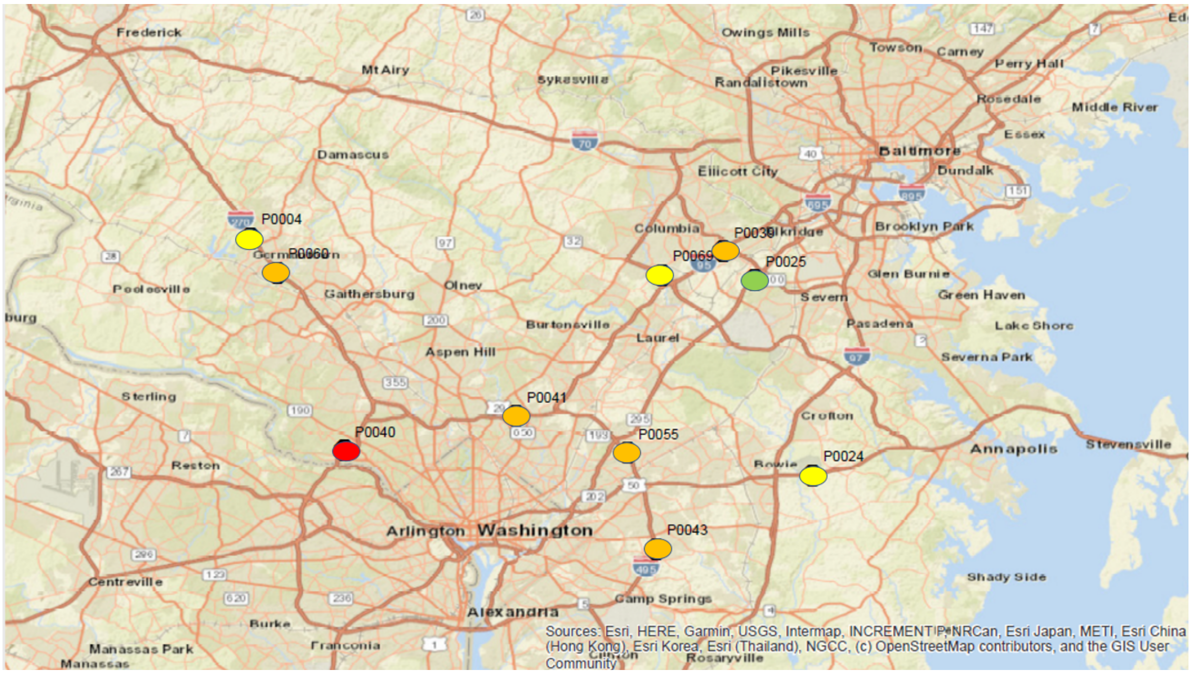

Figure 6-3: Baseline: PM Peak Hours for Maryland

Scenario 1

Scenario 1 considers that an additional 10 percent workers participate in telecommuting in our study area. Table 6-2 indicates the changes in LOS for the ATR locations with respect to the baseline condition. Only the ATR locations for which the LOS has changed have been highlighted for ease of understanding. Most importantly, the LOS E in the east direction for P0040 has improved to LOS D, a significant improvement with only a 10 percent increase in the percentage of workers participating in telecommuting. Significant LOS improvements are observed for all locations except P0023, P0039, P0060, and P0004.

Table 6-2: Scenario 1 LOS for the top 10 busiest ATR traffic volume locations

ATR Location No.	P0040		P0043		P0041		P0055		P0039		P0060		P0004		P0069		P0024		P0025	
Direction	E	W	N	S	E	W	N	S	N	S	N	S	N	S	N	S	E	W	E	W
7 AM – 8 AM																				
8 AM – 9 AM																				
9 AM – 10 AM																				
10 AM – 11 AM																				
11 AM – 12 PM																				
12 PM – 1 PM																				
1 PM – 2 PM																				
2 PM – 3 PM																				
3 PM – 4 PM																				
4 PM – 5 PM																				
5 PM – 6 PM																				
6 PM – 7 PM																				

Figure 6-4 and Figure 6-5 present the average traffic conditions in Maryland both during AM and PM peak hours, respectively. There was no significant improvement of LOS observed in the roads surrounding Washington D.C. and interstates continue to remain more congested than the Maryland roads.

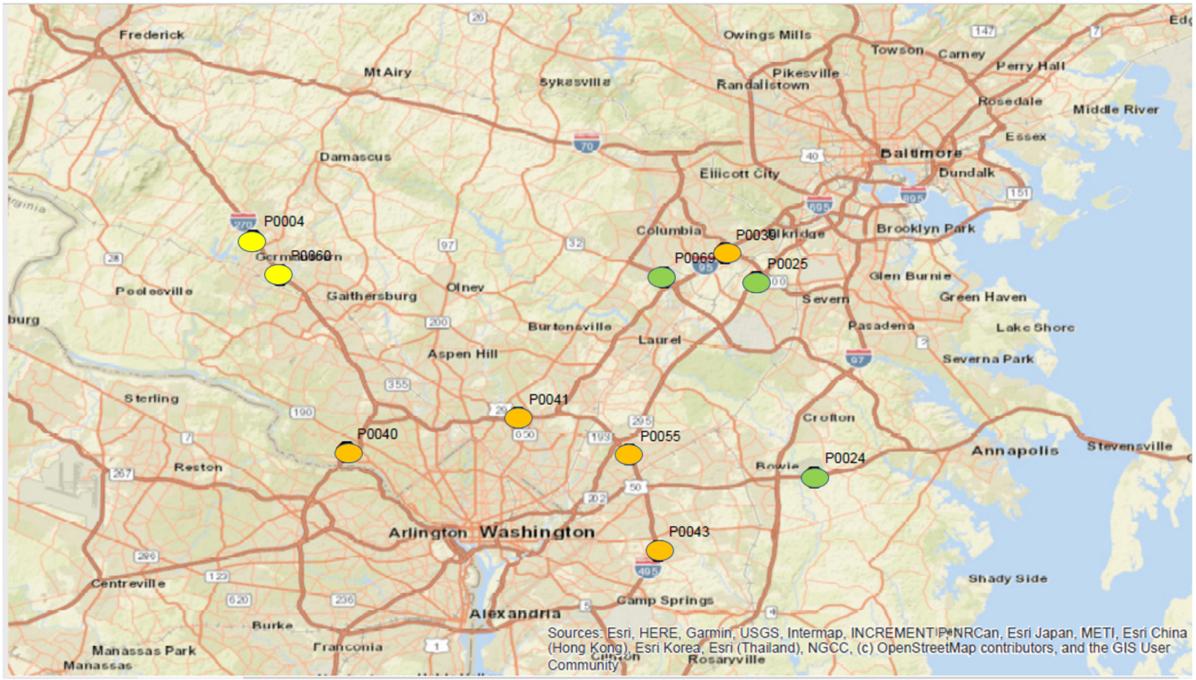

Figure 6-4: Scenario 1: AM Peak Hours for Maryland

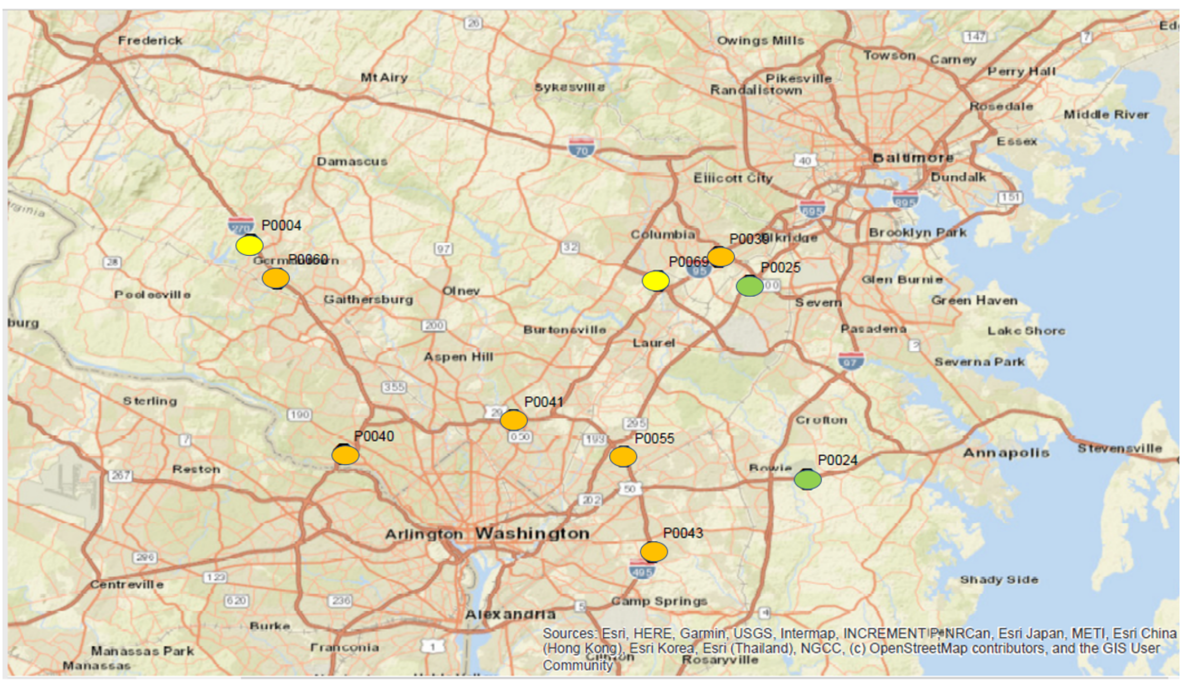

Figure 6-5: Scenario 1: PM Peak Hours for Maryland

Scenario 2

Scenario 2 considers that an additional 20 percent workers participate in telecommuting in our study area. Table 6-3 indicates the changes in LOS for the ATR locations with respect to the baseline condition. Most importantly, the LOS E no longer exists for any direction for P0040, a significant improvement with only a 20 percent increase in the percentage of workers participating in telecommuting. Significant LOS improvements are again observed for P0036, P0060, P0004, P0069, P0024 and P0025.

Table 6-3: Scenario 2 LOS for the top 10 busiest ATR traffic volume locations

ATR Location No.	P0040		P0043		P0041		P0055		P0039		P0060		P0004		P0069		P0024		P0025	
Direction	E	W	N	S	E	W	N	S	N	S	N	S	N	S	N	S	E	W	E	W
7 AM – 8 AM																				
8 AM – 9 AM																				
9 AM – 10 AM																				
10 AM – 11 AM																				
11 AM – 12 PM																				
12 PM – 1 PM																				
1 PM – 2 PM																				
2 PM – 3 PM																				
3 PM – 4 PM																				
4 PM – 5 PM																				
5 PM – 6 PM																				
6 PM – 7 PM																				

Figure 6-6 and Figure 6-7 present the average traffic conditions in Maryland both during AM and PM peak hours for Scenario 2. Still, no significant improvement of LOS is observed in the roads surrounding Washington D.C. though interstates experience a slight improvement in LOS conditions.

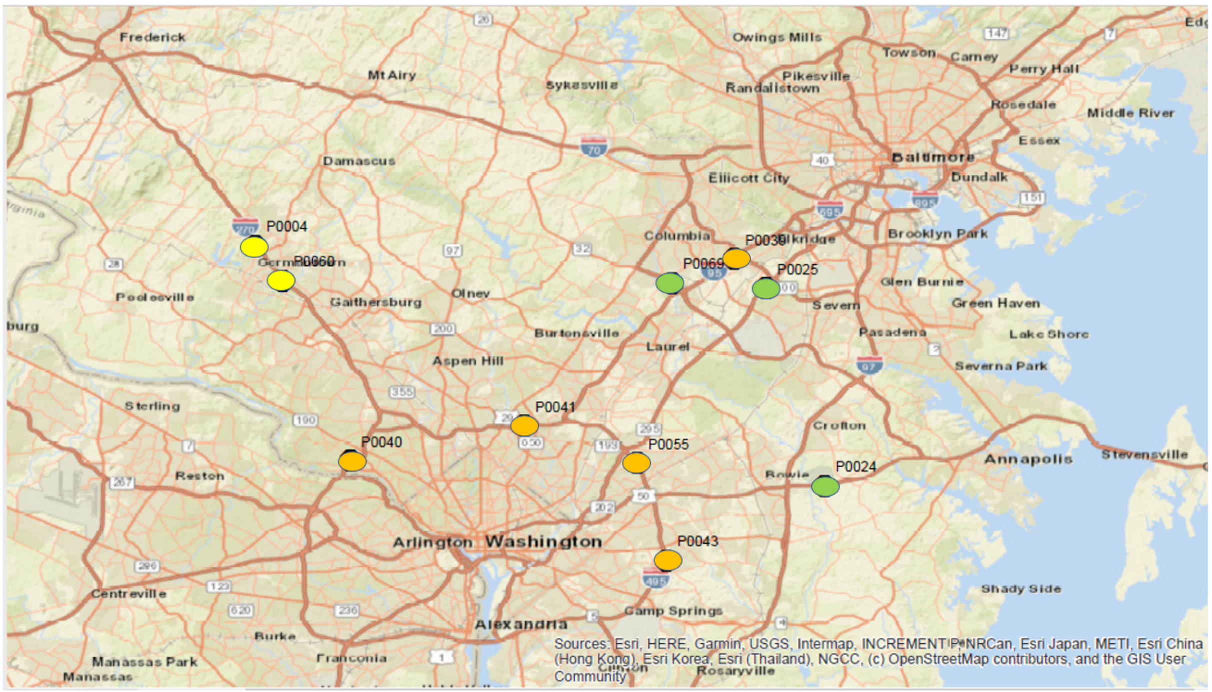

Figure 6-6: Scenario 2: AM Peak Hours for Maryland

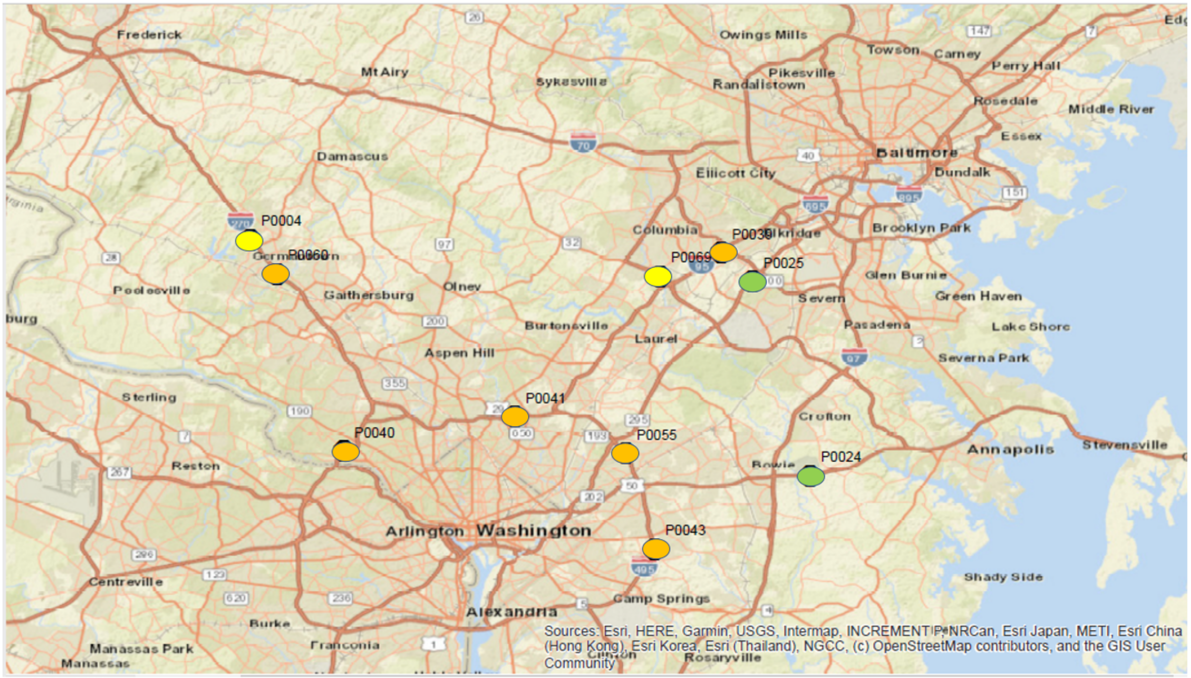

Figure 6-7: Scenario 2: PM Peak Hours for Maryland

Scenario 3

Scenario 3 considers that an additional 30 percent workers participate in telecommuting in our study area. Table 6-4 indicates the changes in LOS for the ATR locations with respect to the baseline condition. LOS improvements are observed for P0055, P0060, P0043, P0004, P0024 and P0025.

Table 6-4: Scenario 3 LOS for the top 10 busiest ATR traffic volume locations

ATR Location No.	P0040		P0043		P0041		P0055		P0039		P0060		P0004		P0069		P0024		P0025	
Direction	E	W	N	S	E	W	N	S	N	S	N	S	N	S	N	S	E	W	E	W
7 AM – 8 AM																				
8 AM – 9 AM																				
9 AM – 10 AM																				
10 AM – 11 AM																				
11 AM – 12 PM																				
12 PM – 1 PM																				
1 PM – 2 PM																				
2 PM – 3 PM																				
3 PM – 4 PM																				
4 PM – 5 PM																				
5 PM – 6 PM																				
6 PM – 7 PM																				

Figure 6-8 and Figure 6-9 present the average traffic conditions in Maryland both during AM and PM peak hours for Scenario 3. A small improvement of LOS is observed in the roads surrounding Washington D.C. and the local roads in Maryland, with interstates also experiencing a slight improvement in LOS conditions. Particularly, there was an improvement in the AM peak LOS at location P0043.

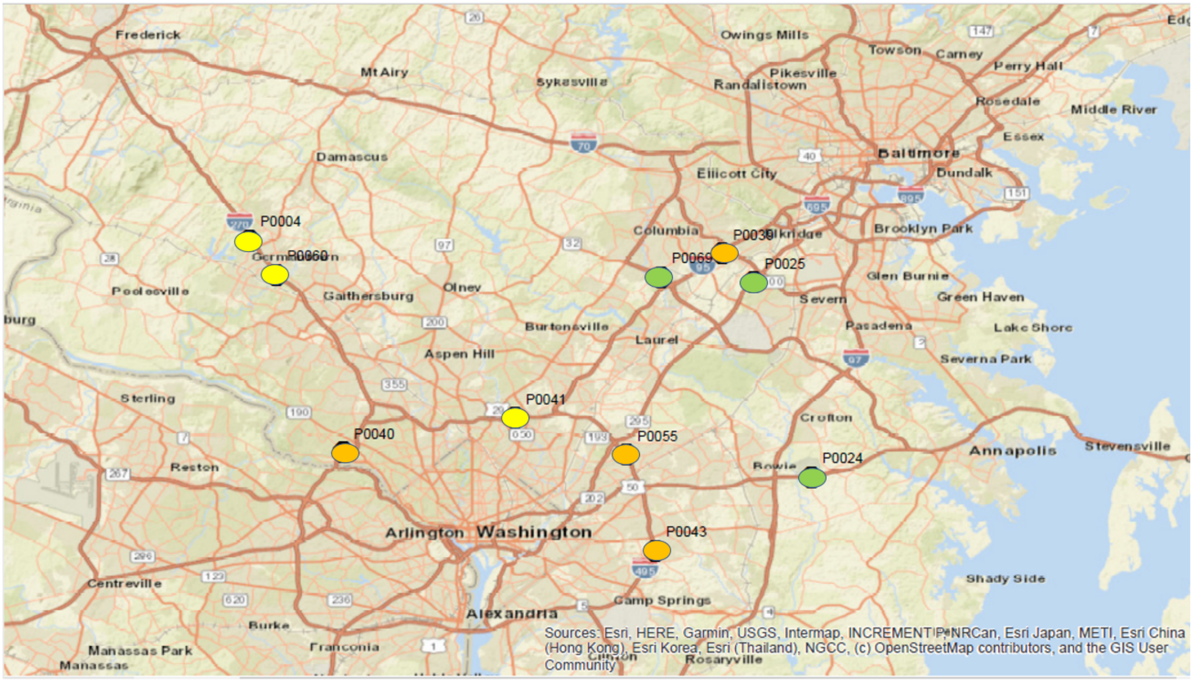

Figure 6-8: Scenario 3: AM Peak Hours for Maryland

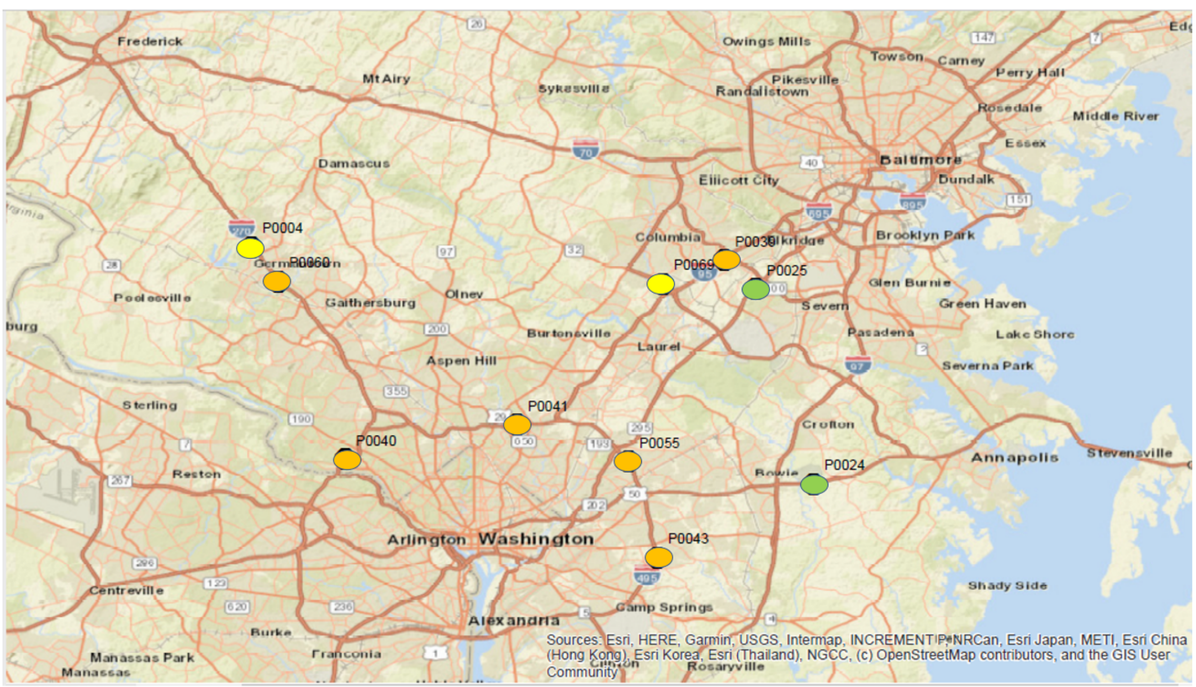

Figure 6-9: Scenario 3: PM Peak Hours for Maryland

Scenario 4

Scenario 4 considers that an additional forty percent workers participate in telecommuting in our study area. Table 6-5 indicates the changes in LOS for the ATR locations with respect to the baseline condition. Significant LOS improvements are observed for P0055, P0039, P0004, P0024, P0069, and P0025.

Table 6-5: Scenario 4 LOS for the top 10 busiest ATR traffic volume locations

ATR Location No.	P0040		P0043		P0041		P0055		P0039		P0060		P0004		P0069		P0024		P0025	
Direction	E	W	N	S	E	W	N	S	N	S	N	S	N	S	N	S	E	W	E	W
7 AM – 8 AM																				
8 AM – 9 AM																				
9 AM – 10 AM																				
10 AM – 11 AM																				
11 AM – 12 PM																				
12 PM – 1 PM																				
1 PM – 2 PM																				
2 PM – 3 PM																				
3 PM – 4 PM																				
4 PM – 5 PM																				
5 PM – 6 PM																				
6 PM – 7 PM																				

Figure 6-10 and Figure 6-11 present the average traffic conditions in Maryland both during AM and PM peak hours for Scenario 4. Again, a small improvement of LOS is observed in the roads surrounding Washington D.C., the interstates, and the local roads in Maryland.

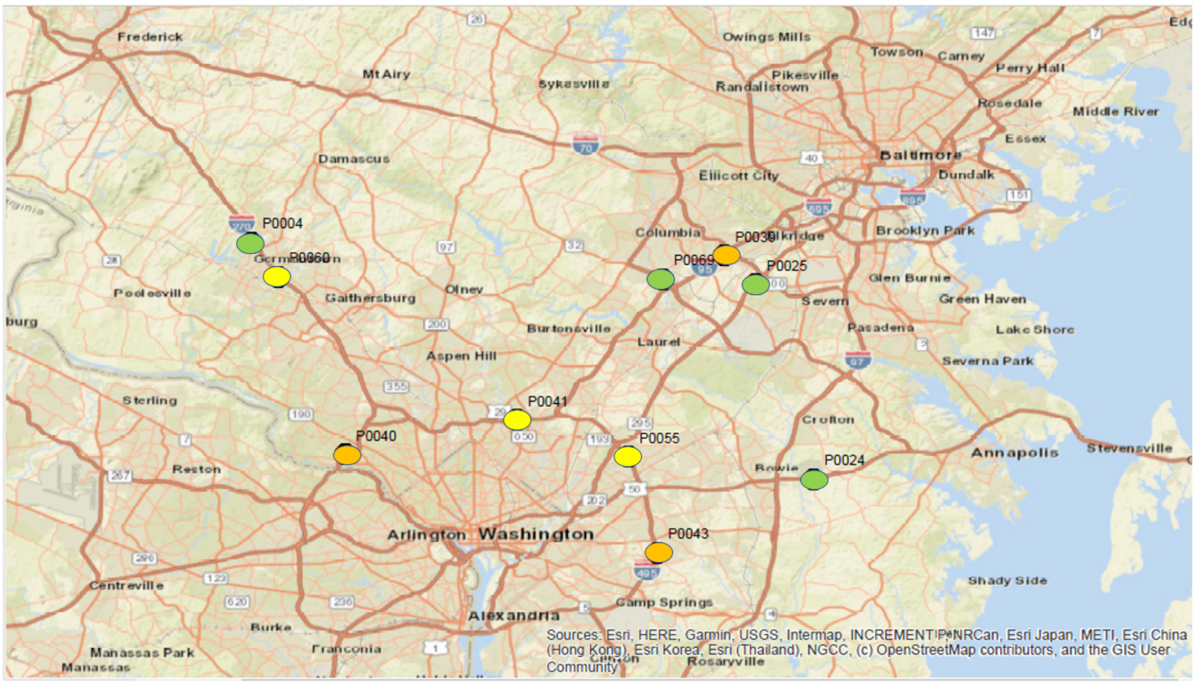

Figure 6-10: Scenario 4: AM Peak Hours for Maryland

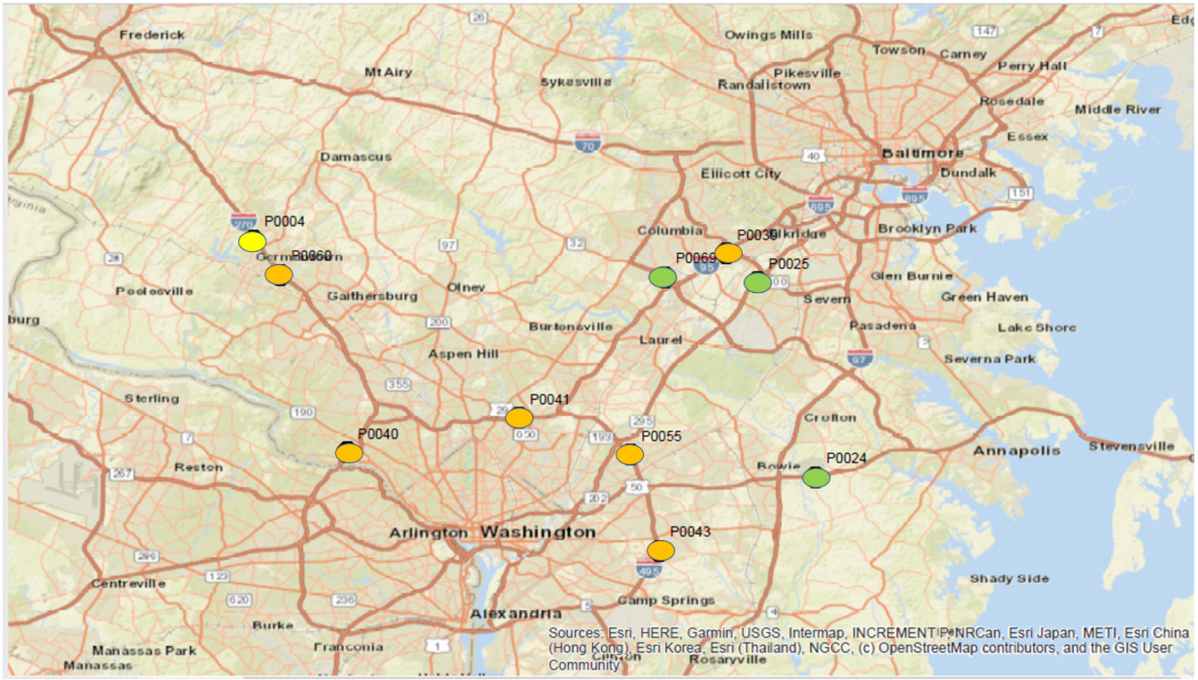

Figure 6-11: Scenario 4: PM Peak Hours for Maryland

Summary

Figure 6-12 shows a summary of the LOS results carried for the various telecommuting scenarios. Although there was no LOS of A for each increase in percent WFH, there is a decrease in the percentage of observed LOS D instances and an increase in percentage of observed LOS B. This means that as the percentage of people WFH increases, there are more roadways with stable flow, slight delays, and reasonably unimpeded volume/capacity (v/c) ratios. Additionally, with only 20 percent of the population telecommuting, there are no more roadways operating at LOS E near capacity. We also observed that the improvement in LOS is more significant in the AM peak hours rather than the PM peak hours for Maryland.

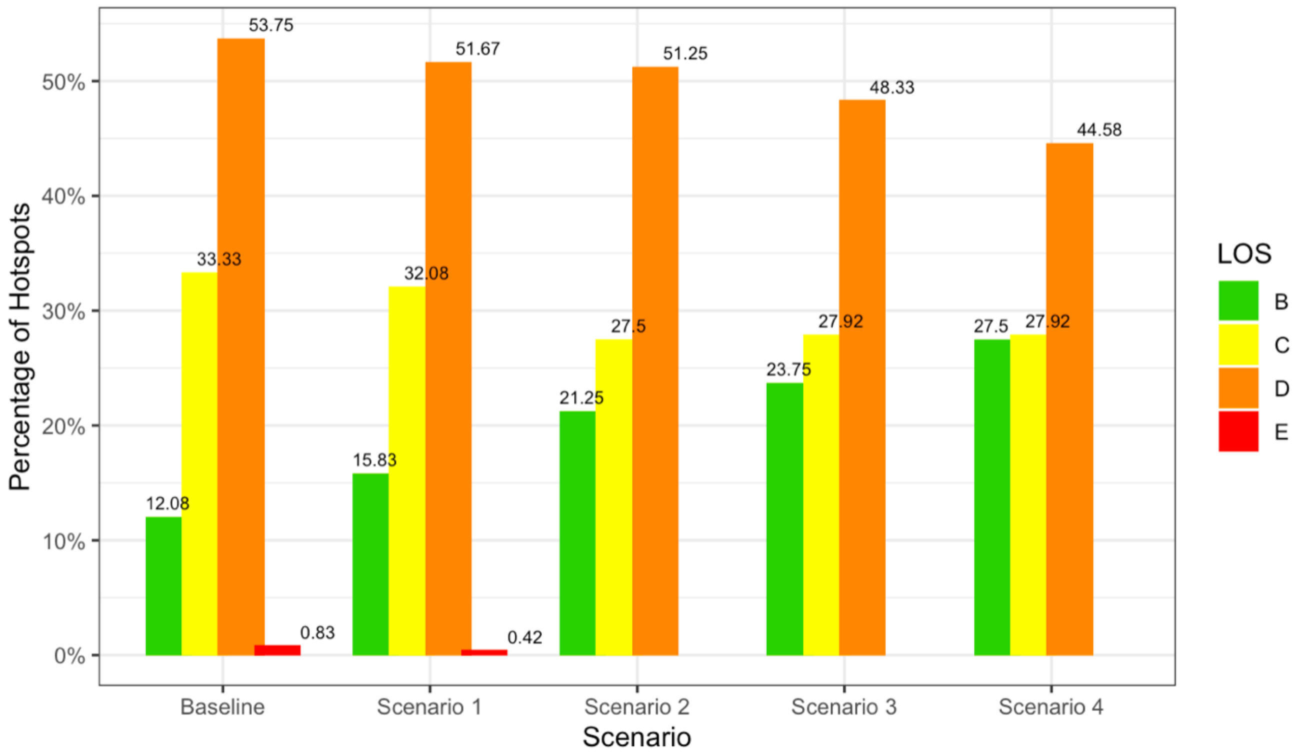

Figure 6-12: Summary of Telecommuting Scenarios

6.2 HOV lanes

This section contains results of the HOV analysis. Figure 6-13 presents the comparison between the total number of vehicles using the HOV and non-HOV lanes every hour for the month of January 2016 for I-270 in Maryland. We can observe that the general-purpose lanes or the non-HOV lanes carry a significantly higher number of vehicles than the HOV lanes overall.

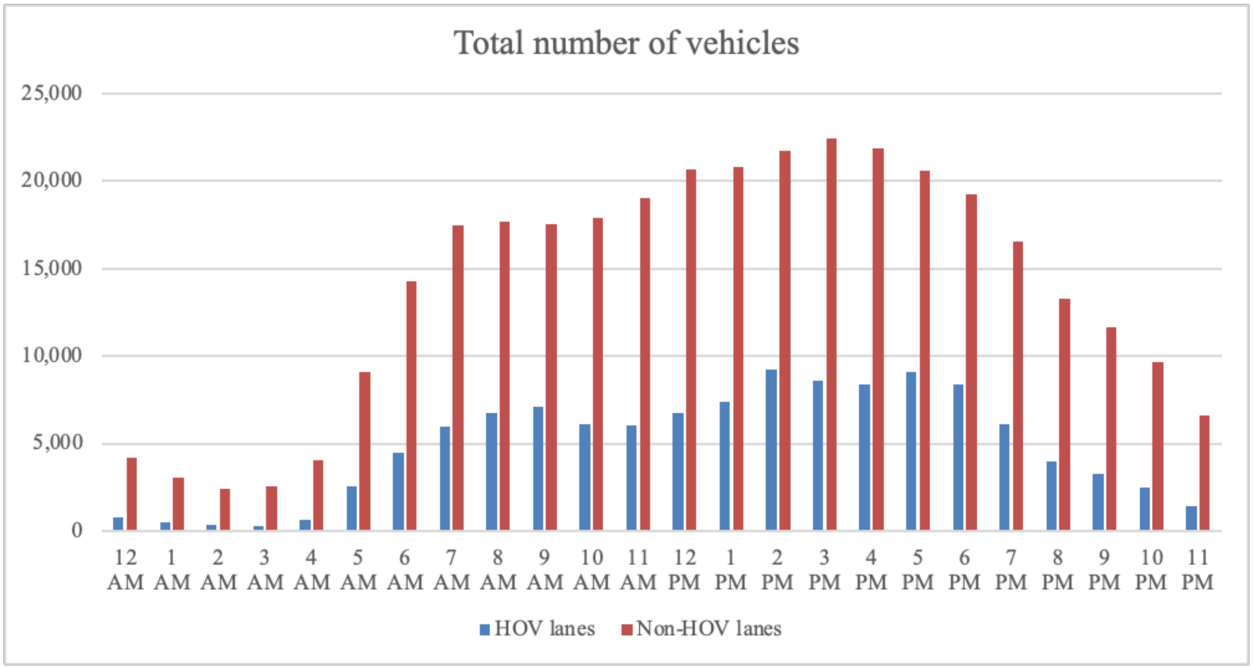

Figure 6-13: Total number of vehicles using each lane for the month of January 2016

Then, we compare the total number of occupants carried by each lane in Figure 6-14. We again observe that the general-purpose lanes carry a significant number of more occupants than the HOV-lanes.

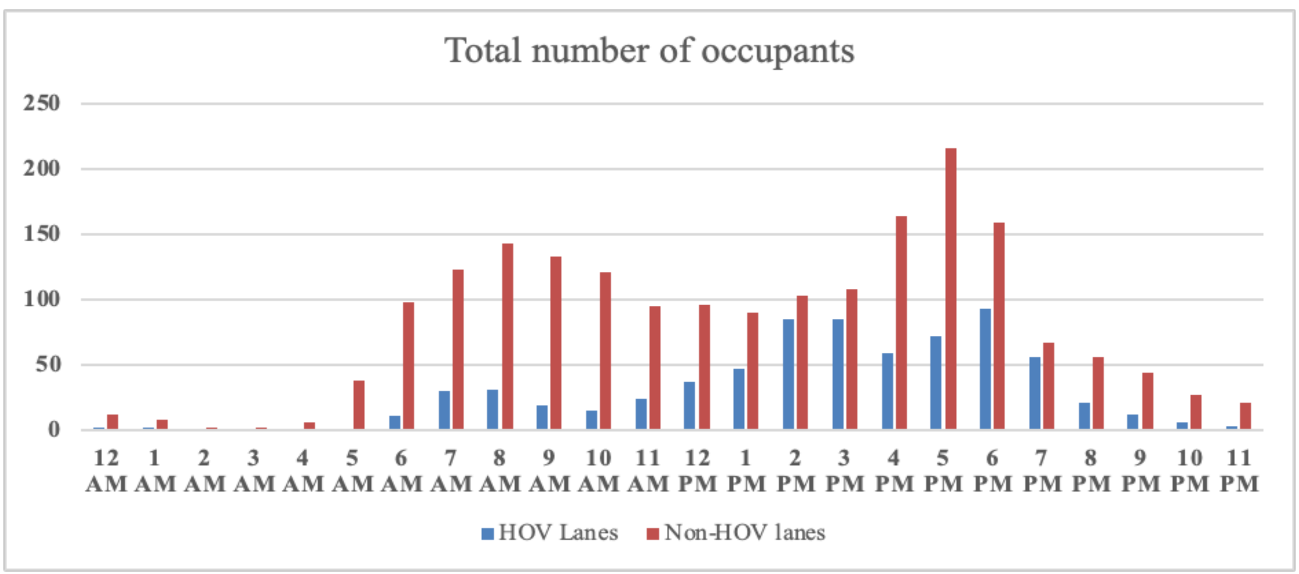

Figure 6-14: Total number of vehicles using each lane for the month of January 2016

And finally, we compare the average occupancy per vehicle for each lane in Figure 6-15. We observe that the HOV lanes carry more occupants per vehicle than the general-purpose lanes during the morning hours (6 – 11AM). This also coincides with the morning peak hour duration between 6 to 9 AM when these HOV lanes are in implementation.

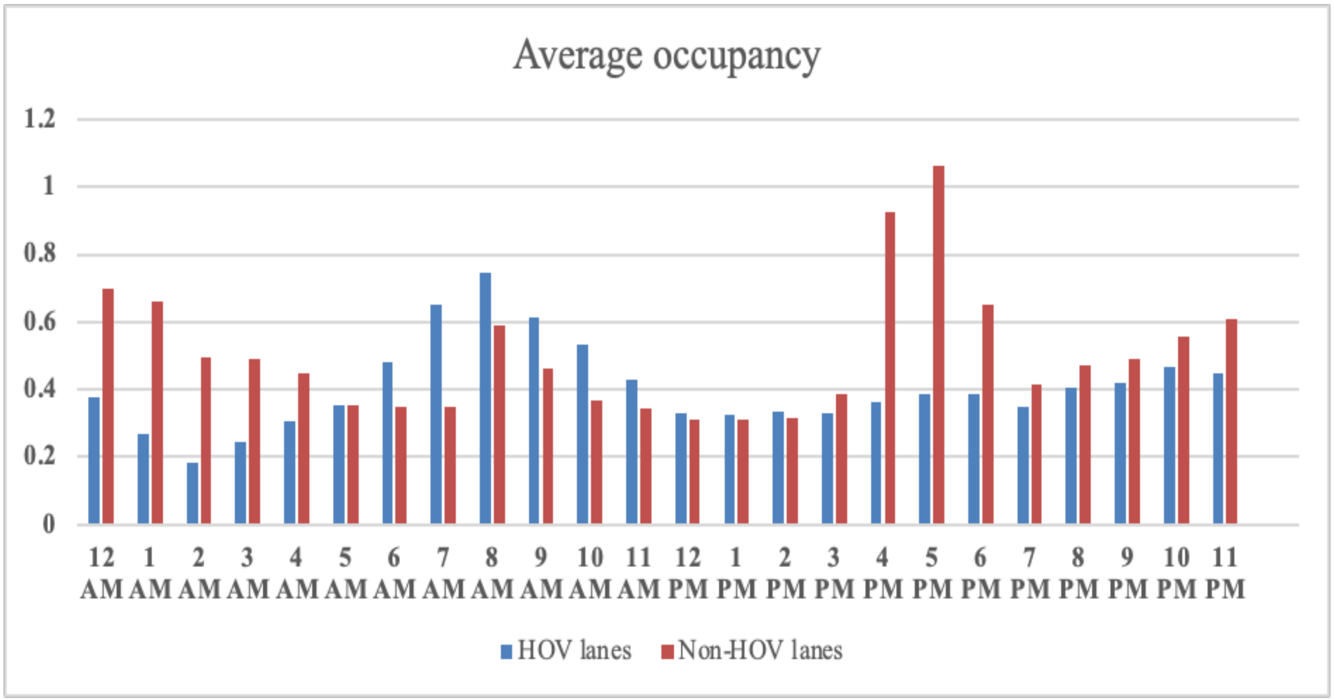

Figure 6-15: Average occupancy of vehicles using each lane on I-270

From the above plot, we determine that the HOV lanes carry 1.9 times more occupants during the morning peak hours (6-9 AM) on I-270. We use this factor (of 1.9) to redistribute the total occupants into the vehicles carried by the freeway, considering that the leftmost lane of the freeway is converted into an HOV-only. We only consider this for freeways in Maryland that have more than two lanes in each direction.

Thus, in a summary of the LOS in Figure 6-16, as we can see with the implementation of the HOV lanes, the LOS improves significantly for all the identified congestion hotspots during the morning peak hours. With the implementation of the HOV-lanes, the share of locations with LOS D decreased from 50 percent to 20 percent whereas the LOS levels B and C increased from 15 percent and 35 percent to 33.33 percent and 46.67 percent.

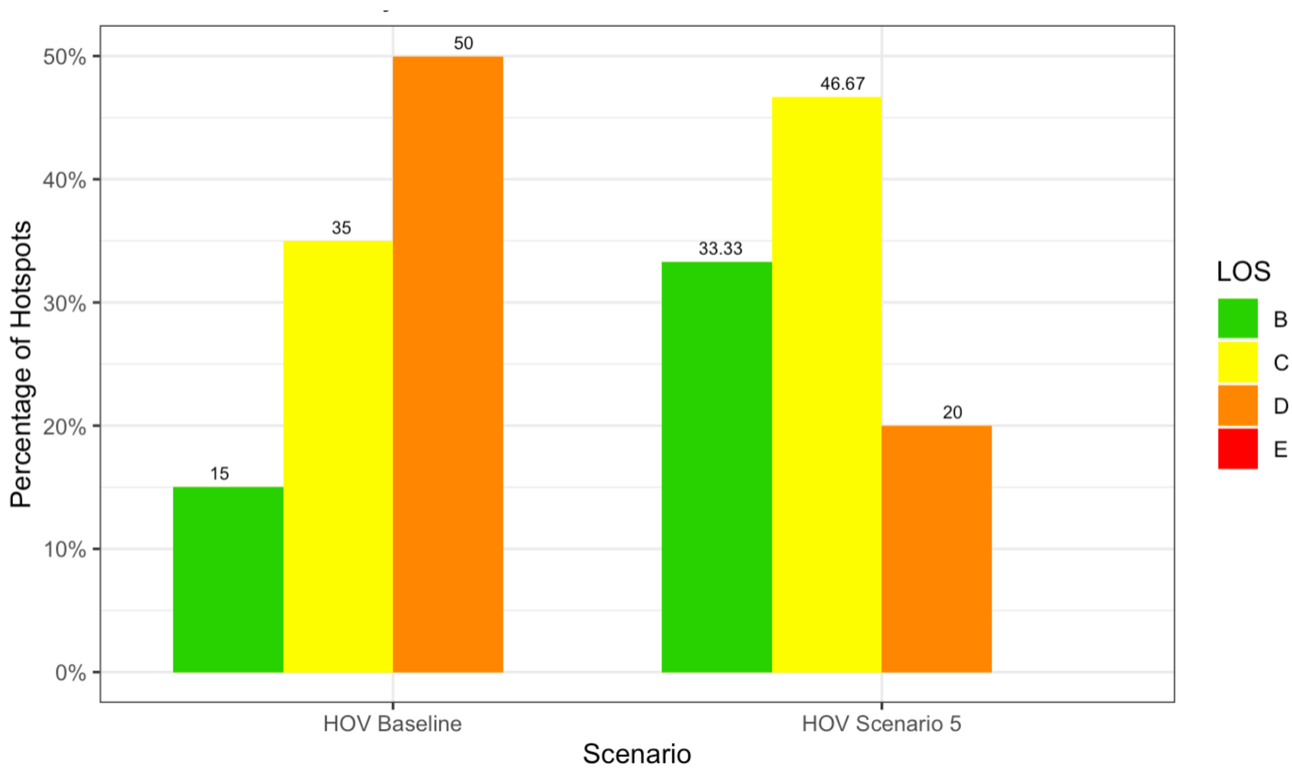

Figure 6-16: Scenario 5- HOV implementation during the morning peak hours (6-9AM)

Chapter 7: Policy proposals

Policies like Telecommuting and HOV lanes provide an effective and a low-cost way for highly populated metropolitan areas to reduce traffic demand and energy consumption if successfully implemented (Lin et al., 2006). Telecommuting has the potential to bring a wide range of benefits to both employers and employees. The two major recommendations of this research are sustainable implementation and promotion of telecommuting and HOV lanes. We also recommend supplementary policies to prevent potential negative effects such as the rebound effect, inequity, and to help maintain a healthy balance for telecommuting. These supplemental policies and recommendations are divided into three main categories. Category A: Reduce non-work vehicle trips, Category B: Reduce work vehicle trips, and Category C: Support for telecommuters.

7.1 Category A: Reduce Non-Work Vehicle Trips

1. Promote online shopping – Our exploratory data analysis in chapter five showed that while work vehicle trips remained low, non-work vehicle trips increased above pre-pandemic levels. Abdullah et al. (2020) investigation further showed that during COVID-19, the primary purpose of traveling significantly changed from work and study to shopping. Work trips reduced from 58 percent before COVID-19 to only 30 percent, while shopping increased from four percent to 44 percent, making it the primary travel purpose (Abdullah et al., 2020). To reduce non-work vehicle trips, we should consider promoting online shopping and

addressing the barriers of ecommerce such as consumer protection, connectivity challenges etc. (OECD, 2020).

2. Remove food deserts and/or encourage delivery of groceries in neighborhoods – A large portion of the non-work-related vehicle trips during the pandemic were made by households to shop for groceries (Martin-Neuninger & Ruby, 2020). Free, fast, and clean grocery delivery options incentivize telecommuters to take less non-work vehicle trips for shopping. Therefore, policies that encourage retailers to offer home-delivery and focus on cleaner freight vehicles for making the last-mile delivery should be investigated to reduce the negative externalities associated with the delivery.

3. Promote active transportation infrastructure – Working remotely from home (telecommuting) can lead to fatigue and may result in an increase in long-distance non-work trips for leisure (Zhu & Mason, 2014). Improving the bicycling and walking infrastructure within the city can help convert a portion of these motorized non-work leisure trips to non-motorized ones.

7.2 Category B: Reduce Work Vehicle Trips

1. Federal government support for telework- Initiatives that foster telework advocacy programs are necessary and should be supported. Telecommuting should also be promoted as a valid TDM and pollution reduction strategy in future transportation and energy policies. Although not in effect, Maryland has enacted

Bill HB73 which provides grants to assist businesses in implementing teleworking policies (*MD - HB73*, 2021). Government agencies such as Department of Energy, Environmental Protection Agency, Department of Transportation, the Council on Disability, etc. can all gain from telework (Lister & Harnish, 2011). Even with existing barriers to promoting telecommuting prior to the pandemic, government agencies were quickly able to set up infrastructure and procedures in place to enable federal employees to continue working from home (Schuster et al., 2020). The government agencies should make use of the existing infrastructure and procedures to encourage a significant portion of federal employees to continue working from home even after the pandemic.

2. Incentivize companies that allow telework- Teleworking is a powerful tool for recruiting and retaining employees who appreciate or need flexible work arrangements and schedules (DBAM, 2021). Programs such as The Telework Exchange, TelecommuteConnecticut, Commuter Challenge in Seattle, 36 Commuting Solutions in Denver, M-ATAC in Washington DC, TelCo etc. incentivize companies to adopt telecommuting. (Lister & Harnish, 2011). TeleworkVA, for example, offers cash incentives to companies that allow employees WFH. Continuing such programs and initiating similar programs can motivate companies to allow telecommuting post-COVID-19 (Pabilonia & Vernon, 2021).

3. Promote ride sharing- HOV lanes are often underutilized and need to carry at least the same amount of people as unrestricted lanes to be fully effective (Veldhuis & Clemens, 2003). Policies and apps such as incenTrip, Uber, and Lyft and other employer and commuter resources that encourage commuters to utilize HOV lanes should also be supported (Chan & Shaheen, 2012; Zhang & Zhang, 2018).

4. Offer Small Business Innovation Grants (SBIR) to inspire technology that supports telework (Lister & Harnish, 2011)

7.3 Category C: Support for Teleworkers

1. Establish standard WFH guidelines- Companies need to set guidelines and training for teleworking to prevent workers from feeling isolated, not supported or overworked. Also, where necessary, companies need to provide the necessary support tools such as computers, internet access, software, etc. (Oakman et al., 2020).

2. Equip people to work remotely- During the initial stages of the pandemic many people lost their jobs, particularly lower income workers as they did not have education or facilities to telework (Couch et al., 2020). Ubiquitous high-speed broadband access should be a priority for successfully promoting telework. Companies should ensure that employees are fully supported with the necessary tools and equipment for remote work. Also office tax credits should be provided for people who WFH part time and employees should be allowed to deduct their home office equipment costs if necessary (Lister & Harnish, 2011).

Chapter 8: Conclusion and Future work

8.1 Conclusion

Telecommuting has become an increasingly popular topic in the public interest ever since the COVID-19 pandemic began. In 2020, we witnessed unparalleled changes in the transportation sector. Roadways that were previously highly congested were suddenly empty during the peak commute periods, as work and school transitioned online. Most teleworkers reported that they get more done and are more satisfied with their jobs as a result of teleworking. The shortened commute decreases employee travel expenses and commuting stress, while enhancing work-life balance. The wide-spread impact of the COVID-19 pandemic presented an opportunity for the transportation policy makers to learn from the change in transportation behaviors, and propose policies in favor of resilient, sustainable, and socially equitable transportation. Rather than spend billions of dollars trying to increase the capacity of roadways, the series of events have shown that reduced travel and vehicle demand can be effective in reducing the congestion and emission issues that the transportation industry faces.

This study investigated two low-cost travel demand management policies: implementing telecommuting and implementing HOV lanes on the performance of roadways in the DMV region. Below is a list of the key findings of this study:

a) The average daily non-work-related vehicle trips fluctuated throughout 2020 while the work-related vehicle trips remained low and did not increase or fluctuate much after the stay-at-home order in 2020.

b) The work- related vehicle trip trend, volume trend, and the %WFH trends were similar. The three trends did not fluctuate or increase significantly after the stay-at-home order which leads to believe there was a nexus amongst them.

c) Prior to the SAH order, less than five percent of the workforce in the DMV was telecommuting. However, at the peak we observed upwards of 50 percent of the DMV population telecommuting.

d) On average there was 18.9 percent decrease in volume between 2019 and 2020, and on interstates there was 28.4 percent decrease in average hourly volume for the locations studied.

e) The peak hours in 2019 and 2020 were 8-9 AM and 3-5 PM respectively and did not change.

f) There was a significant reduction (22 percent) of hourly traffic volume on the freeways.

g) Telecommuting affected morning commute hours more than evening commute hours. During the AM peak hours there was upwards of 20 percent reduction in volume and during PM peak hours there was above 10 percent reduction in volume of traffic.

h) For each increase in percent WFH there is a decrease in the percentage of observed LOS D and an increase in percentage of observed LOS B.

i) With only 20 percent of the population telecommuting, there are no more roadways operating at an LOS E near capacity in Maryland.

j) Converting a lane to an HOV lane during the peak hours has the potential to significantly improve the LOS of the freeways.

k) Teleworking reduces travel demand during typical commute hours, while the implementation of more HOV lanes promotes ridesharing and reduces vehicle demand during commute hours.

While teleworking reduces congestion and emission from vehicles, there are concerns that come with it. Some major concerns covered in the literature review were, equity in a telecommuting work environment, loss of transportation revenues from fuel and cars, and the rebound effect. Chapter seven highlights supplementary policies to ensure teleworking is done properly and supported by both government and private companies.

There are still debates around the future of telecommuting as a viable demand management strategy. To some, theoretically, this solution can never be achieved: people need to travel for work, leisure, running errands, and other purposes (Du et al., 2020). While others say at first glance telecommuting is a simple way of avoiding commuting - especially during rush hour - and of replacing movements across space with virtual interactions (Ravalet & Rérat, 2019).

While the long-term travel impacts of the pandemic are still uncertain as we write, COVID-19 pandemic has dramatically illustrated the need for preparation for future disruptions (Hendrickson & Rilett, 2020). Addressing this issue is not an easy task and requires a rethink of both the supply and demand of transport (Ravalet & Rérat, 2019). How such decisions affect the transportation system will take many years of study (Hendrickson & Rilett, 2020). But for the foreseeable future, many organizations will continue mandating working at home (WAH) (Oakman et al., 2020). Therefore, this research is essential and timely in understanding teleworking as a way to relieve commuter congestion.

8.2 Future work

In this study, we have specified a model based on the mobility statistics for the DMV region. The data for all the states in the United States could be considered for creating such a model in future. The economic and environmental costs and benefits associated with each of the policy measures could also be investigated. Another area of possible research could be exploring the feasibility and acceptance of HOT lanes in Maryland. In this study, we assume that everyone in the study region would have equal access and benefit in an equal manner from the proposed TDM strategies. This study would have gained from investigating equity in demographic group mobility and telework patterns. Further research could focus on investigating other barriers associated with successful implementation of such policy measures.

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