Ways to Consider Driverless Vehicles in Virginia Long-Range Travel Demand Models

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16. Abstract:

Regional travel demand models are an institutionalized element of the transportation planning process and require multiple years to develop, calibrate, and deploy. Because transportation planners are being asked immediately how a new technology, i.e., driverless vehicles (DVs), may affect travel demand, this study, using a case study approach with one particular region, identified how such models can be modified to incorporate the potential impacts of DVs and to answer related questions of interest to stakeholders. The DVs described in this report are presumed to be completely autonomous and are what SAE International refers to as Level 5 vehicles.

A key finding is that it is possible to address some impacts of DVs in the model, such as changes in capacity, mode share, travel by age groups that traditionally have had less access to vehicles, trip length, and sharing of such DVs. Execution of the regional model using these modifications provided answers to some questions of interest; for example, a decrease in capacity during the transition period to DVs could lead to a substantial increase in delay (a 46% increase in vehicle hours traveled [VHT] in the case study area, whereas greater access to DVs by groups that traditionally have not had access to a vehicle suggests only a modest increase in delay (a 3.3% increase in VHT). Incorporation of such impacts into the model can also inform policies; for example, it is possible that the advent of DVs could encourage commuters to seek to avoid parking fees by either sending privately owned vehicles back home or sharing subscription-based DVs. Both situations increased zero occupant vehicle trips in the case study model, but the former increased nitrogen oxide emissions by an estimated 11.64% whereas the latter increased them by 2.08% to 6.65% depending on the manner in which the sharing occurred.

The study recommends that language indicating how DV impacts may be incorporated into existing regional models be added to VDOT’s *Travel Demand Modeling Policies and Procedures* manual when the manual is next updated. Draft language for implementation of this recommendation is provided in Table ES3 in the Executive Summary and in Table 29 in the body of the report.

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FINAL REPORT

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Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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DISCLAIMER

LIST OF ACRONYMS

CBD	Central business district
DV	Driverless vehicle
HBO	Home-based other
HBU	Home-based university
HBW	Home-based work
HDORMU	Home-based university dormitory
ITE	Institute of Transportation Engineers
IX	Internal-external
MPO	Metropolitan planning organization
MTT	Mean trip time
NHB	Nonhome-based
SOV	Single occupant vehicle
TAZ	Transportation analysis zone
TRP	Technical review panel
TPRAC	[Virginia Transportation Research Council's] Transportation Planning Research Advisory Committee
VAMPO	Virginia Association of Metropolitan Planning Organizations
VDOT	Virginia Department of Transportation
VMT	Vehicle miles traveled
VHT	Vehicle hours traveled
VTRC	Virginia Transportation Research Council
XX	External-external
ZOV	Zero occupant vehicle

EXECUTIVE SUMMARY

Introduction

Regional travel demand models are an institutionalized element of the transportation planning process, requiring a multiyear investment from collaborating agencies that rely on model outputs to assist with project prioritization and community visioning. Such models are typically developed over a multiyear period: as of February 2018, a sample of 15 of Virginia's regional models showed that the year of model development was from 2003-2017, with an average age of about 8 years (Virginia Department of Transportation [VDOT], 2017a). This multiyear development period enables participating agencies (e.g., VDOT, localities, metropolitan planning organizations [MPOs], and the Federal Highway Administration) to come to agreement during the interagency consultation process, where details such as zonal population forecasts and the level of geographical detail are resolved. As these models have presumed fairly consistent vehicle characteristics in terms of capacity and appeal to travelers, analysts have had the benefit of creating specific guidance for how these models are to be developed, such as VDOT's *Travel Demand Modeling Policies and Procedures* manual (Cambridge Systematics, 2014).

A challenge identified by the Virginia Transportation Research Council's Transportation Planning Research Advisory Committee (TPRAC) (TPRAC, 2016) suggests that travel demand modeling needs might be shifting dramatically owing to the arrival of what in 2016 were termed "connected/autonomous" vehicles. Such vehicles can reflect any one of several possible gradations of automation as classified by the National Highway Traffic Safety Administration (Campbell et al., 2016) or SAE International (2014). TPRAC (2016) further emphasized that transportation planners are now being asked how to adapt their models to incorporate potential impacts of these vehicles, such as changes in capacity, auto ownership, and travel behavior, in terms of modal shifts or trip length. This report focuses on one class of such vehicles: those that do not require human intervention and are referred to as "driverless vehicles" (Isaac, 2016a).

Yet much remains to be learned about driverless vehicles (DVs) in terms of both their technological capabilities and their impacts on travel choices. As an example of the former, some have forecast that DVs could lead to an increase in capacity; there are estimates of increases from 8% (Campbell et al., 2016) to 500% (Williams, 2013). Further, there is a study underway at the Virginia Transportation Research Council (no date) to determine how DVs may affect freeway capacity. As an example of the latter, some have suggested that the need for parking may shift dramatically owing to vehicles being able to return home (Chakraborty, 2017); others have stated that such an action would be "risky" for travelers who have unexpected schedule changes (Anglyn and Anglyn, 2017). Because the impacts of DVs are not known, Shogan (2016) suggested that "scenario planning" can be used to consider the impacts of DVs where scenarios incorporate these unknowns (e.g., a small versus a large capacity increase or no change versus a large change in parking behavior). Krechmer et al. (2015) strongly emphasized that it is impossible to know which impacts or technologies will transpire, admonishing planners instead to consider a variety of potential scenarios and then update these scenarios as new information emerges.

The problem facing Virginia is that it is not clear how to modify regional travel demand models in a cost-effective manner—that is, without rebuilding and recalibrating the entire model—to incorporate the multiple potential impacts of DVs. The ability to adapt existing models, including those in more rural locations, to consider the potential impacts of DVs was thus the goal of this study.

Purpose and Scope

The purpose of this study was to identify ways in which Virginia might (1) alter existing travel demand models in order to consider the impacts of DVs, and (2) use such models to inform questions of interest to regional planners. Because the behavioral impacts of DVs are not known, the study examined how five sets of alternative futures regarding DVs could be incorporated into the regional model for the Charlottesville [Virginia] area, which includes the City of Charlottesville and a portion of Albemarle County (The Corradino Group, 2009) as a case study for both potential model modifications and alternative futures and, by extension, related policy questions that might arise.

The scope excluded performing original research on DV impacts. For example, Chakraborty (2017) suggested the possibility that DVs could shift to a subscription-based service rather than continue to be privately owned, whereas Anglyn and Anglyn (2017) suggested such a shift was unlikely. Although an objective of this study was to determine how to incorporate these two alternative futures into the regional model, execution of the model does not reveal which future is more likely to transpire. The model can forecast only impacts, such as the change in vehicle miles traveled (VMT), given that one of those futures does occur (and that other assumptions in the model hold true).

Methods

A case study approach was used where the Charlottesville regional travel demand model was used to determine how to incorporate DVs through several iterative tasks. With the assistance of the technical review panel (TRP), the researchers first conducted a literature review regarding ways to consider the impacts of DVs within the transportation planning process, including impacts on capacity, the generation of zero occupant vehicle (ZOV) trips, transit's mode share, sharing of DVs, and use of DVs by persons who lacked access to a vehicle. Then, based on comments made by attendees at a March 2017 Charlottesville Model Design Workshop, an outreach exercise was held on June 9, 2017, where 40 members of the Virginia Association of Metropolitan Planning Organizations (VAMPO) were asked questions regarding the role of DVs. Prior to the exercise, attendees were provided a packet of relevant background information, such as expected 2040 volumes and speeds near two major parking areas (see Appendix A). At the exercise, following short presentations given by staff from the Virginia Transportation Research Council and the Thomas Jefferson Planning District Commission, attendees were divided into groups that ultimately provided types of DV impacts that would be of interest to study further.

Then, based on the literature review, the VAMPO outreach exercise, and comments from the TRP in March, June, July, and December 2017, five types of scenarios were developed and refined:

1. DVs may alter capacity (reducing it based on operator comfort or later increasing it as platoons result).

2. DVs may increase ZOV trips (of privately owned vehicles) as travelers seek to avoid parking fees. In some urban locations, parking lots might be replaced with additional development.

3. DVs may alter transit's mode share, either decreasing it because DVs make auto travel more appealing by comparison or increasing it through shared DVs, which reduce transit's waiting time. DVs might also lead to a willingness by travelers to take longer trips because of increased comfort.

4. DVs may increase ZOV trips through nonfamilial sharing of DVs. This ZOV trip is the distance between the leading trip's termination and the following trip's origin.

5. DVs may increase travel by age groups with traditionally lower access to vehicles such as teens and persons age 65+ (see Appendix B).

Using the Charlottesville regional travel demand model (hereinafter the "Charlottesville model") as a case study and based on ranges of potential impacts of DVs as reported in the literature, the scenarios were incorporated into the model. For example, the first scenario, which involved changes to capacity, may be considered. Because the literature reported that capacity might change by amounts such as a 30% increase (Bierstedt et al., 2014; Childress et al., 2015); a 100% increase (Bierstedt et al., 2014); and a 32% decrease (Le Vine et al., 2015), scenarios that reflected such capacity changes were developed reflecting each of these values. As another example, Childress et al. (2015) suggested that the discomfort of in-vehicle travel time may be reduced by 35% for households having access to a DV. Thus, travel impedances used by the regional model were altered in order to have mean trip times (MTTs) increase 35%. Implementation of these scenarios in the regional model used the Cube travel demand modeling package, with specific changes made, as shown in Appendix C. Table ES1 summarizes the five original scenario categories that were executed in order to consider DVs and then lists a sixth "combined" scenario that includes elements from multiple scenarios and a particular policy tradeoff. In short, the scenarios represented a relatively wide range of alternative futures, with the limitation that not all possible futures would be captured; for example, there is no scenario that includes a 500% increase in capacity, although Williams (2013) noted this possibility.

For each scenario, the impact on VMT, vehicle hours traveled (VHT), and MTT was recorded, as well as performance measures of interest for each scenario. For example, for Scenario 3, which focused on transit, the changes in mode share (i.e., drive alone, carpool, bus, walk, and bike) were examined given that stakeholders had indicated an interest in transit. For capacity-based Scenario 1, the proportion of facilities that were congested (defined as a volume/capacity ratio of 0.80 or higher) was obtained. Because stakeholders had also mentioned an interest in air quality, the potential impacts on nitrogen oxide (NO_x) emissions, a precursor of ground level ozone, was examined: for some scenarios, this emission varies as a function of speed and for passenger autos tends to be minimized at moderate speeds (i.e., generally above 10 mph but below 50 mph). Emissions factors in grams per vehicle mile as a function of speed (California Air Resources Board, 2013) were used in conjunction with assigned volumes from the model. The researchers deliberately did not presume a change in vehicle fuel consumption or emissions properties in order to distinguish the behavioral impacts of DVs from the technological impacts of changes in the vehicle fleet.

Table ES1. Summary of Scenarios

Scenario	Type of Impact	Model Change
1	Driverless vehicles (DVs) may increase or decrease capacity.	Change capacities in the capacity lookup table by -32%, +30%, and +100%.
2	In the short term, persons may choose to send their privately owned DV home rather than park it.	For the home-based work trip, double the origin-destination trip matrix just after the mode choice step. Report the results for drive alone, carpool, transit, walk, and bike modes.
	In the long term, regions may develop parking lots for other uses.	Add a new column to the land use data for the model; this column will show the number of trips in each transportation analysis zone (TAZ). Modify the script to subdivide these trips by purpose.
3	DVs may lead to greater transit use (through a shared DV that takes a person to the transit stop) or less transit use (since the customer chooses to remain in the DV).	In the mode choice step, make these modifications: • *For greater transit use:* if shared DVs are available for the first and last mile, replace waiting time and walking time with 65% of drive time to the transit stop. • *For less transit use:* reduce the disutility of in-vehicle travel time by 35% for the modes of drive alone and carpool.
	DVs may lead to longer trips to the extent that the task of not having to drive increases comfort.	In the trip distribution step, adjust travel impedances (i.e., friction factors for the doubly constrained gravity model or parameter values for the singly constrained gravity model) to increase mean trip time by 35%.
4	In the short term, persons may choose to share DVs, which could lead to an increase in zero occupant vehicle (ZOV) trips if the termination point of the leading trip is not the same location as the origin point of the following trip.	• *High degree of matching:* for a given DV, presume the destination of the leading trip is close to the origin of the following trip (i.e., a high degree of matching) and increase off-network (e.g., intrazonal) vehicle miles traveled (VMT) based on the size of the zone. • *Medium degree of matching:* presume the size of the catchment area is roughly 5 TAZs. Calculate the average length of a ZOV trip based on that catchment area size in a GIS and determine additional on-network VMT that should result. Then, increase the number of nonhome-based vehicle trips to yield this additional VMT. • *Low degree of matching:* repeat the calculations but with a catchment area that is approximately 50 zones in length.
5	DVs may increase trips as some seniors, some youth, and others who do not have access to a vehicle take advantage of DVs.	Add 3 new columns to the land use data for the model showing the percentage of persons age 65+, age 13-17, and age 18-64 in each TAZ. Modify the script to increase the number of trips by purpose for each TAZ based on these percentages as described in Appendix B.
6	DVs may decrease capacity (Scenario 1), lead to greater development in urban areas as parking lots are replaced (latter part of Scenario 2), and lead to additional trips by persons without access to a DV (Scenario 4), but not all vehicles are driverless.	Implement Scenarios 1, 2, and 4, and then modify the model to incorporate two different possibilities: • *DVs are not shared:* for the commute trip, the model reflects that 24.8% of DVs are sent home rather than parked as per the earlier part of Scenario 1. • *DVs are shared:* for the commute trip, the model reflects DV sharing as per Scenario 4 but uses a 24.8% multiplier (see Appendix C) with medium and low degrees of matching affecting the size of the catchment area.

Results and Discussion

Three key modifications were made to the regional model in consultation with the TRP: (1) the trip production rates were adjusted to align with those in the user's manual (The Corradino Group, 2009); (2) a script to obtain the MTT was added; and (3) a feedback loop was connected to ensure that fares were included in the mode choice step as intended. Then, the model was executed for year 2040, and generally this became the base model against which the results in the scenarios were compared with one exception: for Scenario 3, a new base scenario was developed that included a revised multiplier of 100 for the transit fare for the local bus in the utility function. As pointed out by the TRP, although the multiplier was not present in the original utility function, it should have been.

Table ES2 shows the results of the scenarios relative to the base scenario (e.g., year 2040 without DVs). For example, if DVs were to lead to a capacity decrease of 32%, a possibility reported by Le Vine et al. (2015), the model suggests that with DVs, VHT could increase 46% in year 2040 relative to a 2040 base case where no DVs are present. Yet if capacity were to increase by 100% in year 2040, a possibility reported by Bierstedt et al. (2014), the model suggests that VHT could decrease by 13% relative to a 2040 base case where no DVs are present.

For comparisons within a scenario, the results suggest that concerns about the alternative futures do not carry equal weight. For example, in Scenario 1, a capacity reduction attributed to DVs having lowered acceleration rates increases total travel time (VHT) by 46%. By contrast, a capacity increase attributed to DVs potentially having shorter headways reduces travel time, but only by 8% (for a 30% increase) or 13% (for a doubling of capacity). If DVs are shared without a change in occupancy or trip patterns (e.g., a DV makes one trip and then travels without passengers to begin another trip), the empty vehicle will increase VMT. Scenarios 4b and 4c show that this increase might be from 2.3% to 7.3%, depending on the degree to which matching occurs.

For comparisons across scenarios, the results can inform various policy initiatives. For example, the number of ZOV trips may increase through self-parking by a privately owned DV (e.g., the owner sends the vehicle back home or to a lower cost parking area) or a shared DV traveling from one person's destination to another person's origin. Every commuter, regardless of mode, could choose to use a DV, but it is unknown whether such DVs will be privately owned or shared. Scenarios 2c and 4, respectively, suggest that although both situations may increase VMT, the former could increase VMT much more than the latter. For the former, Scenario 2c increased VMT by 12.9%; for the latter, Scenarios 4b and 4c increased VMT by 2.3% to 7.3%, depending on the degree of geographical and temporal matching between a leading trip's destination and a following trip's origin. The scenarios also were informative in that some impacts were not as dramatic as might have been expected. For example, because the number of persons age 65+ is expected to double by 2040, Scenario 5a examined how travel demand might change if all persons age 65+ suddenly had access to a vehicle. Based on extraction of insights from Truong et al. (2017) and Zmud et al. (2016) and data from the Weldon Cooper Center for Public Service (hereinafter "Weldon Cooper Center") (2012), there would be roughly a 15.3%

increase in trips for persons age 65+. That particular scenario leads to an increase in VHT as expected, but as shown for Scenario 5a, the increase is only about 1.5%.

Table ES2. Summary of Scenario Impacts[a]

Scenario		VMT[b]	VHT[b]	MTT[b]
0	Base case	1.000	1.000	1.000
1a	Decrease 32%	1.040	1.460	1.290
1b	Increase 30%	0.990	0.920	0.950
1c	Increase 100%	0.990	0.870	0.910
2a	Replace HBW parking with ZOV trips (drive alone)	1.091	1.160	1.014
2b	Replace HBO parking with ZOV trips (drive alone and carpool)	1.120	1.215	1.023
2c	Replace HBW parking with ZOV trips (all modes)	1.129	1.236	1.020
2d	Convert CBD parking lots to other uses	1.020	1.020	1.010
3a	DVs solve the last mile problem for transit	0.998	0.996	1.001
3b	DVs capture transit market share	1.000	1.000	1.000
3c	DVs make longer trips more appealing	1.256	1.480	1.351
4a	A match is found within the same TAZ[c]	1.005	N/A	N/A
4b	A match is found within nearby TAZs	1.023	1.043	0.997
4c	A match is found but may be several TAZs away	1.073	1.136	0.995
5a	Additional travel by persons age 65+	1.008	1.015	1.000
5b	Additional travel by persons age 13-17	1.002	1.004	1.001
5c	Additional travel by persons of all ages	1.017	1.033	1.001
5d	Double growth in the region	1.388	2.016	1.292
6a	New combined base case	1.108	1.383	1.247
6b	Do not share DVs	1.148	1.507	1.279
6c	Share DVs (low degree of matching)	1.126	1.434	1.250
6d	Share DVs (medium degree of matching)	1.114	1.411	1.254

VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time; HBW = home-based work; ZOV = zero occupant vehicle; HBO = home-based other; CBD = central business district; DVs = driverless vehicles; TAZ = transportation analysis zone; N/A = not applicable because changes in VHT and MTT occur off the network and are thus not captured.

[a] All scenario numbers reflect the doubly constrained model and a base model where VMT = 6,829,605.34; VHT = 167,101.64; and MTT = 20.89 for 2040 except for Scenario 3; for Scenario 3, because of a modification in the utility function for transit (a 100 multiplier for the fare), VMT = 6,828,131.94 and VHT = 167,293.27. MTT was unchanged at 20.89.

[b] Values are relative to the appropriate base case. For example, Scenario 1a led to a 4.0% increase in VMT and a 46% increase in VHT.

[c] Because the sharing occurs within the same zone, the only increase was in off-network VMT, which was 33,910 compared to a base scenario of 6,829,605.34, which yields an increase of 0.5%.

Interpretation of Results to Address Stakeholder Interests

The results in Table ES2 are useful only to the extent that they inform concerns raised by stakeholders—that is, the value of a model derives from its ability to help planners inform stakeholders of the impacts of potential decisions (Meyer and Miller, 2013). The ability to incorporate alternative futures into legacy regional planning models can help provide insights into some, but not all, local issues of interest to stakeholders for this particular region:

- *Stakeholder concerns about the transition period during which DVs might result in a reduction in capacity (Scenario 1a) or longer trips (Scenario 3c) are justified.* VHT increases by 46% if capacity drops. A similar increase (48%) is possible if increased comfort leads to longer trips as per Scenario 3c. Both the supply impact (a drop in capacity) and the demand impact (a willingness to make longer trips) are possible but not proven based on the appropriate literature, i.e., studies by Le Vine et al. (2015) and Childress et al. (2015), respectively, but they suggest that possible reductions in capacity (when DVs are first introduced) and possible increases in trip length (resulting from increased comfort of DVs) may merit attention. By contrast, additional travel by persons without access to a vehicle increases VHT by only 3.3% (Scenario 5c).

- *There may be ample development opportunities in the central business district (CBD) and adequate facilities if capacity remains unchanged.* Planners in this region wanted to know about potential impacts on development if parking was no longer needed. Scenario 2d examined how conversion of parking lots in the CBD (e.g., in the Charlottesville downtown area) to other land uses could affect travel conditions, assuming new development resulted. (Scenario 2d reflects a situation where net new development at these former parking lots occurs, rather than development being transferred from other locations.) The results indicated a 2% increase in VHT overall and speed decreases of no more than 5 mph in the downtown area (Scenario 2d). Of the 191 links in the CBD, 1 had a speed increase of a bit less than 1.5 mph, 36 had speed increases of less than 1 mph, 126 had speed decreases of less than 1 mph, and 16 had speed decreases between 1 and 5 mph. The analysis, based on a geographic information system (GIS), showed substantial land development potential in the downtown areas.

- *DVs can potentially increase transit's mode share (an outcome of interest to stakeholders)—but the impacts are nuanced.* Scenario 3a showed that DVs have the potential to increase transit's mode share from about 0.26% to 3.36% of commute trips if they eliminate transit waiting time and increase the ability to travel from the origin and destination to the transit line. This impact is not large in absolute terms, but in relative terms it is, potentially a 12-fold increase in transit's mode share. Yet DVs might also make auto travel more appealing. Again, the impacts are nuanced: the changes in absolute shares were modest, with mode shares for drive alone, carpool 2, and carpool 3+ increasing from 93.86% to 94.14% as per Scenario 3b. Yet the greatest impact for Scenario 3b was on nonmotorized modes: whereas transit trips decreased by about 5%, bicycle trips decreased by about 6%.

- *Emissions are affected but to varying degrees, which may suggest a relevant policy role regarding sharing and not sharing of DVs.* Stakeholders had mentioned an interest in air quality impacts. Generally, induced travel will increase emissions, but not all types of induced travel are of equal concern. Based on Scenario 5c, an increase in travel by persons in all age groups who presently do not have access to a vehicle increases NO_x emissions by 1.51%. If empty DVs are sent back to their origin rather than parked and all commuters follow this practice, NO_x emissions increase by 11.64% (Scenario 2c). If longer trips become more feasible because of DVs offering increased comfort (Scenario 3c), NO_x emissions increase by 21.65%. Thus, changes in behavior because of additional vehicle access increases NO_x emissions slightly (by less than 2 percentage points) by 1.51%—but longer term

> behavioral changes are much more problematic, with NO_x emissions increases that are more than 10 times that amount. How can emissions be reduced? The contrast between Scenarios 2c and 4 suggested an insight: the 11.64% increase in NO_x emissions from Scenario 2c (no sharing) becomes an increase of only 6.65% with a low degree of matching in Scenario 4c—or even a smaller increase of 2.08% if there is a high degree of matching between leading trip destinations and following trip origins as per Scenario 4b. Such contrasts among Scenarios 2c, 4b, and 4c potentially inform a policy initiative of public support for sharing DVs, rather than privately owning DVs, if NO_x emissions reduction is a priority.

Five Caveats for Modifying Legacy Regional Planning Models to Incorporate DVs

The first caveat is that not all questions of interest to stakeholders can be addressed through modifications to the model. In some cases, the question may be beyond the scope of a regional travel demand model depending on how the question is framed. One example is the manner in which DVs should affect the design of pickup and drop-off lanes at businesses that will attract many DV trips. If congestion (or lack of congestion) at such DV lanes will have a similar effect on travel behavior as congestion on other parts of the roadway network, the access time can be modified for the zones containing these businesses; such access time can be reflected in the friction factor (for the doubly constrained gravity model) or the zone-to-zone travel time (for the singly constrained gravity model). If, however, there is a belief that travelers will not alter their behavior and will travel to or from a particular zone regardless of congestion at such DV lanes, some additional off-network processing must be performed to calculate the time savings (or time loss) in a manner comparable to what was done with Scenario 4a.

The second caveat is that in some cases, the question is within the scope of the model but may point to a need for further study. For instance, the sharing of DVs may be considered: if motorists will seek to avoid parking the vehicle anywhere but at home, sharing of DVs by commuters rather than a doubling of work trips is clearly preferred if reducing the increase in VMT is desired. However, a comparison of Scenarios 2c and 4c suggested that this sharing yields a more dramatic reduction (i.e., even with a poor degree of matching, sharing increases VMT by 7.3% compared to not sharing, which increases VMT by 12.9%), whereas a comparison of Scenarios 6b (no sharing) and 6c (sharing with a poor degree of matching) suggested that the corresponding VMT increases are 14.8% and 12.6% (less of a difference than was the case between Scenarios 2d and 4c). These results are not contradictory, as combined Scenario 6 presumed a lower penetration rate of DVs than did Scenarios 2 and 4, but these results show that as knowledge about future impacts becomes clearer, there can be a need to examine some impacts more closely. In this particular example, such impacts include vehicle penetration rates and the impacts of changes in capacity on different facility types.

The third caveat is that the sensitivity of the model to changes in travel impedance (such as capacity changes in Scenario 1 or transit attractiveness in Scenarios 3a and 3b) is influenced by whether the trip distribution step uses a singly or doubly constrained gravity model. The original Charlottesville model is doubly constrained such that forecast attractions and computed attractions are equal; this is not normally the case for a singly constrained gravity model. Assuming that forecast productions are required to be equal to given productions after the trip distribution step is executed, selection of the doubly or singly constrained version depends on the extent to which there is greater confidence in forecast attractions or transportation impedance. Both models were tested in this study and generally yielded similar trends; for example, in both cases, an elimination of waiting time for the local bus could increase transit's mode share by about 3 percentage points in Scenario 3. There were a few cases, however, where the singly constrained gravity model showed a greater magnitude of change than the doubly constrained version or showed different results. For example, redevelopment of parking lots in the CBD in Scenario 2 increased total VHT by 4% (for the singly constrained model) compared to the 2% as reported for the doubly constrained version. Another example is the impact on NO_x emissions: for the singly constrained gravity model only, Scenario 1a (a decrease in capacity) actually shows an improvement. The reduction in capacity (and hence speeds) may be associated with a 2.51% decrease in emissions—owing to the parabolic relationship between emissions rates and speeds (Figure ES1).

The fourth caveat is that the modeler must decide what scenario is plausible. For instance, Scenarios 2a, 2b, and 2c reflect a case of a commuter sending the empty DV back home. A more moderate scenario might be that only commuters who work in areas with expensive parking exhibit this behavior and, further, that they send the DV to closer-in parking locations. A more extreme scenario might be the case where this use of empty DVs occurs not just with commute trips but also home-based other trips.

The fifth caveat is that the impacts of DVs are generally not as important as key socioeconomic parameters that drive the model. For example, if the region's population and employment doubled unexpectedly (Scenario 5d), VHT would increase by 102% and NO_x emissions would increase by 34.8%—easily dwarfing the increases in almost all of the other scenarios discussed herein.

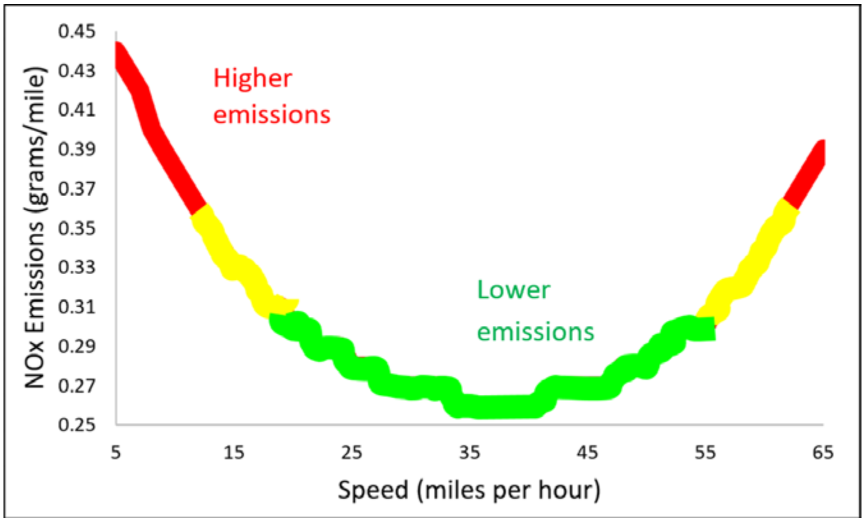

Figure ES1. Impact of Speed on Emissions. Red, yellow, and green colors signify areas of higher, moderate, and lower emissions, respectively. Drawn from data from California Air Resources Board (2013).

Applicability to Other Virginia Locations

Because the results presented here are specific to the case study region, the impacts shown in Table ES2 are not necessarily generalizable to all other locations, just as stakeholders elsewhere may have concerns other than those reflected in the scenarios listed in Table ES1. However, the practices herein—that is, the modifications to the travel demand model made here—can be replicated elsewhere in Virginia. The approaches suggested indicate how transportation agencies can begin to incorporate potential impacts of DVs replacing conventional vehicles into their existing modeling efforts—just as those agencies periodically examine other types of unexpected changes in land development, regional growth, and the transportation network. Because of the uncertainty associated with DVs (e.g., whether they will lead to longer trips), the scenario-based approach used in this study is one way to examine potential impacts relatively quickly.

Such a quick determination of impacts can then support further study of potential action steps as more information about impacts becomes available. For instance, for this particular region, it was interesting that whereas potentially longer trips because of DVs providing greater comfort (Scenario 3c) could increase VHT by 48%, redevelopment of downtown parking lots (Scenario 2d) increased VHT by only 2%. If the experience at other locations suggests that the trip-lengthening impacts in Scenario 3c are likely to occur, a policy response could be to look at local land use policies that would support redevelopment in a central location, potentially to offset the likelihood of longer trips.

Conclusions

- *There are several ways to alter existing travel demand models to address DV-related topics of interest to regional planners*. Examples include the following:

  — Alter the capacity in the capacity lookup table (to examine impacts of DVs having shorter headways that can increase capacity).

  — Adjust the friction factors or the travel impedance parameter (to examine how increased comfort of DVs may lead to longer trip lengths).

  — Modify the utility function in the mode choice step (to examine how a system of shared DVs that reduced out of vehicle waiting time could affect transit use).

  — Increase trip generation rates for certain zones based on forecast change in age groups (to examine how increased access to DVs might affect travel by persons without access to a vehicle, such as teens without a driver's license).

  — Increase trips in the origin-destination vehicle matrix that follows the mode choice step (to examine the impact of privately owned DVs being sent home empty rather than parked for the day at the place of employment).

  - In conjunction with a separate GIS-based analysis, increase nonhome-based trips (to examine the impact of shared DVs traveling from the leading person's destination to the following person's origin).

- *For the purposes of discussing DVs, scenario planning can generate useful discussion even if the model inputs are uncertain, and this discussion may proceed in a qualitative or quantitative manner.*

  - *As a qualitative example,* when this work began, MPO staff indicated in March 2017 that they were interested in knowing how DVs might affect parking. Because the parking-related scenario had not been developed at the time the MPO expressed an interest, the research team put together an outreach exercise showing the degree to which parking might be affected if DVs led to a doubling of all trips. Despite this model input (doubling all trips) being different from a later model input (doubling only commute trips), the participants in the June 2017 outreach exercise were able to provide areas of concern that were later used to refine model scenarios.

  - *As a quantitative example*, uncertainty in the utility function did not seem to affect the results dramatically provided the model was executed in a consistent manner. The following question may be used as an example: If DVs eliminate waiting time for transit and also reduce walk time, what would be the impact? The answer based on the doubly constrained model is either (1) DVs could increase transit's mode share by 3.10% (e.g., raising mode share from 0.26% to 3.36% as shown for Scenario 3a) or (2) DVs could increase transit's mode share by 2.97% (e.g., raising mode share from 0.39% to 3.36% as shown when the original utility functions were used for Scenario 3a). The answer based on the singly constrained gravity model is that DVs could increase transit's mode share by either 2.59% or 2.71%, depending on whether the utility function included the "100" multiplier for local bus fares. In sum, the model suggests that DVs have the potential to raise transit's mode share by about 3 percentage points under a scenario where the waiting time is eliminated and the access time is replaced by a DV, which, in turn, has a 35% reduction in discomfort compared to driving to the stop in a conventional vehicle.

- *Some, but not all, policy-related questions can be examined by the regional model, and those that can be examined have varying levels of difficulty. Table 4 in the full report shows that although some issues of interest to stakeholders are not easily addressed with the model (e.g., curbside access management), other macroscopic questions (e.g., the impact of DVs affecting capacity) are feasible within the modeling structure. The effort required to implement the issues that are feasible will vary (meaning that the simplest changes can be started first). For example, only a few person hours were required to modify the capacity in the lookup table, with most of that time being used for conversions between the various database formats. By contrast, knowledge of the proprietary scripting language was necessary in order to increase trips for the population age 65+ and both scripting and calibration procedures were required to develop an appropriate singly constrained gravity model.*

- *The regional model may be used to prioritize areas of concern to local stakeholders. For this region in particular, incorporation of DVs yielded the following observations in response to concerns identified by VAMPO attendees.*

  - The model suggests that if parking is not needed, there is substantial land development opportunity in downtown areas. Scenario 2d suggests that parking garages and lots in the downtown area, not including street parking, have roughly 3.4 million square feet of redevelopment potential in the downtown area—and the model suggests that the existing transportation network may be able to accommodate this development.

  - Concerns about the transition period during which DVs might result in a reduction in capacity are justified. VHT was estimated to increase by 45% for the doubly constrained gravity model. By contrast, the model showed that the impact of additional travel by persons who had not had access to a vehicle—another potential concern—had a far less detrimental impact on performance: VHT was estimated to increase by only about 1%.

  - The impact of DVs being shared versus not shared is substantial. With regard to the commute trip (i.e., home-based work purpose) only, for the doubly constrained gravity model, if DVs are not shared, VMT increases by 12.91% and if DVs are shared, VMT increases by 2.33% to 7.26% depending on whether there is a moderate degree of matching (e.g., the termination of one person's trip and the origin of the next person's trip is a few transportation analysis zones apart) or a low degree of matching (e.g., the DV must traverse many zones). A high degree of matching among shared DVs would increase VMT by only one-half of a percentage point.

  - The impact on other modes is not substantial in absolute terms but is substantial in relative terms. A transit-favorable scenario suggested DVs can modestly increase transit's mode share from a current value of roughly one-fourth of 1% to more than 3%. Although this range is small in absolute terms, in the model it reflects a 12-fold increase in transit's mode share. Further, with transit's mode share in the model being relatively low, the mode share appeared unlikely to drop substantially; however, a competing scenario where DVs offer increased comfort and hence willingness to travel could reduce the nonmotorized mode share by about one-fourth of a percentage point.

  - If vehicle types do not change, emissions may increase, but the increases would be higher for nonshared DVs than for the case of induced travel by persons who do not have access to a vehicle. The worst-case scenario for commuters choosing to send DVs back home to park increases NO_x emissions by 11.64%—and this increase results from just a change in behavior for a single purpose (the home-based work) trip. By contrast, an increase in DV use for persons who do not have access to a vehicle is estimated to increase NO_x emissions by 1.51%.

- *Socioeconomic parameters—population and employment—continue to be of critical importance for the model. Of all the results presented here, the most dramatic change in absolute percentages resulted from a population and employment increase of 100%: Scenario 5d showed that VMT and VHT increased by 39% to 40% and 102% to 116%,* *respectively. The ranges reflect the use of the doubly constrained or singly constrained gravity models.*

- *The aggregate performance measures may mask important distinctions in more detailed performance measures. The researchers had initially expected to focus on three aggregate measures of performance: VHT, VMT, and MTT. However, for some scenarios, differences in these measures were slight—yet the scenario demonstrated an impact in other areas. Notably, for example, although the transit-favorable Scenario 3a showed a drop of about 0.20% in VMT or 0.37% in VHT, the mode shift—an increase in transit's mode share from 0.26% to 3.36%—was far more dramatic. Other modal shifts were also of interest: in Scenario 3b, which asked a question opposite to that in Scenario 3a (i.e., what if the increased attractiveness of DVs results in them taking market share from transit), although the number of transit trips decreased slightly, the number of nonmotorized trips decreased by about 20 times that amount.*

Recommendations

1. *VDOT's Transportation and Mobility Planning Division should consider adding material regarding ways to incorporate DVs in VDOT's Travel Demand Modeling Policies and Procedures manual* (Cambridge Systematics, 2014) *when it is next updated. A proposed draft of that material is shown in Table ES3, although it may be modified by the TRP or others updating the manual.*

Table ES3. Proposed Additions to VDOT's *Travel Demand Modeling Policies and Procedures* Manual

Section (Title)	Excerpt of Current Text[a]	Potential Additional Text[b]
2.1 (Purpose and Need for Modeling in Transportation Planning Analysis)	[Lists examples such as] "Evaluation of the effects of transportation and planning policies (such as pricing and land use)."	[Add this example] "Evaluation of potential demand and supply impacts of new technologies, such as driverless vehicles."
2.4.2 (Major Revisions)	"The major difference between major revisions and model development is that major revisions do not result in significant changes to the model structure."	"For example, some of the ways to incorporate driverless vehicles into alternatives scenarios, such as changing capacities and altering parameters for the waiting time, do not entail a major revision in the model structure. Others, such as adding a new mode, may constitute such a major revision."[c]
4.1.3 (Transportation Networks)	"Networks for other scenarios, such as Vision Long-Range Plan (VLRP) and interim years other than those prepared for by air quality conformity, may be prepared but are not required."	"For example, for a scenario with driverless vehicles, a new scenario network might entail any combination of the following: • Altered capacities in the capacity lookup table for all or some functional classes[b] • Altered parameters for the utility function for some or all transit and highway modes • Altered population and employment values to reflect new development • Altered friction factors or impedance parameters to reflect greater ease of travel."

Section (Title)	Excerpt of Current Text[a]	Potential Additional Text[b]
	"An example of a fictitious capacity lookup table is shown in Table 4.11." [The table shows that in the central business district, freeways have a capacity of 1,600.]	"For example, if literature suggests that driverless vehicles might increase the capacity of freeways by 30%, then an alternative scenario to include the arrival of such vehicles would increase the capacity of freeways in the CBD from 1,600 veh/hr/lane to 2,080 veh/hr/lane."
4.1.2 (Land Use / Socioeconomic Data)	"Local agencies are responsible for the base-year and forecast land use data necessary for travel demand forecasting."	"Local agencies may wish to consider multiple forecasts for land use data. For example, to consider driverless vehicles, an agency might wish to have an additional scenario where parking lots in the CBD are converted to other land uses."
5.1.1 (Trip Purposes)	"Home-based school (HBSc) travel also is unique in terms of travel modes (since most students are too young to drive and some are so young that they require escorting)."	"It may be appropriate to increase certain types of trips in modeling alternative scenarios if new technologies will provide greater access to vehicles than is presently the case. For example, a scenario might increase the number of HBSc trips by vehicle for persons age 13-17 to account for high school students who do not have access to a vehicle but who can travel unescorted."
6.1.4 (Singly versus Doubly Constrained Models)	"There is no consensus on best practice concerning whether it is always better to have a singly constrained or doubly constrained trip distribution model."	"MPOs may wish to execute the model twice—once using the doubly constrained gravity method and once using the singly constrained gravity method—to determine if the impacts of driverless vehicles vary substantially between these two methods."
9.1.2 (Modes)	"Auto can be segmented into single-occupant vehicles (SOV) and high-occupancy vehicle (HOV) . . ."	"and zero occupant vehicle [ZOV] if the model considers either (1) the replacement of parking with ZOV trips or (2) shared driverless vehicles. The latter can be implemented by increasing NHB trips on the network or may be an off-network calculation."
13.2.2 (Long- and Short-Range Transportation Planning)	"This often involves scenario analysis, where groups of projects are analyzed together to determine their cumulative impacts over the long term."	"Scenario analysis may also include consideration of alternative futures. For example, one scenario might presume no major changes in vehicle technology, and another scenario might presume driverless vehicles by year 2040."
13.2.4 (Evaluation of Transportation Improvements and Infrastructure Investments)	"There are some types of projects for which models may not be as well suited for analysis [and then examples are listed]."	"For example, evaluating the needed increase in curbside access required by large numbers of driverless vehicles at a particular commercial location is better addressed through microscopic models than through regional travel demand models."

[a] From VDOT's *Travel Demand Modeling Policies and Procedures* manual (Cambridge Systematics, 2014).

[b] The proposed additional text in the third column would follow the sentence in the second column.

[c] For examples of ways to revise a legacy model, see Table ES1.

FINAL REPORT

WAYS TO CONSIDER DRIVERLESS VEHICLES IN VIRGINIA LONG-RANGE TRAVEL DEMAND MODELS

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INTRODUCTION

Regional long-range transportation plans are developed with a 20-year horizon; the long period allows for careful consideration of infrastructure investments based on expectations of changes in activity (e.g., population, employment, land development, and other factors that generate transportation demand) and infrastructure (e.g., highways, guideways, bus service, operational improvements, and other ways of satisfying this demand). Within metropolitan areas, such long-range regional plans are supported by travel demand models, which forecast how various transportation improvements may affect regional measures, such as vehicle hours traveled (VHT), as well as more local measures, such as how an improvement at a given location may affect congestion levels. At present, Virginia has 13 such regional models, serving large metropolitan areas (e.g., the Washington, D.C., metropolitan region, which includes Northern Virginia and suburban Maryland with a population of 6.3 million) and smaller areas (e.g., the Danville model serves an area of roughly 70,000) (Virginia Department of Transportation [VDOT], 2017a).

The Role of Travel Demand Models in Transportation Planning

Travel demand forecasts from such models may influence project selection, a process that entails the participation of both metropolitan planning organizations (MPOs) and VDOT. For example, a candidate project that reduces transit headways in an urban area may be forecast to shift a certain percentage of motorists to transit. The resultant reduction in vehicles on certain links will be forecast to have a reduction in crash frequency, and the anticipated growth rate in vehicle volumes will help determine how the candidate project affects person hours of delay. Virginia’s statewide prioritization process uses the results of regional travel demand models, such as forecasts of vehicle miles traveled (VMT) and VHT, to help evaluate how candidate projects affect safety, congestion, and modal choices (Commonwealth Transportation Board, 2016). Such models are also used regionally: the long-range transportation plan for the Richmond Region (Richmond Area MPO, 2014) used these forecasts to determine future projects such as improved signals on Midlothian Turnpike (Route 60), the addition of another lane to Route 360, and sidewalk construction to improve school travel in Hanover. Models also inform strategic planning (e.g., determine how rail improvements may support freight) and community visioning (e.g., examine the impact of land use policies on the highway network) (Meyer and Miller, 2013).

Generally, these transportation plans have presumed fairly consistent vehicle characteristics in terms of capacity, ease of use, and appeal to users. For example, in long-range transportation plans, factors that typically influence the choice of owning a vehicle are household size, income, and location, with higher rates of auto ownership in rural locations that offer fewer modal choices. Further, when there have been changes to engineering or planning calculations that use vehicle characteristics, such changes have tended to be incremental. For example, in the current *Highway Capacity Manual* (Transportation Research Board, 2010), which is periodically updated and in which the information provided can inform the capacities used in long-range transportation plans, the ultimate (Level of Service E) capacity for an idealized interstate highway segment is 2,400 "passenger cars per hour per lane"; however, the 1985 *Highway Capacity Manual* used a maximum value of 2,000 passenger cars per hour per lane (Garber and Hoel, 1988). The units of "passenger cars per hour per lane" represents a conversion of other types of vehicles, such as trucks, buses, and recreational vehicles, to "passenger car equivalents" or "PCEs" based on the grade of the freeway segment in question (Transportation Research Board, 2010).

Potential Changes in Travel Demand Models Because of a New Vehicle Type

Yet a research need identified by the Virginia Transportation Research Council's (VTRC) Transportation Planning Research Advisory Committee (TPRAC) (TPRAC, 2016) suggests that contrary to this quarter century of relatively incremental change, transportation planning might be poised to shift dramatically, owing to the arrival of what at the time were described as "connected/autonomous" vehicles. This research need further articulated that although additional information is forthcoming, planners need to understand when and how to consider such vehicles now. That is, stakeholders who participate in the transportation planning process may now ask questions such as the following: What will be the impacts on highway capacity in two decades? Will such impacts affect all functional classes of roadways in a roughly similar manner? Should behavioral expectations for auto ownership be modified? Would increases in the penetration of such vehicles be expected to reduce demands for new infrastructure (given potential capacity increases) or might such vehicles increase demand for infrastructure (if this mode reduced transportation impedance from what is faced at present)?

Although the initial terminology used by TPRAC (2016) was "connected/autonomous," additional literature illustrates that there is not a single definition for this terminology. The National Highway Traffic Safety Administration defined five levels of functionality that automated vehicles can achieve (Campbell et al., 2016). Levels 0, 1, and 2 provide warning systems and very limited automation of a few driver functions: Level 0 provides information only (e.g., a warning to the driver when a vehicle is about to move from a lane or hit another vehicle), and Levels 1 and 2 automate only a few specific functions (e.g., adaptive cruise control or assistance with staying in the lane or braking in time) that absolutely require driver intervention. Level 3 automates operation under certain circumstances with capabilities such as interpreting the communication received from a traffic signal and require some supervision for complex situations. Level 4 has fully autonomous operation (Campbell et al., 2016). SAE International (2014) provides six levels of automation, differentiating between "high automation" at Level 4 and "full automation" at Level 5. Urmson (2015) used the term "self-driving vehicles"; Isaac (2016a) used the term "driverless" vehicles and explicitly pointed out that such vehicles "are capable of sensing their environment and navigating roads without human input," with such vehicles corresponding to SAE Level 5. Based on Grier (2016) and Isaac (2016a), this report uses the term "driverless vehicle" or "DV" and explicitly focuses on vehicles that correspond to SAE Level 5, i.e., vehicles that do not require human intervention.

Substantial literature has been devoted to including such vehicles in transportation plans, recognizing that such vehicles may affect a variety of improvements such as long-term infrastructure leases; for example, Pascale (2016) noted the almost 60-year lease for the Midtown Tunnel in Hampton Roads, Virginia. Hedden (2015) suggested that nonrecurring congestion may decrease substantially and that the shared economy will dramatically alter the extent to which vehicles are owned, with fewer capacity expansions being needed. Bertini and Wang (2016) suggested that regional models may need changes in trip routes, vehicle ownership, and work/residence locations. The literature suggests ways to incorporate DVs into regional models. One approach is to make large-scale changes; Zhao and Kockelman (2017) combined the trip distribution and trip assignment steps in the Austin [Texas] MPO model, replacing the gravity model with a simplified multinomial logit model and reducing the modes from 20 to 4. Another approach is to replace the more macroscopic travel demand model with the use of microscopic techniques to capture driver behavior better, as noted by Campbell et al. (2015). To be clear, therefore, the literature makes the case for new approaches for estimating travel demand, where such new approaches could replace existing travel demand models entirely.

A Case for Modifying Existing Regional Models

There are at least three considerations that may affect the decision to modify rather than replace regional models, modifying such regional models for the purposes of considering these new types of vehicles.

First, such models are typically developed over a multiyear period. A sample of 11 of Virginia's regional models as of February 2018 showed that the year of model development was from 2003-2009 inclusive for 7 models, with the remaining 4 models being developed from 2013-2017 (VDOT, 2017a). At present, two additional models are "in progress": one was last updated in 2009. Part of the reason for the long model development time is that such models require a substantial amount of institutional knowledge in order for modifications to be made. Although such models may use well-known analysis techniques found in standard texts, regional models are the product of many individual choices of the analyst who built the model. Examples are the method for disaggregating zone level socioeconomic data for the purposes of trip generation, the manner in which feedback among model components is established, the selection of the volume delay function, and the parameters used for the utility choice expressions (The Corradino Group [Corradino Group], 2009). In order for someone unfamiliar with the development of the model to make modifications, some fairly detailed documentation or institutional knowledge is needed.

Second, the calibrated base case model reflects assumptions that result from the interagency consultation process. For example, agencies may have invested time agreeing on key elements that might affect air quality determination, such as vehicle ownership rates (Federal Highway Administration, 2015), number of zones, and estimation of VMT on facilities not represented in the network (Michiana Area Council of Governments, 2007). Agencies may also have discussed how they would represent concepts such as differentiation by time of day (e.g., is there a single 24-hour period only, a 24-hour model plus a single peak period, a separate morning or evening peak period, and so forth); the manner in which freight is included (or not included) in the model; the source of auto occupancy rates for the various trip purposes; and the percentage of trips that may occur during various periods (Cambridge Systematics, Inc., et al., 2012). As an illustration of the diversity of choices in the model, Cambridge Systematics, Inc., et al. (2012) examined the value of time for nonwork trips that either began or ended at home based on the coefficients for eight mode-choice models. The implied value of 1 hour ranged from very low values (21 cents or less for three models), to moderately low values (48 and 80 cents for two models), to moderately higher values ($1.40 and $3.69 for two models). Although such values reflect on data either collected for the model or borrowed from other sources, they represent the product of interagency coordination.

Third, outside entities may already have processes that rely on the existing regional model. An example is Virginia's Smart Scale statewide prioritization process (Commonwealth Transportation Board, 2016). The Smart Scale process explicitly cites regional travel demand models as one potential source for the number of "peak period person hours of delay" for a particular project. Regional models are also cited as a source for two other measures: person throughput (which can include vehicle travel as well as travel on other modes) and safety, since regional models provide VMT for various scenarios that inform a different measure, i.e., the equivalent property damage only crashes, which in part use VMT. The Central Virginia Regional Planning Organization (2015) awarded points to projects in part based on the volume/capacity ratio for the project as reflected in the travel demand model (e.g., for a project that could increase capacity, scores of high, medium, and low were established for three ranges of the volume/capacity ratio: 1.10 or more, between 0.8 and 1.09 inclusive, and less than 0.8). Although capacity can be measured in a variety of ways, it is clear in this context that what mattered was the impact on the volume/capacity ratio within the regional model.

A Case for Scenario Planning

Regardless of the modeling approach that is chosen, Krechmer et al. (2015) strongly emphasized that it is impossible to know which technologies—or which impacts—should be expected in the future. Instead, planners should consider a variety of potential scenarios and then update these scenarios as new information emerges, leading Krechmer et al. (2015) to state the following:

> Long-range planning activities may shift to development of "alternative futures" that make different assumptions about technologies, market adoption, and impacts on the transportation system. These assumptions would then be reviewed on a regular basis and the long-range plan modified based on actual developments.

Shogan (2016) also indicated that “scenario planning” can be used to consider the impacts of DVs, where scenarios could consider the factors such as the impacts on capacity; a supply measure; adoption rates (as previously discussed); vehicle occupancy; and, perhaps most challenging of all, how persons would respond to these new options. Twaddell et al. (2016) explained that scenario planning can incorporate “potentially radical shifts in conditions over which local, regional, and State agencies have little or no control.” An example is the introduction of new vehicle technologies and the resultant behavioral shifts in response to those new technologies. One location cited therein that used scenario planning—Baltimore—showed the necessity of considering alternative futures, where, during a scenario planning exercise with stakeholders, two points of view were expressed regarding future vehicle technologies: (1) they might improve congestion, and (2) they might lead to “increased ‘sprawl.’” Although these two points are not necessarily contradictory, the Baltimore Metropolitan Council (2016) noted that “opinions were divided” on this topic. In their consideration of how “self-driving vehicles” might alter the future, Brenden et al. (2017) considered alternative futures not just for technology but also for public behavior: although one scenario entailed strong public support for sharing of vehicles, another envisioned a future where the desire to own a vehicle increased.

Although multiple alternative futures may thus be one important component of scenario planning, the Federal Highway Administration (2017) noted also that scenario planning should have an active public involvement component, where stakeholders both (1) see their value incorporated into the planning process and (2) are informed regarding “growth trends and trade-offs.” For example, Krechmer et al. (2015) suggested that regional plans should include “alternative futures and their impacts on land use.” A scenario planning exercise would include not only alternative ways in which new vehicle technologies might alter capacity, therefore, but also (1) how stakeholders might want to see land develop, and (2) how new vehicle technologies might affect land development compared to a baseline case without those technologies. The scenarios, therefore, should be of interest to stakeholders and thus may be refined based on their input (Reed et al., 2011).

PURPOSE AND SCOPE

The purpose of this study was to identify ways in which Virginia might (1) alter existing travel demand models in order to consider the impacts of DVs, and (2) use such models to inform questions of interest to regional planners.

The scope was limited to adapting regional travel demand models to impacts that are becoming known about DVs rather than performing original research on such impacts. For example, one potential impact of DVs is that they might lead to an increase in capacity. This study did not attempt to simulate this increase in capacity but rather drew on studies that have suggested how capacity might change and then demonstrated how to incorporate such findings into the regional model.

METHODS

Overview

A case study approach was used for this study in which one Virginia region's travel demand model, the "Charlottesville model" (Corradino Group, 2009), which includes the City of Charlottesville and a portion of Albemarle County, was used as a way of testing how DVs could be incorporated into the model. This particular model was chosen for two reasons: (1) it was not the most recent model (which made it a reasonable test case for developing techniques that could likely be replicated with other models), and (2) it reflected a location near the researchers (which made it easier to interact with local staff of the Thomas Jefferson Planning District Commission, which also staffs the Charlottesville-Albemarle MPO, who could help identify policies of interest. Five tasks guided this case study approach.

1. Conduct a literature review regarding ways to consider the impacts of DVs within the transportation planning process.
2. Review and modify as appropriate the Charlottesville model to understand potential ways of incorporating impacts.
3. Identify issues of local interest the regional model can help address.
4. Develop and refine scenario categories reflecting ways to incorporate DV impacts into the case study region's travel demand model.
5. Execute the scenarios.

Task 1: Conducting the Literature Review

The literature review was largely performed in two stages. First, the research team initially identified sources based on a search of the TRID database using a variety of terms such as "autonomous vehicles" and "transportation planning." A review of these initial sources showed a range of potential impacts of DVs on capacity and VMT. For example, Isaac (2016a) mentioned that research suggests that an increase in lane capacity of "500 percent" could result in cases of platooning of autonomous vehicles, whereas Campbell et al. (2016) noted that an increase of 8% might initially result from truck platoons.

Second, after the initial results of the literature review were provided to the technical review panel (TRP) in November 2016, a more detailed review was conducted focusing on impacts that the researchers believed could be included in the travel demand model. For example, Bierstedt et al. (2014) noted that DVs could potentially affect mode share by making the trip from the origin to the transit stop more palatable, with the TRP noting that this could be incorporated into the utility component of the travel demand model. Accordingly, literature that examined how DVs might influence the perception of time was reviewed.

Task 2: Reviewing and Modifying the Charlottesville Model

The model was examined to understand the key assumptions therein. A user's guide provides some documentation of key modeling decisions (Corradino Group, 2009); however, some details can be learned only from reviewing the model's proprietary scripting language. An effort was made to understand both the computation of outputs and behavioral assumptions. As an example of the former, trip productions and attractions as reported in the user's guide were compared to trip rates from the model; in this particular case, a modification was made to render the model consistent with the user's guide. As an example of the latter, examination of the scripts for the mode choice step within that particular model showed that free flow speeds are used for nonwork trips whereas congested speeds are used for work trips; this did not require a change, but it explained some of the sensitivity of the model.

The Charlottesville model has several trip purposes that are found in other regional models: home-based work (HBW), a trip between a home and a place of employment; home-based other (HBO), a trip between a home and any other destination; nonhome-based (NHB), a trip that has neither the origin nor the destination end at home); internal-external (IX), a trip that begins within the modeled area and terminates outside of it or vice-versa); and external-external (XX), a trip that passes through the entire study area without beginning or ending therein. In addition, the Charlottesville model has two other categories that apply only to students at the University of Virginia: (1) home-based university (HBU), a trip between a student's off-campus housing location and some other location, and (2) home-based university dormitory (HDORMU), a trip between a student's dormitory of residence and some other location. As shown in Appendix D, it was possible to examine the number of trips within these categories in order to understand their relative importance. For instance, Table D1 in Appendix D showed that external-external vehicle trips, which are those passing entirely through the study area, accounted for about 3% of the total vehicle trips in the model.

Task 3: Identifying Issues of Local Interest the Regional Model Can Help Address

A meeting for an outreach exercise was held on June 9, 2017, where 40 members of the Virginia Association of Metropolitan Planning Organizations (VAMPO) were asked questions in person concerning how replacing conventional vehicles with DVs could generate planning-related concerns related to parking. (An earlier March 2017 Charlottesville Model Design Workshop attended by the researchers had indicated that the impact of DVs on parking was of interest.) The overall goal of the exercise was to determine the extent to which the regional travel demand model could help address a particular subset of policy concerns related to DVs. Key questions in the exercise included the following:

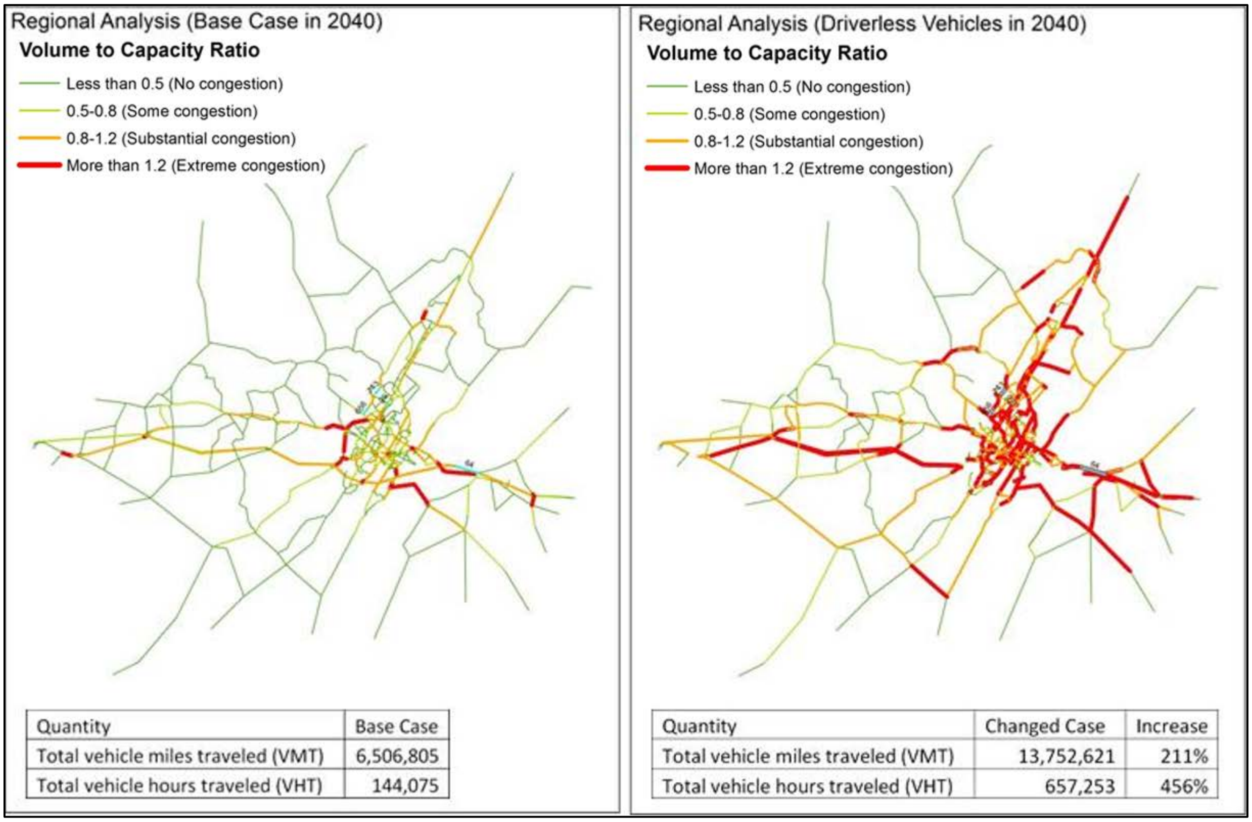
1. What is the role of the planner as we consider the impacts of driverless vehicles on the parking industry?

2. What are the opportunities or risks if driverless vehicles affect (or do not affect) future demand for parking?

3. For either question 1 or 2, what policy tools (if any) can be considered by decision-makers?

4. Consider the tools noted in question 3. Would any of them be adversely affected if you simply did not worry about driverless vehicles at this point in time?

In advance of the meeting where the questions were posed, attendees were provided with a packet of background information (see Appendix A) containing the amount of land currently used for parking (e.g., about 9% of land in the Charlottesville portion of the region serves that purpose) and, based on the most current regional model, expected 2040 volumes, speeds, and volume/capacity ratios for two major parking areas: one in the central business district (CBD) near an outdoor pedestrian mall, and one in a suburban area near an indoor shopping mall. To stimulate discussion, attendees were also provided information regarding one potential extreme situation where DVs might lead to a doubling of trips (Figure 1). Staff of the Charlottesville-Albemarle MPO had suggested that the researchers include an “extreme” case in the information packet whereby the impacts could be assessed if DVs led to a large change in behavior.



Quantity	Base Case
Total vehicle miles traveled (VMT)	6,506,805
Total vehicle hours traveled (VHT)	144,075

Quantity	Changed Case	Increase
Total vehicle miles traveled (VMT)	13,752,621	211%
Total vehicle hours traveled (VHT)	657,253	456%

Figure 1. Example of Information Provided to MPO Attendees of the Outreach Exercise in June 2017. Attendees were provided 14 figures. This figure shows the v/c ratio, with the left being a business as usual scenario and the right being an extreme scenario in which the number of trips doubled. In January 2019, it was brought to the attention of the researchers that with these ranges, a facility with a v/c ratio of exactly 0.5, 0.8, or 1.2 could fall into two categories. A re-examination of the data showed that in this case, there were no facilities with exactly those values. (The geographic information system software computed v/c ratios to 5 decimal places, so, for example, for year 2040, the facility with the ratio under 0.5 but closest to 0.5 had a ratio of 0.49994; the facility with the ratio above 0.5 but closest to 0.5 had a ratio of 0.50772.) MPO = metropolitan planning organization; v/c = volume/capacity.

At the meeting, a 10-minute presentation was given by five staff from VTRC and the Thomas Jefferson Planning District Commission. Each person spoke for approximately 2 minutes. One person spoke first and last, introducing the exercise and concluding with next steps for attendees to perform. Between the first speaker's presentations, the other four staff covered the following topics: the concept of scenario planning and potential capacity impacts of DVs (Presenter 1); potential ways in which DVs might affect comfort (Presenter 2); how DVs might affect the ability of persons to travel more than is presently the case (Presenter 3); and how DVs might affect vehicle sharing and the demand for parking (Presenter 4). Then, attendees were divided into five groups of approximately eight persons each, and each group had a facilitator and note-taker. Then, the groups provided responses to the questions during the outreach exercise.

Task 4: Developing and Refining Scenario Categories

Based on the literature review, five rough scenarios were initially developed pertaining to changes in capacity; changes in parking behavior (where DVs might self-park in less expensive areas); shifts in mode share (where DVs might increase or decrease transit use); the occurrence of zero occupant vehicle (ZOV) trips where DVs might be shared; and the increase in travel that might result from a greater proportion of younger persons (age 10-17) and older persons (age 65+) being able to have access to a vehicle than has historically been the case (see Appendix B). In practice, each "scenario" reflects multiple model runs because there are multiple ways to execute each potential impact within the regional model. For example, capacity may be increased by changing the capacity in the model's speed lookup table (which would affect, conceptually, both the destination of trips and the route such trips take) or altering the volume delay function (which should affect the route but not necessarily the origin or destination). Further, the trip distribution component may be executed as a singly or doubly constrained model (Cambridge Systematics, 2014).

The scenarios were refined based on a meeting with the TRP on March 27, 2017, and as suggested by the TRP, the Charlottesville Model Design Workshop (Hudson, 2017) held on March 28 at the office of the Thomas Jefferson Planning District Commission. As an example of input from the former, it was suggested that a new scenario be added that could result from DVs having a higher margin of safety when they are initially introduced. As an example of input from the latter, when the researcher in attendance asked attendees what types of impacts they were most interested in, two impacts rose to the top of the list: (1) deadheading of vehicles (and how that might affect emissions), and (2) the potential for parking in the CBD to be converted to other uses if parking was no longer needed. This caused the researchers to begin to put extra emphasis on these scenarios.

The scenarios were then further refined based on the results of the task in which, in some cases, the researchers identified ways to alter the scenarios to reflect issues of interest to the stakeholders in the task. Although the literature review (Task 1) found a variety of techniques, the researchers focused on those most relevant to the policy areas of interest identified in Task 3 or the earlier portion of this task. For example, because one concern from Task 3 was that DVs might initially require a greater headway than conventional vehicles, the researchers sought to incorporate a corresponding reduction in capacity into the model within Scenario 1. Because emissions had been mentioned as a result of Task 3, the researchers sought to show how a few scenarios could affect nitrogen oxide (NO_x) emissions, a precursor of ground level ozone, which can affect some regions in Virginia.

Task 5: Executing the Scenarios

Table 1 summarizes examples of feedback from the TRP, TPRAC, and local stakeholders that influenced this work.

Table 1. Examples of Feedback From the Technical Review Panel (TRP), Transportation Planning Research Advisory Committee (TPRAC), and Local Stakeholders That Influenced This Work

Task	Description	Date	Examples of Lessons Learned Based on Feedback
1	Provide initial literature review to TRP showing potential impacts of DVs and ways to incorporate them into the model.	November 16, 2016	One way to reflect the improved attractiveness of DVs is to modify the out-of-vehicle travel time utility specification associated with transit.
1, 2	Present project to TPRAC.	November 30, 2016	The literature review should distinguish between impacts that can be reflected in existing travel demand models and impacts that cannot be reflected in existing travel demand models.
2, 4	Meet with TRP to discuss proposed scenario categories with the regional model.	March 27, 2017	Recognize that contrary to the researchers' initial suggestion, intrazonal trips will not appear on the network, so these must be accounted for separately in Scenario 4.
2, 4	Meet with attendees at the Charlottesville Model Design Workshop to hear areas of interest.	March 28, 2017	Document the types of steps taken so that others can replicate the results. For instance, note how deadheading (e.g., trips made by DVs without any occupants) is incorporated into the model. The impact on parking should be examined as one of the scenarios.
3	Conduct an outreach exercise with members of VAMPO.	June 9, 2017	Stakeholders are interested in a variety of impacts, some of which can be addressed by modifying the regional model, notably emissions.
5	Provide initial results for Scenario 1 to TRP.	July 27, 2017	Although these particular results show that VHT is more sensitive to changes in demand than VMT, the reverse would be the case if the trip distribution step used the distance rather than travel time in the impedance function.
5	Provide initial results for Scenario Categories 2,3, and 5 to TRP.	December 22, 2017[a]	For Scenario 2d, where parking lots are replaced with land development, use percentages for trip purposes based on trips in the central business district rather than trips from the entire model.[a]
4, 5	Meet with TRP to discuss the overall results.	May 11, 2018	For Scenarios 2a-2c, where ZOV trips result from commuters sending their vehicle back home, do not double HBW productions in the trip generation step. Rather, double the matrix following the mode choice step where trips by mode are converted from productions and attractions to origins and destinations.

DVs = driverless vehicles; ZOV = zero occupant vehicle; VAMPO = Virginia Association of Metropolitan Planning Organizations; VHT = vehicle hours traveled; VMT = vehicle miles traveled; HBW = home-based work.

[a] Based on this feedback, a revised version of Scenarios 2, 3, and 5 was provided to the TRP on February 1, 2018.

The scenarios were executed, and for each scenario, the impact on VMT, VHT, and mean trip time (MTT) was recorded. In addition, performance measures of interest for each scenario were also obtained. For example, for a scenario that focused on transit, the changes in mode share (e.g., drive alone, carpool, bus, walk, and bike) were examined. For a scenario that focused on capacity, the change in number of facilities that are congested was obtained.

Although it had been the intention to perform these five tasks sequentially, in practice, Tasks 2, 3, and 5 were highly iterative. For example, based on Task 2, the original utility function for the local bus included a term for the bus fare; this term was the product of a parameter (-0.005) and the fare itself (75 cents). In discussions with the TRP after an initial transit scenario was developed that modified this utility function in response to DVs being available (Task 3) and executed (Task 5), it was pointed out that the original utility function should have included a “100” multiplier. Thus, the scenario was redone, using the 100 multiplier, and the results between the original scenario and the revised scenario were compared.

RESULTS

Literature Review

The literature review showed that DVs may potentially have a variety of impacts, including a change in capacity, a reduction in urban parking, changes in mode share, longer trips, and increased trip-making by nondrivers. Because these impacts are behavioral in nature, it is not surprising that the literature gave a range of values with regard to quantifying these impacts, leading to an admission of uncertainty noted herein.

Changes in Capacity

Bierstedt et al. (2014) noted that capacity increases of 25% to 35%, and 100% for freeways, are possible, and Childress et al. (2015) in their evaluation of alternatives for Puget Sound (in Washington State) noted an increase of 30%. Campbell et al. (2016) suggested that a 2- to 3-fold capacity increase is possible. Isaac (2016a) cited research suggesting that platooning could increase lane capacity by 500%, a percentage also noted by Williams (2013). DVs might also differentially increase capacity by vehicle type (Campbell et al., 2016) and facility type (Zhao and Kockelman, 2017). Farmer (2016) noted that the doubling of freeway capacity may be accompanied by faster travel at capacity (50 mph vs. 40 mph at present). Greater highway capacity owing to DVs being closer to each other was also noted for the Sarasota/Manatee Florida MPO (2016).

Yet capacity may also drop: Litman (2016) suggested that users may choose to have lower acceleration or deceleration rates, owing in part to passengers tending to be more sensitive to acceleration than drivers are. Le Vine et al. (2015) suggested that DVs might reduce capacity by 12% to 32%; the authors conducted simulations based on 25% of the traffic stream having DVs and setting the rates of longitudinal acceleration equal to those of light rail and high speed rail. When the headway between the leading and following vehicle was increased to ensure that passengers in the following vehicle suffered no discomfort because of a sudden change in acceleration by the lead vehicle, capacity was reduced by 12% for the light rail case and 32% for the high speed rail case (Le Vine et al., 2015).

Changes in Parking Needs of Driverless Vehicles

Williams (2013) suggested that DVs' self-parking might reduce the use of parking lots in urban locations, citing previous research that suggested such parking locations could be located farther away than is presently the case from the destinations they serve. Grush et al. (2016) noted that the reduction in parking in the CBD could result in a substantial boon for developers who might want to use expensive land for other purposes, noting that the value of all U.S. parking is equal to the value of all U.S. motorized vehicles. Zhao and Kockelman (2017) found that pricing of travel options affects VMT: in an Austin [Texas] case study, when parking costs were one-half the CBD parking costs, VMT for self-parking DVs increased by 4%; when parking costs outside the CBD were nil, VMT increased by 8%. However, Isaac (2016b) suggested that in some highly urban locations, the lack of drivers needing to search for a space could reduce VMT by 30%.

Changes in Mode Share

Polzin (2016) suggested that DVs could either "complement transit in first-mile/last-mile services" (thereby increasing transit use) or lead to transit being used for only "very high volume fixed guideway operations." Based on regional travel demand models (including those of Atlanta [Georgia), Los Angeles [California], Puget Sound [Washington State], San Francisco [California], and Washington, D.C.), Rixey (2017) found that transit trips might decrease by 43% or increase by 16%. Elsewhere, the Committee for Review of Innovative Urban Mobility Services (2015) reported that transit can be thwarted or supported by new modes: bike sharing users replaced some transit trips with bicycle trips in one location, but in another transportation network, companies could "complement" public transportation, including providing an alternative during an emergency.

Changes in Comfort

Levin (2015) noted that the increased comfort of DVs may reduce disutility associated with in-vehicle travel time. Childress et al. (2015) suggested that the discomfort of in-vehicle travel time may be reduced by 35% for households having access to a DV. The 35% estimate came from a finding that light rail travel time was 65% of the disutility of an equivalent amount of local bus travel time, with the difference attributed to comfort levels. Zhao and Kockelman (2017) used three multipliers—25%, 50%, and 75%—to convert between driverless time and conventional vehicle time. Jaffe (2014) cited research suggesting that commute times may remain relatively fixed should speeds increase—suggesting that trip distances may grow. Isaac (2016a) suggested that if the tendency to be willing to live about one-half hour from one's place of employment were to hold, then with higher speeds (e.g., 120 mph on freeways), DVs could result in increased commuting distances, where more farmland would be converted to residential use and costs of infrastructure to support such distances could increase.

Increased Trips by Nondrivers

DVs offer a "mobility externality" since persons who do not have access to a vehicle or public transportation may be able to take advantage of a DV (Transportation Research Board, 2016). For example, more than one-half (54%) of adults age 75+ without a disability tend not to drive at night (Transportation Research Board, 2016). Truong et al. (2017) found that DVs could increase trip generation by slightly more than 4%, with the largest increase for persons age 76+ (where trip generation increases by 18% relative to the case of DVs not being available). Although not restricted to nondrivers per se, additional trips are a possibility envisioned by one MPO: documentation for one of the regional models used by the Florida Department of Transportation discusses future plans to modify the model to accommodate certain elements of DVs including additional trip generation, with "an increase in easy-access one-way trips in urban areas" (Sarasota/Manatee MPO, 2016).

The Uncertainty of Impacts

The aforementioned review shows that although it may be possible to incorporate such impacts into the regional model, the numerical value is uncertain (e.g., should a change in capacity be presumed, and if so, should this amount be 25%, 35%, or 100%—or should it be a decrease?). It is also possible that the impacts of DVs could be better reflected as changes to the inputs into the regional model, such as population and employment locations. For example, Chase (2016) suggested that highly automated connected vehicles could potentially reduce the costs of housing by 25%, since parking would not be required. Such a behavioral impact would not immediately be captured by a travel demand model (or a microscopic simulation model) and would require a better understanding of human behavior. However, such a change might thus affect the location and quantity of new housing in a region, which would, in turn, alter the location of population in the regional model.

A comment by Plosky (2016) implied that the inputs to travel demand models may need to be nonlinear in order to accommodate some behavioral changes. Plosky (2016) provided an example: some freight stakeholders have suggested that the minimum age for driving a heavy vehicle be reduced from 21 to 18 in order to accommodate an increased need for tractor trailer drivers. However, in theory, with fully automated (driverless) tractor trailers, the need for such drivers would be zero. Thus, a travel demand model can be envisioned where, over a relatively long horizon, the need for heavy vehicle drivers would increase (from the point at present) and then, at some point in the future, start to decrease.

Review and Modification of the Charlottesville Model

Overview

With the assistance of the TRP, the researchers examined the Charlottesville model to understand the assumptions therein. In total, six modifications were made:

1. Alter trip production rates.

2. Add a script to obtain the trip length frequency distribution.
3. Directly incorporate fares into the mode choice step.
4. Incorporate both a singly constrained and doubly constrained gravity model.
5. Adjust the fare parameter in the utility function in the mode choice step.
6. Add geographic information to the roadway and zone shapefiles.

Three initial changes were made to the model structure prior to the execution of any scenarios (Modifications 1, 2, and 3). Then, three additional modifications were made incrementally as insights became apparent during the execution of the scenarios (Modifications 4, 5, and 6). As per discussions with one TRP member, the “S2040_all29” version of the Charlottesville model was used, as that version contained planned projects. (Certain figures of the Charlottesville model, notably Figures 3, 7, 8, 11, and 12, are included in order to illustrate where key changes in the Charlottesville model were made, but except where specific changes are noted, the figures generally show portions of the Charlottesville model in their original form.)

Modification 1: Alter Trip Production Rates

When calculating productions by trip purpose in the trip generation step, the researchers noticed a difference between the rates computed from the model and rates computed by hand for one zone in Albemarle County, but there was no such error in the rates for the City of Charlottesville. The problem appeared to be in a script in the trip generation step showing an “if . . . else” function, indicating that different land use types have different trip generation rates, where Area Types 1 and 2 correspond to the City of Charlottesville and Area Type 3 corresponds to Albemarle County (Corradino Group, 2009). However, the model appeared to use Area Type 3 (the county) incorrectly in these city rates. Accordingly, as shown in Figure 2, the line “if (zi.2.atype=1-3)” was changed to “if (zi.2.atype=1-2)” (Xiao, 2016).

```
if(zi.2.atype=1-3)

else      ;Calculate Productions for County Zones
```

Figure 2. Excerpt of Script Used in Trip Generation. The figure was redrawn based on a screen capture of the script that was used to execute the Charlottesville model. The colors are indicative of what one sees when using the editor associated with the Cube software; for instance, “if” and “else” are in the same color (orange).

Modification 2: Add a Script to Obtain the Trip Length Frequency Distribution

Within the model, there was a Sequence 13 showing the mean trip length in time; however, this trip length reflected free flow conditions. Accordingly, several lines of code were added to show the mean congested travel time and the shape of the trip length frequency distribution, as described in Appendix C.

Modification 3: Directly Incorporate Fares Into the Mode Choice Step

Initially, when transit fares were altered from a low value of $0.75 cents to a high value of $5.00, the initial mode split did not change. As suggested by Xiao (2016), the root problem was that a feedback link needed to be added to the model, as shown in Figure 3. This link connects model Sequence 10 (see the output file “Matrix File 1”) and Model Sequence 11 (see the input file “Matrix File 1”); after this correction is made, changes to transit fare do affect mode split. This was the only change made in this particular figure; the remaining items were in the original Charlottesville model.

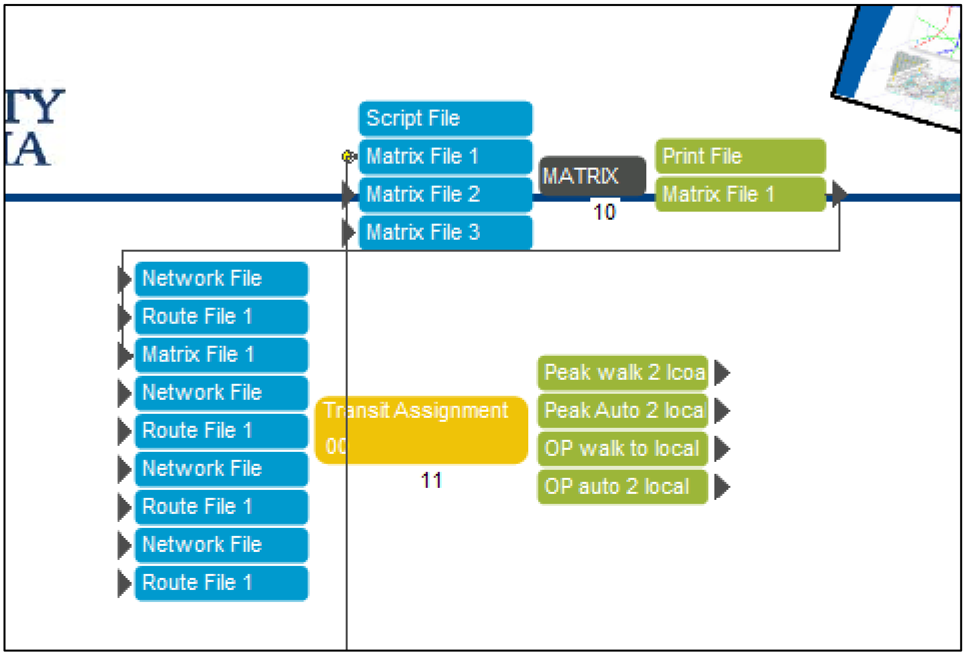


Figure 3. Adding a Link From Sequence 10 to Sequence 11. The correction was suggested by Xiao (2016). Except for this correction, no other changes were made to the Charlottesville model in this particular figure. The four boxes in the lower right section of the figure indicate the following types of trips: walking to local transit service during the peak period, driving to local transit service during the peak period, walking to local transit service during the off-peak period, and driving to local transit service during the off-peak period.

Modification 4: Incorporate Both a Singly Constrained and Doubly Constrained Gravity Model

A common form of the gravity model is the doubly constrained gravity model (Garber and Hoel, 1988; Meyer and Miller, 2013), meaning that within the trip distribution step, forecast productions are equal to given productions and forecast attractions are equal to given attractions. The Charlottesville model is also doubly constrained for all trip purposes. (A *production* refers to the home end of a trip, and an *attraction* refers to the nonhome end of a trip. If a trip does not involve a home, then the production is the origin and the attraction is the destination.) By contrast, for a singly constrained model, this equalization is forced only for productions or attractions (usually the former). Assuming that forecast productions are required to be equal to given productions, the difference between a doubly constrained gravity model and a singly constrained gravity model depends on the extent to which there is greater confidence in forecast attractions (hence the doubly constrained model would be preferred) or the impedance function used in the gravity model (hence the singly constrained gravity model would be preferred). VDOT (2014) pointed out that although this is acceptable, there is “no consensus” regarding whether a singly or doubly constrained gravity model is preferred while also noting that results should be checked for “reasonableness.” This suggests that for work trips, a doubly constrained gravity model could be used but for other trips, the singly constrained gravity model could be used.

As a consequence, the researchers implemented both versions when executing the scenarios: a doubly constrained gravity model and a singly constrained gravity model. Implementation of a singly constrained gravity model in Cube does not use friction factors; rather, a function as shown in Equation 1 of the form friction factor = $e^{(c*\text{travel time})}$ is used. Equations 1 and 2 simply obtain the parameters for the singly constrained gravity model based on the friction factors used for the doubly constrained model via linear regression. For example, Figure 4 shows the resultant fit of the HBW trips where a parameter of c = -0.08001 yields a function that matches the friction factors used in the model. The parameter is used to scale the function, and it may be eliminated from the model (Cambridge Systematics, Inc., et al., 2012; Martin and McGuckin, 1998). As shown in Figure 4, different parameters may be obtained, but the general pattern is that travel time offers the greatest impedance for NHB trips and a lesser impedance for HBW trips.

$$\text{Friction factor (for purpose i and travel time j)} = a_j * \exp(c_i t_j) \qquad \text{[Eq. 1]}$$

$$\ln(FF_{ij}) = \ln(a_j) + c_i t_j \qquad \text{[Eq. 2]}$$

A more detailed approach for determining the parameters associated with the singly constrained gravity model is available based on Martin and McGuckin (1998), where model runs are performed and the parameters are updated based on those runs and existing survey data, which in this case were the 5-year estimates from the American Community Survey (U.S. Census Bureau, undated). The researchers did use this method for Scenario 1. However, because the method was considerably more detailed, the simplified approach here may make the use of the singly constrained gravity model feasible in other locations; thus, the simplified approach was used for Scenarios 2 through 5.

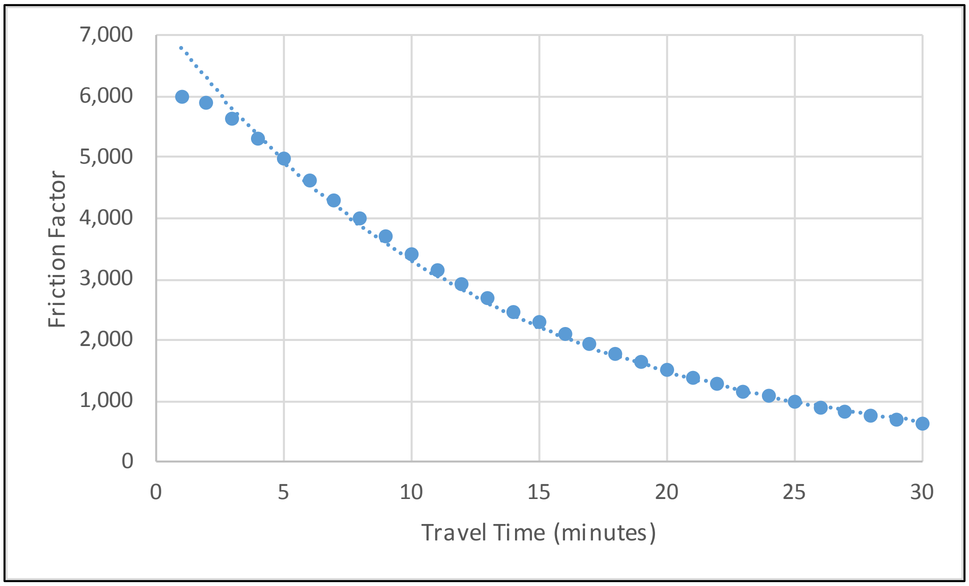


Figure 4. Fit of Friction Factors for Home-Based Work Trip to Equation 1 (c = -0.08001, a = 7,371)

Use of different parameters will affect the model results, but not substantially, suggesting that the more transferable approach may be preferable. For example, as a test case, Scenario 5d, which doubled growth in the area such as population, autos owned, school attendance, households, and employment, may be considered. Doubling the growth, relative to the base scenario, showed that VMT increased by 44%, VHT increased by 168%, and MTT increased by 71%. Both the base scenario and Scenario 5d used the parameters shown in the far left column of Table 2. With the simplified approach, the base scenario and Scenario 5d (which doubles growth) used the parameters shown in the second column from the right of Table 2. Similar values were obtained for Scenario 5d: i.e., doubling growth leads to an increase of 40% for VMT (rather than 44%), 116% for VHT (rather than 168%), and 71% for MTT (rather than 48%). The script for implementing the singly constrained gravity model is shown in Appendix C.

Table 2. Parameters for Exponential Function in Singly Constrained Gravity Model

Trip Purpose	Calibration With Friction Factors and New Additional Census Data (Scenario 1)	Calibration With Friction Factors Only From Model (Scenarios 2-5)	Default Value From NCHRP Report 716 (for MPO Under 250,000)[a] (Not Used)
Home-based work	-0.04259	-0.08001	-0.052
Home-based other	-0.09881	-0.18959	-0.126
Nonhome-based	-0.18995	-0.22559	-0.232
Students living off campus	-0.10779	-0.20830	N/A
Students living on campus	-0.10779	-0.20830	N/A
Internal-external	-0.10516	-0.20004	N/A

[a] NCHRP Report 716 (Cambridge Systematics, Inc., et al., 2012) provides default values for the Gamma function F = $(\text{time}^{b})e^{(c*\text{time})}$. These were fit to the exponential function in order to show the values in the rightmost column.

Modification 5: Adjust the Fare Parameter in the Utility Function in the Mode Choice Step

As shown by the line "MW[15]=(mi.3.pkopcostlb*100)*HBWCCST," in determining the utility for using the bus, the local bus operating cost (i.e., the fare) was modified to be multiplied by 100. As suggested by the TRP, this modification was made for Scenario 3 such that the 100 multiplier applies for the operating cost for all three transit modes: walk to local bus, walk to premium transit, and drive to best available transit service.

A justification for changing the multiplier for the local bus is evident from considering the utility function for two modes shown in the model, i.e., drive to best available transit service and walk to local bus, where this fare is multiplied by a cost parameter of -0.005. The product has a multiplier of 100 in the script for the former mode but not the latter. As shown in Table 3, fare has relatively little impact on mode choice. An illustration of these variables is evident from examining data for travel between Zone 9 in the CBD and three other zones: Zone 20 (near the CBD with transit service), Zone 113 (farther away with transit service), and Zone 99 (farthest away without transit service). These zones are shown in Figure 5. Table 3 shows the components of the utility for each mode under peak conditions. The utilities are calculated by multiplying each variable by the appropriate parameter. The effort for two elements of the trip—(1) moving between the origin or destination to or from the bus, and (2) waiting for the bus—generally accounts for 62% to 83% of the utility. For these reasons, the utility functions suggest that for DVs to affect transit's mode share positively, the key mechanism would be to reduce the discomfort associated with waiting, traveling to the stop, or traveling from the stop.

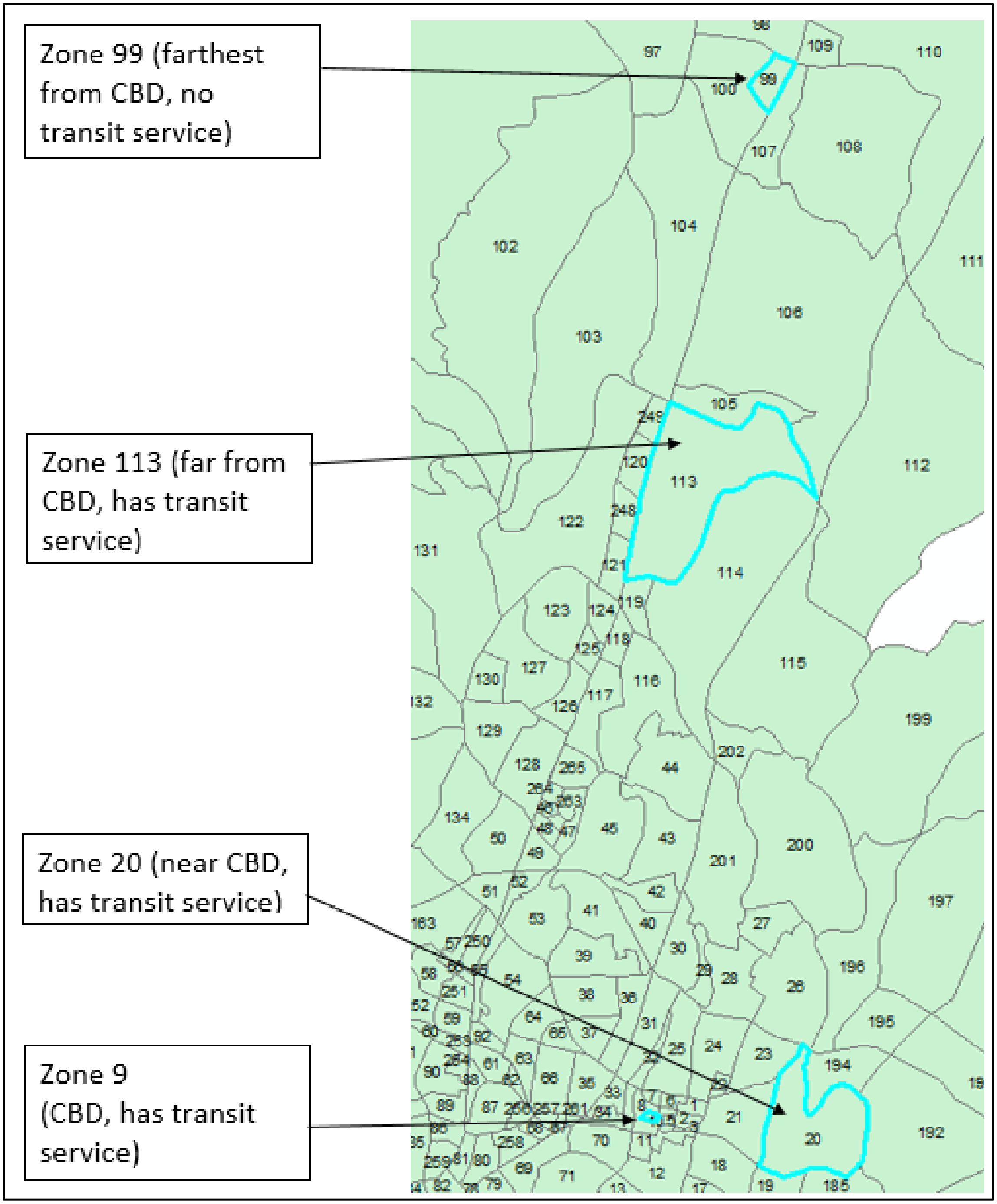


Figure 5. Four Zones of Interest in the Regional Model: Zone 9 (CBD), Zone 20 (near CBD), Zone 113 (far from CBD), and Zone 99 (farthest from CBD). CBD = central business district.

Table 3. Components of Peak Period Utility for the Transit Mode

Zones	Variable Label	Variable Description	Variable Value	Parameter Value	Parameter Label	Utility	% of Total Utility
20 to 9	pkwktimeBA	Drive time to local bus	17.38	-0.049	HBWCOVT	-0.85162	25
	pkwttimeBA	Wait time for local bus	32	-0.049	HBWCOVT	-1.568	46
	pkivtimeBA	Bus riding time	25.22	-0.025	HBWCIVT	-0.6305	18
	pkpkcostBA	Parking cost	1.8	-0.005	HBWCCST	-0.009	0
	pkopcostBA	Operating cost (fare)	0.75	-0.005	HBWCCST	-0.375	11[a]
	Total utility for Zones 20 to 9 (mode is drive to bus)					-3.43412	100%
20 to 113	pkwktimeBA	Drive time to local bus	11.38	-0.049	HBWCOVT	-0.55762	11
	pkwttimeBA	Wait time for local bus	51	-0.049	HBWCOVT	-2.499	51
	pkivtimeBA	Bus riding time	58.61	-0.025	HBWCIVT	-1.46525	30
	pkpkcostBA	Parking cost	6.4	-0.005	HBWCCST	-0.032	1
	pkopcostBA	Operating cost (fare)	0.75	-0.005	HBWCCST	-0.375	8[a]
	Total utility for Zones 20 to 113 (mode is drive to bus)					-4.92887	100%
20 to 9	pkwktimelb	Walk time to local bus	17.24	-0.049	HBWCOVT	-0.84476	29
	pkwttimelb	Wait time for local bus	32	-0.049	HBWCOVT	-1.568	54
	pkivtimelb	Bus riding time	7.98	-0.025	HBWCIVT	-0.1995	7
	pkpkcostlb	Parking cost	0	-0.005	HBWCCST	0	0
	pkopcostlb	Operating cost (fare)	0.75	-0.005	HBWCCST	-0.00375	0[a]
	SUM[I]	Pedestrian environment	10	0.117	HBWPTI	0.2925	10[b]
	Total utility for Zones 20 to 9 (mode is walk to bus)					-2.90851	100
20 to 113	pkwktimelb	Walk time to local bus	21.35	-0.049	HBWCOVT	-1.04615	22
	pkwttimelb	Wait time for local bus	51	-0.049	HBWCOVT	-2.499	52
	pkivtimelb	Bus riding time	39.71	-0.025	HBWCIVT	-0.99275	21
	pkpkcostlb	Parking cost	0	-0.005	HBWCCST	0	0
	pkopcostlb	Operating cost (fare)	0.75	-0.005	HBWCCST	-0.00375	0[a]
	SUM[I]	Pedestrian environment	10	0.117	HBWPTI	0.2925	6[b]
	Total utility for Zones 20 to 113 (mode is walk to bus)					-4.83415	100%

[a] In the script, a multiplier of 100 is given in the script for “pkopcostBA” but not for “pkopcostlb,” which is why the utility for the latter is so low.

[b] Note that the pedestrian environment component of utility, shown as the “HBWPTI” parameter, is positive but all other components are negative. Thus, the “total” utility reflects the 5 negative utilities minus the positive pedestrian environment utility. A multiplier of 0.25 is given in the script, which is why the utility is the product of the parameter*variable*0.25.

Modification 6: Add Geographic Information to the Roadway and Zone Shapefiles

Some scenarios used Census data. Although data from the U.S. Census Bureau (2015a) and the travel demand model are available in a GIS format, it was not possible to overlay these layers immediately because of two distinct problems: (1) what appears to be a relatively minor translation challenge in the travel demand model roadway shapefile, and (2) what appears to be a more serious projection challenge in the travel demand model socioeconomic shapefile.

To correct the first problem, a spatial adjustment procedure suitable for vector layers was performed where the researchers created "links" between certain locations in the roadway shapefile (such as the intersection of I-64 and U.S. 250 at the western end of the travel demand model) and the same location in real-world coordinates. Then, an affine transformation (Esri, 2016), which is one way of performing a spatial adjustment using ArcGIS 10.3 software, was implemented based on these 15 links, as shown in Figure 6 (*left*). Although this improved the accuracy of the location of the roadway shapefile, errors were still visible, especially in the more urban portion of the model; thus, this process was repeated with an additional 41 links, as shown in Figure 6 (*right*). A process similar to that shown in Figure 6 was used for the socioeconomic layer except the initial projection information was deleted (otherwise the roadway layer would have been placed west of the Gulf of California); then a single affine transformation was performed; and then the projection information was added to the layer.

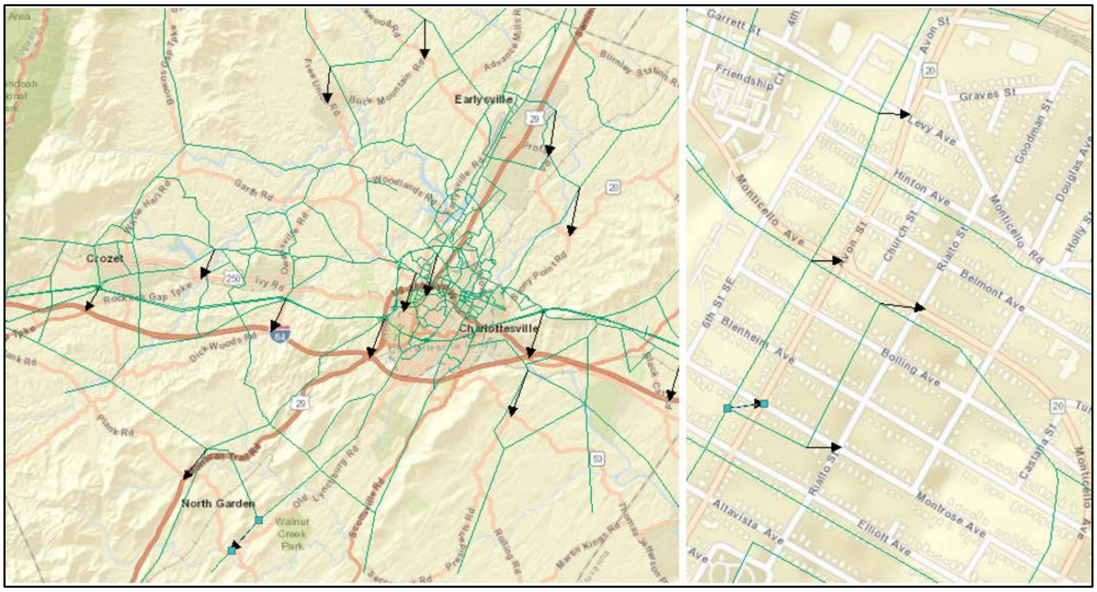


Figure 6. Example of Performing Spatial Adjustments to Correct the Location of the Roadway Layer

Issues of Local Interest the Regional Model Can Help Address

Attendees at the June 2017 annual meeting of VAMPO, who had been provided outreach information of the type shown in Figure 1 and Appendix A in addition to presentations on potential impacts of DVs, were divided into five groups of approximately eight persons each, and each group had a facilitator and note-taker. Then, the groups provided responses to certain questions (described in Task 3 in the "Methods" section and in Appendix A) during the outreach exercise. The complete set of responses is available from the authors, but a summary of findings as they relate to parking concerns is provided here. Table 4 maps related concerns to potential modeling strategies.

Table 4. Ways to Consider Issues of Interest Concerning Impacts of Driverless Vehicles (DVs) Identified by Attendees of the VAMPO Meeting on June 9, 2017

Issue of Interest [Scenario Relating to Issue of Interest]	Relevant Analytical Approach	Feasibility of Using a Regional Model
Change current zoning ordinances that mandate a minimum number of parking spaces.	Original research on how DVs will influence behavior is needed.	Low: data are not available for the model.
Encourage vehicle sharing rather than ownership of DVs [Scenario 6].[a]	If the policy tool is a tax on vehicle ownership, possibly an incremental logit model could be used, but original research on how cost influences decisions is needed.	Low: requires extensive revisions to the regional model. (However, certain impacts of sharing may be modeled.)
Convert existing parking decks to other land uses (and increase property values) [Scenario 2].[a]	Within the regional travel demand model, what-if scenarios can be performed that examine how changes in population and employment in certain zones will influence VMT.	Medium: existing models can be used for this analysis, although some modifications to specific zones are required.
Discourage additional growth outside existing areas through higher property taxes.[b]		
Strengthen the role of transit in serving rural park and ride lots [Scenario 3].[a]	Modify the model to include additional park and ride lots at key nodes and higher capacity transit from such nodes to the CBD. (This can include examining how DVs can serve persons without mobility options.[a])	Medium: extensive model revisions are needed.
Increase enforcement of traffic ordinances regarding curb access for DVs.	With queuing models, how arrivals, departures, and waiting time affect facility performance can be examined.	Low: a regional model is not sufficiently detailed for this analysis.
Advocate for more drop-off and pickup lanes next to businesses.[b]		
Ensure good access for pedestrians and bicyclists with such lanes.	Modify the queuing models to account for different modes (e.g., bicycle vs. pedestrian).	
Provide information about how parking pricing might influence where DVs are parked.[b]	Within a regional travel demand model or a stand-alone mode choice model, how the price of parking vs. the price per extra mile traveled influences whether a trip is taken by a ZOV can be tested.	Medium: extensive revisions to the mode choice component are needed.
Reduce transit costs by eliminating the need for a driver.	Perform a benefit-cost analysis that compares the costs of purchasing a DV with the reduction in labor costs by eliminating the driver.	Low: a regional model is not appropriate for this purpose.
Quantify the reduced need for infrastructure investments given that DVs may require less right of way than conventional vehicles.		
ZOVs may increase because of DVs self-parking [Scenarios 2, 4].[c]	Increase the number of trips in the regional travel demand model to account for such ZOVs.	High: some modifications can be made to the model.
DVs may require a higher margin of safety initially (such as increased headways) [Scenario 1].[c]	Initially reduce the capacity in the regional travel demand model and examine the impact on VMT and VHT.	High: capacity impacts can be captured in the regional model.
The increased use of DVs may lead to higher emissions [Scenarios 1, 5].[c]	The model by itself will not provide an answer but can provide key inputs (VMT, VHT, and speeds).	Medium: emissions factors can be used in conjunction with outputs from the regional model.

VAMPO = Virginia Association of Metropolitan Planning Organizations; CBD = central business district; ZOV = zero occupant vehicle; VMT = vehicle miles traveled; VHT = vehicle hours traveled.

[a] An issue of interest that is partially but not completely addressed in the modeling in Task 5.

[b] An issue of interest that is not addressed in Task 5 but that appears feasible to address if more information is obtained, as discussed later in the report.

[c] An issue of interest that is directly addressed by the modeling in Task 5.

Role of the Planner

Planners may have a more active land use role in terms of changing current zoning ordinances, reusing existing parking areas, and discouraging growth outside existing areas. Planners might also have a new traffic engineering role to ensure curbside access at building entrances (e.g., advocacy for pickup lanes used by DVs while ensuring pedestrian access). Information sharing regarding how pricing (e.g., parking costs in the CBD or per-mile vehicle operating costs) affects behavior was also suggested as a role, as was outreach to the parking industry. Another possibility was for planners not to take a role but rather simply to let market decisions dictate any changes to parking wrought by DVs. A comment was made that the answer (to the question of what is the role of the planner as we consider the impacts of driverless vehicles) also depends on whether the planner has a regional versus a local focus.

Opportunities for DVs

DVs could further increase downtown land values, especially as former parking lots are turned into other uses (e.g., housing or public uses)—serving as catalysts for infill development. The advent of more green space (which could reduce the "urban heat density"), reduced noise, and reduced congestion could improve the downtown living areas, the last of which could be enhanced by the parking industry's adoption of new technologies to tell motorists where parking is available. DVs could also enhance transit connections between rural and urban areas, where rural commuters could park autonomous vehicles in a park and ride lot and use a high-capacity mode such as bus rapid transit to the CBD. Finally, as fleet penetration rates approach 100%, the needed roadway infrastructure—parking spaces and travel lanes—could be reduced as the likelihood of human error is reduced. One group of participants had noted that discussions of vehicle automation have occurred at "aging and disabled community service type meetings," which, if DVs were viewed as a way to provide mobility to persons who presently cannot drive, would support a benefit noted in the literature (Transportation Research Board, 2016).

Risks of DVs

DVs are associated with at least four potential risks with respect to parking. The first risk is a lack of needed cooperation between jurisdictions for parking use; an urban city might adjust its parking regulations after considering DVs, but an adjacent and more rural county might not be ready to do so, leading to a "shell game" where congestion and parking problems are relocated from one jurisdiction to the next. Second, elimination of parking in the CBD may lead to an increase in VMT attributable in part to the use of ZOVs by owners who choose not to park. (One group noted "increased congestion from zero-occupant vehicles" as a risk and noted the number of trips might double; another group noted the potential emissions impacts of such trips.) This increase in VMT may also alter peaking characteristics; for example, instead of traffic peaks inbound for employment areas in the morning and outbound in the evening, traffic peaks may occur in both directions in both the morning and evening. Third, DVs might lead to expansion of development into rural areas, and hence an increase in VMT, if DVs are more comfortable than regular vehicles. Fourth, during a transition period to DVs, capacity might decrease if DVs initially require a higher margin of safety (e.g., a longer following distance) than conventional vehicles; in fact, one group noted "may not get capacity increase" as a potential risk.

Potential Policy Tools

One policy is pricing, where the owners of DVs could be charged based on the number of times they enter a congested area to serve passengers; such a policy could reflect consideration of both congestion levels and emissions in setting a fee. As one reviewer of this report noted, this suggestion was reminiscent of a practice London initiated in 2003 of charging drivers a fee when they enter the CBD (Terrill et al., 2017).

Another policy is building DV-specific lanes where efficiency would be affected less than for conventional lanes when riders are picked up or dropped off. An implication is that there could be two entrances for pickup and drop-off at some buildings—one reserved for DVs, and one reserved for conventional vehicles (the latter might or might not also include parking). Of interest is how the relative attractiveness of DVs compares to that of transit if reduced emissions or congestion is sought.

The Need (or Lack Thereof) to Consider DVs at Present

Regarding whether it is essential to consider the impacts of DVs on parking at this time, opinions were divided. One view was that it is not necessary to conduct such long-range planning, given that one impact discussed previously is already being seen: in some locations, such as multimodal centers, there are already empty parking places. Although empty spaces at present are not attributed to DVs, an implication is that such an impact does not require a focus on DVs per se. Another reason for not doing such analysis is the timing of the long-range plan: with the transition to DVs being 20 or more years from now (which is at the outer limits of long-range planning horizons), there might be future innovations that will change the view of DVs. In fact, one planning district commission deliberately chose not to consider DVs in its long-range plan. Another view was that it could be productive to consider DVs now in long-range planning efforts. If DVs will tend to be used during peak hours and not at other times, how the "rush and lull" will affect traffic performance can begin to be understood through the use of simulation modeling. In addition, implementation of any regulatory approach (such as a fuels tax) requires detailed analysis and probably cannot be implemented in a short timeframe without such planning. If, for example, parking behavior changes suddenly (e.g., vehicle trips double because of ZOVs), then without additional regulation or infrastructure, the increase in ZOVs could be detrimental to rural facilities that are not equipped to handle heavy traffic volumes.

Feasibility of Incorporating Such Concerns Into the Regional Model

There are parking-related concerns that are not feasible for examination with the travel demand model. For example, DVs may require detailed management of curbside access, and details such as scheduling arrivals and drop-offs at loading zones require too much geographic detail for inclusion in the regional model. The responses also suggested that regional models could help address some concerns; for example, the risk that DVs may initially require a greater following distance than conventional vehicles can easily be addressed by altering the capacity in the regional model. For the issues that are feasible with the model, the level of difficulty varies by task; for instance, adjusting capacity in the capacity lookup table (which influences the impedance function in trip distribution) is simpler than modifying the script to alter capacity in trip assignment (where just a few lines of code require alteration), which, in turn, is simpler than representing a new rural transit access mode (where DVs would augment rural park and ride lots by collecting passengers from individual locations in rural areas and enabling them to take higher speed transit to more urban areas).

Throughout the discussion, comments from several groups indicated a variety of unknown impacts of DVs. One concerned environmental effects: To what extent will emissions change if DVs are driven more frequently to run errands or to return home to park because parking in commercial areas is expensive? A second concerned resources: What is the most effective use of resources? Other unknowns about the technology included cybersecurity, expected rate of fleet turnover, multiple states' inspection requirements, the future of retail if another technology (drones) replaced vehicle-based delivery, and public acceptance; one group drew a connection with the Segway (a new technology that did not revolutionize transportation but does have some niche applications).

Table 4 summarizes one way to address the issues of interest identified by attendees. As shown in the left column, there are five issues that modifications to the regional model can potentially address: (1) DVs may require increased headways (which could potentially reduce capacity); (2) existing parking decks can be converted to other land uses if parking is no longer needed; (3) DVs could strengthen the role of transit; (4) ZOVs may increase because of self-parking; and (5) the increased use of DVs may lead to higher emissions. Issues 1, 2, 4, and 5 can be directly covered within the regional model. Issue 3 can be partially covered in that how DVs affect transit use can be examined without specifically focusing on rural areas. In reviewing these scenarios, the researchers recognized three potential additions:

1. For Issue 4 (that ZOVs may increase because of self-parking), ZOVs might also increase because of the travel from Person 1's destination to Person 2's origin. Thus, Issue 4 could be addressed through two scenarios: a scenario that generates ZOV trips by privately owned DVs (what later became Scenario 2), and a scenario that generates ZOV trips by shared DVs (what later became Scenario 4).

2. For Issue 5, that ZOVs might increase emissions, this could potentially be covered in all scenarios. This issue could be addressed in particular, however, through two scenarios: a scenario that looks at how changes in capacity might affect emissions (what later became Scenario 1), and a scenario that looks at how additional travel by persons who do not have a vehicle affects emissions (what later became Scenario 5).

3. For Issue 3, that DVs could strengthen the role of transit, it is also possible that DVs could weaken the role of transit. This issue could be addressed through two scenarios that examine how the components of a potential transit trip (walking or driving to the stop, waiting at the stop, and riding the vehicle) and a potential auto trip are affected by changes in comfort offered by DVs.

There are likely multiple ways in which each of these issues can be modeled. For example, Issue 5, the impact on emissions, can be considered. The quantity of emissions from any vehicle (not just a DV) traveling 1 mile at a particular speed is influenced by multiple factors, including the extent to which acceleration and deceleration occurs, promulgation of vehicle emissions standards, and manner in which the vehicle is powered. Eilbert et al. (2017), for example, showed that compared to regular vehicles, vehicles with a higher degree of automation had the potential both to increase and decrease NO_x emissions, although noting that generally because of more constant speeds, emissions should drop. Reed et al. (2016) suggested that for one particular set of conditions, vehicles with a higher degree of automation would see either a 32% or 17% reduction in NO_x emissions, depending on whether the particular roadway's volume was above capacity. In reference to greenhouse gas emissions, Fulton et al. (2017) noted that although the use of electric DVs could yield environmental benefits, the extent of this benefit depended heavily on the extent to which power plants use carbon-based sources. Thus, the manner in which the baseline is constructed may influence the results. For example, if DVs had a much higher rate of electrification than non-DVs and stationary sources did not rely on fossil fuels, based on a review of Fulton et al. (2017) any scenario that compared shared electric DVs to privately owned traditional vehicles that used fossil fuels would be expected to show a benefit. For modeling emissions, the researchers deliberately did not presume a change in emissions properties between DVs and traditional vehicles in order to distinguish the behavioral impacts of DVs from the technological impacts of changes in the vehicle fleet.

Development and Refinement of Scenario Categories

Overview

Five scenarios were developed pertaining to (1) capacity; (2) additional ZOV trips resulting from a change in parking behavior; (3) changes to transit's mode share because of changes in trip comfort; (4) additional ZOV trips because of imperfect matching of shared DVs; and (5) greater access to DVs by age groups with traditionally lower levels of vehicle access. Then, a sixth scenario was developed that incorporated elements of each of these scenarios. All scenarios presumed no change in the perception of safety for a DV versus a conventional vehicle, recognizing that the safety and cybersecurity elements of DV operation are an active field of study; see, for example, National Transport Commission, Australia (2018).

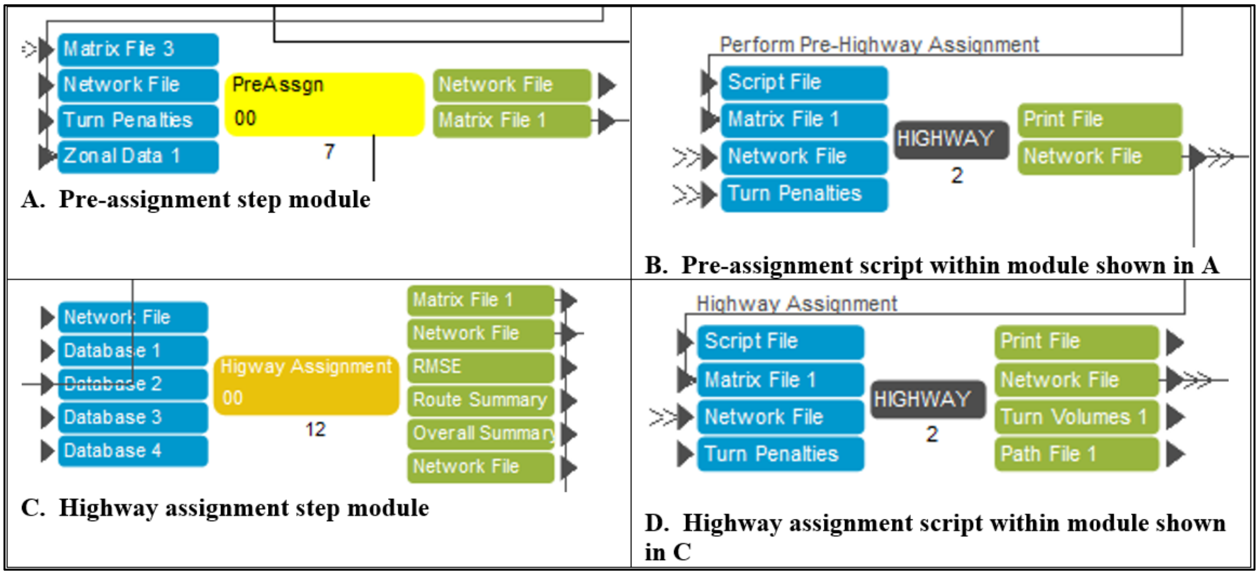
The first five scenarios presumed 100% market share of DVs and analyzed each impact individually. For instance, when changes to transit's mode share were considered based on greater comfort of DVs (Scenarios 3a and 3b), no other impacts, such as capacity changes, were considered. The reason for this was to gain a better understanding of each individual impact (e.g., although changes in comfort and capacity may both matter, which impact is greater?). Scenario 6 took a different approach, combining multiple impacts and presuming the DV market penetration rate was 24.8% (based on a review of Bansal and Kockelman, [2017]) rather than 100%.

Scenario 1: Alter Capacity

Capacity changes of 30% (Bierstedt et al., 2014; Childress et al., 2015); 100% (Bierstedt et al., 2014); and -32% (Le Vine et al., 2015) were used in Scenario 1 in order to obtain a wide range of impacts, although none of these percentages included the 6-fold increase noted by Isaac (2016a). Link capacity values are used in three locations in the regional model: two in the volume delay function and one in the capacity lookup table. The volume delay function equation is used in the pre-assignment step (Sequence 7) and the highway assignment step (Sequence 12). The pre-assignment and assignment sequences are shown in Figure 7.

Figure 8 shows that the volume/capacity ratio is represented by a single variable, i.e., VC. Accordingly, to represent a change in capacity, the researchers added a new variable, vdf, computed as vdf = 1/(1 + percent increase in capacity). For example, if capacity is doubled (i.e., a 100% increase), VC should be multiplied by 1/[1*(1 + 100%)] = 0.5. Rather than enter the value of vdf every time a scenario was executed, a catalog key named "vdf" was added for every facility type; this key represents the volume/capacity ratio in the model, as indicated in Figure 8. Thus, if capacity is unchanged, vdf is 1, but vdf is 0.5 for a capacity increase of 100%. For the changes in capacity of a 32% decrease and a 30% increase, vdf is 1.4706 and 0.769, respectively. Accordingly, the new variable vdf represents changes in capacity of -32%, 30%, and 100% in the assignment step.

A different way of modifying capacity is simply to change the value in the lookup table, which in the model is stored as the file "capacity.dbf." This change does not require modifying the volume delay function.



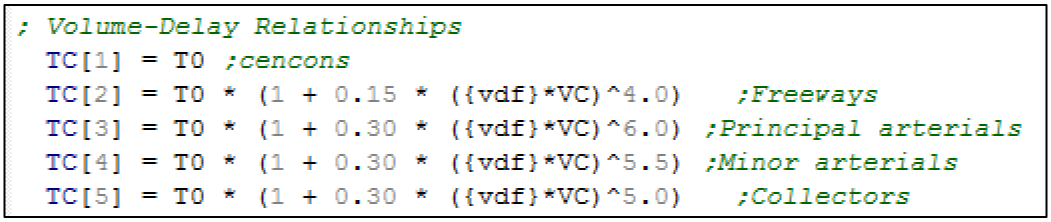
A. Pre-assignment step module

B. Pre-assignment script within module shown in A

C. Highway assignment step module

D. Highway assignment script within module shown in C

Figure 7. Modifying the Travel Demand Model to Accommodate Changes in Capacity. The actual model flowchart has the VDOT logo, a University of Virginia logo, and a photograph of what appears to be the Virginia Transportation Modeling (VTM) Policies and Procedures Manual in the background, which made the flowchart difficult to read. This background was removed. (In block C, in the fifth green output box to the right, the complete description is "Overall Summary.") The figure represents four screenshots taken by the authors when executing the Charlottesville model, where this model was originally developed by The Corradino Group (2009) and was executed by the authors using Citilabs Cube Software Version 6.4.2.



```
; Volume-Delay Relationships
  TC[1] = T0 ;cencons
  TC[2] = T0 * (1 + 0.15 * ({vdf}*VC)^4.0)    ;Freeways
  TC[3] = T0 * (1 + 0.30 * ({vdf}*VC)^6.0) ;Principal arterials
  TC[4] = T0 * (1 + 0.30 * ({vdf}*VC)^5.5) ;Minor arterials
  TC[5] = T0 * (1 + 0.30 * ({vdf}*VC)^5.0)    ;Collectors
```

Figure 8. Catalog Key "vdf" Added to Volume/Capacity Ratio

For Scenario 1, a total of 14 sub-scenarios were executed: a base doubly constrained gravity model; a base singly constrained gravity model; and for each of these gravity model types, changes in capacity of -32%, 30%, and 100%. Each capacity method was deployed in two ways: (1) altering the volume delay function, and (2) altering the capacity lookup table. Because the two methods provided similar results; only the results of altering the capacity lookup table are given in this report.

Scenario 2: Reduce Parking Needs

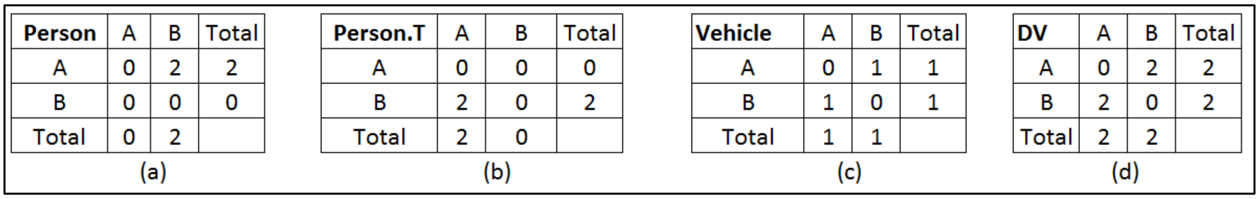
A review of Grush et al. (2016), Isaac (2016a), Williams (2013), and Zhao and Kockelman (2017) suggested that self-parking of DVs could potentially result in two changes: individuals who own a DV might choose not to park it at their destination, and existing parking might be converted to other uses.

1. *One short-term change if DVs are not shared outside the household could be that persons choose to send their vehicle home when it is not needed.* For example, a DV drops a person off at work, is sent home to park, and then makes that same trip again to pick up the person. The researchers initially modeled this behavior by doubling the number of trips in the trip generation step (e.g., changing the production variable "phbw" to "2*phbw" within the script file "TGGEN00A.S"). However, the TRP pointed out two potential concerns with such an approach: (1) doing this prior to trip distribution could result in changing the destination of some work trips, and (2) doing this prior to the creation of an origin-destination matrix could result in erroneously having two peak period trips from home to the CBD, rather than one trip from home to the CBD and one trip from the CBD to home. A third concern is that there may be interest in knowing how changes in behavior by mode affect the results (e.g., what happens if only drivers of a single occupant vehicle [SOV] exhibit this behavior versus what happens if current users of other modes use a DV and send it home while at work?).

Accordingly, as suggested by the TRP, a revised approach was used where the researchers doubled the appropriate trips in the origin-destination vehicle trip matrix. That is, just prior to the vehicle trips being loaded onto the network and after the mode choice step, there are 35 production-attraction person matrices reflecting trips by purpose and mode. For example, one such matrix reflects HBW trips (purpose) where such trips are by SOV (mode). Because these matrices reflect 24-hour trips, the model converts these production-attraction person matrices to origin-destination vehicle matrices by transposing the production-attraction person matrix, adding this to the original production-attraction person matrix, dividing by the vehicle occupancy, and then multiplying the result by 0.5 to reflect the fact that two trip ends yield a single trip.

Such an approach is consistent with the literature for 24-hour trip tables (Martin and McGuckin, 1998), and a simple example of this approach is reflected in Figure 9a-9c, where a single person lives in Zone A and works in Zone B. Then, as shown in Figure 9d, a ZOV trip from Zone B to Zone A (for the morning period) and a ZOV trip from Zone A to Zone B (for the evening period) are added to the matrix. Figures C3 and C4 in Appendix C, and the material preceding these figures, show the script changes necessary to implement this approach.

As discussed in Appendix C, the approach in Figure 9d is appropriate for a region that uses a 24-hour model where such a model also includes a single peak period. The Charlottesville model is one example. However, for locations that have a separate morning and evening peak period, a similar technique but modified as shown in Figure C2 in Appendix C would be used. Both approaches presume that the person sends the ZOV trip back to the origin, i.e., back home. A less extreme scenario would be to modify Figure 9d such that there were 1.5 trips from Zone A to Zone B and from Zone B to Zone A, reflecting the fact that one-half of commuters exhibited this behavior. Alternatively, for regions that wish to model the impacts of having adjacent jurisdictions with disparate parking policies, Figure 9d could be modified such that only for certain zones would there be additional trips. A more extreme scenario would be to apply Figure 9d for trip purposes other than the work trip, such as HBO trips or NHB trips that originated or terminated at the workplace.



Person	A	B	Total
A	0	2	2
B	0	0	0
Total	0	2	

(a)

Person.T	A	B	Total
A	0	0	0
B	2	0	2
Total	2	0	

(b)

Vehicle	A	B	Total
A	0	1	1
B	1	0	1
Total	1	1	

(c)

DV	A	B	Total
A	0	2	2
B	2	0	2
Total	2	2	

(d)

Figure 9. Steps to Model Commuters Sending an Empty DV Home Rather Than Parking It at Work: (a) production-attraction person matrix; (b) transposed production-attraction person matrix; (c) origin-destination vehicle matrix; (d) origin-destination vehicle matrix that includes additional trips by empty DVs. DV = driverless vehicle; A = zone where the person lives; B = zone where the person works; Person.T = transpose of the matrix Person.

2. *One long-term change is that parking lots may be converted to other land uses.* A fourth scenario that differs from Scenarios 2a, 2b, and 2c is thus to convert these parking lots in the CBD to such uses where such land uses attract new development to the region. In Scenario 2d, researchers sought to account for the fact that in close-in locations, existing parking lots could be converted to other uses, thereby increasing productions and attractions within certain inner zones. (Scenario 2d thus induces additional residential and commercial development at these former parking lot locations. An alternative scenario to Scenario 2d would be to reduce development at outer locations such that total growth of the region did not change.) To be clear, Scenario 2d provides an order-of-magnitude example of how the conversion of parking lots to new land development may affect travel demand, as the number of parking lots that are converted, as well as the types of land development to which they are converted, will affect the quantity and types of new trips that result.

In Scenario 2d, a portion of the City of Charlottesville—the area near and including the CBD—was treated as the inner location, and thus parking lots therein were converted to other land uses (Figure 10). The increase in productions was roughly equal to the increase in attractions, and a mix of land development alternatives were considered based on a review of the Institute of Transportation Engineers (ITE) *Trip Generation Manual* (ITE, 2012a, 2012b).

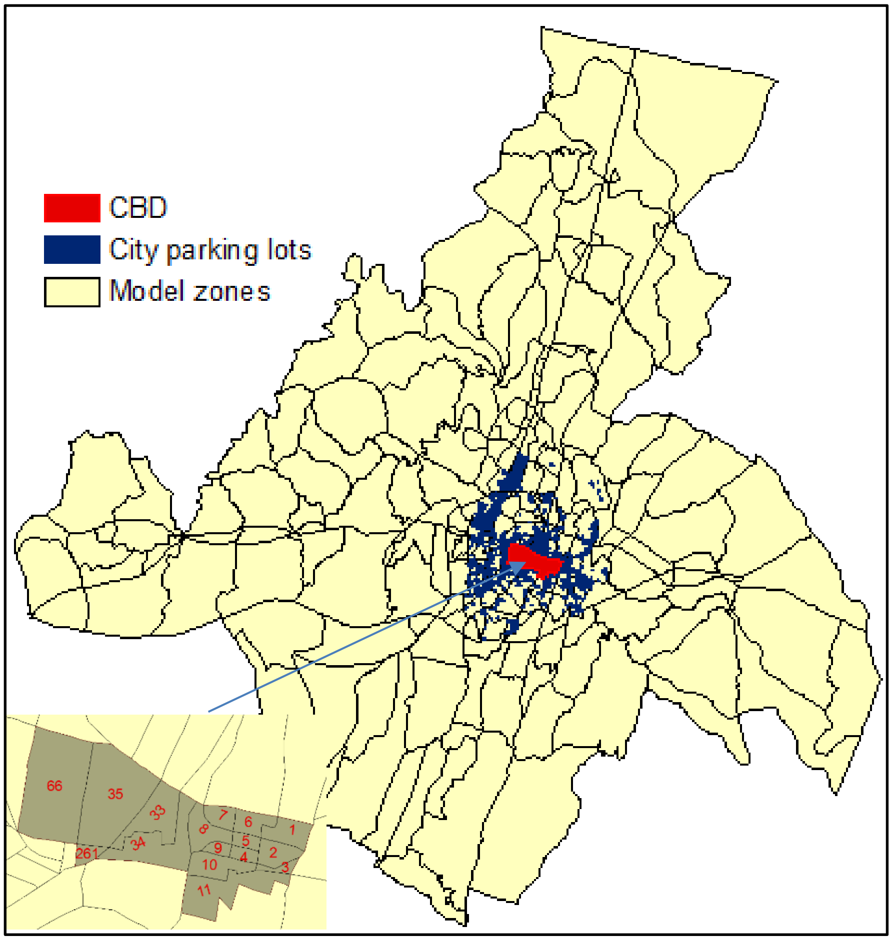


Figure 10. Area of Charlottesville Business District (Red) Where Parking Areas Could Be Converted to Other Land Uses. CBD = central business district.

Steps Required to Develop Scenario

Five steps were required to develop this scenario:

1. Estimate the new employment that could replace existing parking in Figure 10.
2. Estimate the trips that such employment could generate.
3. Adjust the trip estimates to account for multistory parking garages in the CBD.
4. Convert these trips to productions and attractions by trip purpose.
5. Modify the trip generation script to accommodate this increase in trips.

Estimate the New Employment That Could Replace Existing Parking in Figure 10. Because parking data were available only for the City of Charlottesville (rather than the entire region) and for year 2017 (a more recent period than the base year in the model), the researchers used additional data to relate parking to employment. Data for the City of Charlottesville (2017) showed approximately 1,410 parking lots, with a total area of 2,292,425 square meters. Total employment for the City of Charlottesville according to the Bureau of Labor Statistics (2017a) for year 2016 (the last year for which full data are available) was 114,317. The ratio of these two values suggests that there are roughly 20.053 square meters of parking corresponding to one position of employment. Both the parking data and the employment data have limitations in terms of relating parking area to employment: the parking data do not account for multistory parking garages, on-street parking, and the fact that some parking is likely used for residential rather than employment purposes, and employment data do not include military, proprietor, or household employment (Bureau of Labor Statistics, 2017b).

To allocate the 1,410 parking lots in the city to the roughly 115 transportation analysis zones (TAZs) that contain this parking, two operations were performed in GIS after re-projecting these data into Albers equal area. An identity overlay split parking lots spanning two or more zones into smaller polygons, where the size of each polygon was proportional to the amount of parking lot located in each zone. This operation resulted in 1,694 parking polygons, but the total parking area of 2,292,425 square meters did not change. Then, a dissolve operation was used to determine, for each zone, the sum of the parking areas within each zone.

The results suggest that within the CBD shown in Figure 10, there are roughly 2.76 million square feet (256,879 square meters) of parking that could be converted to other uses. This estimate is higher than reality if all such land development is kept to one story, since land development requires a floor area ratio of less than 100% (in fact, a floor area ratio of 40% can be considered relatively high). This estimate is lower than reality if multilevel development (e.g., high-rise condominiums or four-story shopping complexes) is feasible.

Estimate the Trips That Such Employment Could Generate. To create a realistic scenario for the number of new trips that might be generated by additional development; ITE trip generation rates (ITE, 2012a, 2012b); types of housing that have been built in the Charlottesville area (City of Charlottesville, 2007); and typical square footage of housing types (U.S. Census Bureau, 2017) were consulted. Four iterative steps were then followed:

1. *A new imaginary employee was assigned to one of five commercial land uses cited by ITE (2012a, 2012b): general office building, medical-dental office building, discount club, specialty retail center, and furniture store.* There are hundreds of different commercial land uses in ITE's *Trip Generation Manual* (ITE, 2012a, 2012b), and thus other uses could be chosen; these five were selected because they showed a wide range of trip generation rates per employee, they provided trip rates based on number of employees and gross floor area, and they were a manageable number of land uses with which the researchers could experiment.

2. *Three principles were used in determining the percentage of new employees for each land use.* First, because the percentage of employment in the region was expected to rise from 20.2% in 2007 to 22.6% in 2035 (Corradino Group, 2009), the researchers forced retail employment (e.g., discount club, specialty retail center, and furniture store in this case) to be 23.0% of total employment in 2040 (where the 23.0% is an extrapolation of the 2007-2035 trend reported by the Corradino Group [2009]). Second, because the Bureau of Labor Statistics (2015) forecast at the national level in

2024 that the sum of five service employment categories the researchers judged to be comparable to office employment (information, financial activities, professional and business services, federal government, and state and local government) would be 3.41 times higher than the category of health care and social assistance, the researchers forced general office building employment to be 3.41 times higher than medical-dental office building employment. Third, because the number of person trips per household based on data from the National Household Travel Survey (Santos et al., 2011) was 9.50, the researchers altered the percentages of the three categories of retail employment until this value of 9.50 trips per household was attained.

3. *Based on ITE's Trip Generation Manual (ITE, 2012b), the number of commercial trip ends per employee and the square footage of gross floor area that would be required for each commercial land use were estimated.* For the entire region, socioeconomic data in the 2040 travel demand model (i.e., the forecast for year 2040 used to execute the Charlottesville model) suggested a ratio of roughly 1.29 employees per household such that each employee "requires" about 0.777 households. In addition, the number of residential trip ends per new employee was estimated using a weighted average of three types of housing (single family detached dwelling units, condominiums, and apartments) (City of Charlottesville, 2007) and trip generation rates expected for these housing types (ITE, 2012a).

4. *The number of new employees was increased until all the parking area in the CBD had been used by residential or commercial land uses.* The resultant sum of commercial and residential trip ends when divided in half gives the net number of new trips in the CBD.

These results are shown in Table 5.

Table 5. Estimated New Trips From Conversion of Parking Area in the Central Business District

Land Use Type	Trip Ends per New Employee[a]	Trip Ends per New 1,000 ft^2[a]	1,000 ft^2 per New Employee	New Employees	Land Area (1,000 ft^2) Created From Parking Lots	New Trip Ends
General office building	3.32	11.03	0.30	830	250	2,756
Medical-dental office building	8.91	36.13	0.25	243	60	2,169
Discount club	32.21	41.8	0.77	131	101	4,225
Specialty retail center	22.36	44.32	0.50	98	49	2,182
Furniture store	12.19	5.06	2.41	91	220	1,112
Household	5.84	3.90	1.49	1,393[b]	2,083	8,134
Total				1,393[b]	2,763	20,577[c]

[a] Based on data reported by the Institute of Transportation Engineers (2012a, 2012b).

[b] Each employee lives in a household. The sum of employees working in the five commercial land uses equals the sum of employees living in households. These 1,393 employees reside in (0.777)(1,393) = 1,083 households.

[c] The number of new trips generated is equal to one-half the trip ends.

The area occupied by the CBD parking lots if converted to other land uses might support a total increase in employment of 1,393, which would occupy a total land area of about 2.763 million square feet. About 0.250 million square feet would be the general office building land use type, which would generate roughly 2,756 trip ends. The 830 new employees who would work in this type of land use, along with the employees who would work in the other four types of land use (medical-dental office building, discount club, specialty retail center, and furniture store), would live in households that would consume approximately 2.083 million square feet. The results in Table A1 of Appendix A suggest that the combined commercial and residential land uses would generate an additional 20,577 trip ends (e.g., 10,289 trips). Because these trips correspond to 2,763,000 square feet (or 257,000 square meters) of parking, Table 5 suggests that each square meter of parking could result in 0.04 additional daily trips.

These trips were distributed to the CBD zones on the basis of the square meters of parking available in each zone. For example, since Zone 66 has 48,259 square meters of parking, the conversion of parking lots to other land uses could lead to (0.04)(48,259) = 1,933 extra trips.

Adjust the Trip Estimates to Account for Multistory Parking Garages in the CBD. At the regional level, the lack of multistory parking garage data is a relatively small problem compared to the vast amount of surface parking. However, in focusing on the CBD, where parking garages are concentrated, this could be problematic. Based on a draft parking analysis by Nelson\Nygaard Consulting Associates Inc. (2015), there are three relatively large garages in the CBD: the Market Street Garage in Zone 2 (473 spaces), the Water Street Garage in Zone 10 (1,019 spaces), and the Omni Garage in Zone 8 (400 spaces). Based on a planning level analysis by Kavanaugh (2015) of 350 square feet per parking space, these garages would increase the number of trips in Zones 2, 8, and 10 in the CBD by approximately 23%. Thus, whereas Table 5 suggested a total of 20,577/2 = 10,288 trips, inclusion of parking garages increased this number by 23% to 12,752 trips.

Convert These Trips to Productions and Attractions by Trip Purpose. For each of five trip purposes (HBW, HBO, NHB, IX, and off-campus university), the additional trip ends that would result for each zone were summed, giving a total that represents productions and attractions. (The researchers did not perform this operation for a sixth trip purpose—on-campus travel—as those trips reflect students living in dormitories.) The total trips ends for each zone were distributed on the basis of the original percentages for each trip purpose: for example, because IX productions account for 40% of all trip attractions (excluding XX trips and dorm-based trips), 40% of the new trip productions were assigned to that purpose (see Table 6). Thus, the conversion of parking lots to other land uses for Zone 66 would lead to (1,933)(40%) = 773 IX productions for that particular zone.

The initial execution of the original Scenario 2d showed that the observed number of trips was about two-thirds of the expected number of trips. Examination of total trips produced by purpose showed the researchers had initially inadvertently created a combination of two scenarios: for internal trips (e.g., HBW, HBO, NHB, HBU, and trip purposes that stay within the modeling region), Scenario 2d reflects new development, which was the intention for the scenario and was expected.

Table 6. Percentages of Trips That Are Productions and Attractions[a]

Trip Purpose	Productions		Attractions	
	No.	**%**	**No.**	**%**
Home-based work	3,323	5%	14,464	25%
Home-based other	9,691	16%	24,697	42%
Nonhome-based	19,424	32%	19,424	33%
Internal-external[b]	24,168	40%	0	0%
Off campus university	4,535	7%	0	0%
Total	61,141	100%	58,585	100%

[a] These percentages are based on two files: "TGEN_HB.dbf" and "UVAPANDA.dbf." A related file ("TGEN_PA.dbf") gives similar percentages; however, that file appears to include multipliers for certain trip purposes. For compatibility with the original script, the researchers believe that the percentages shown are more appropriate.

[b] For productions, these normally reflect a traveler living in the region and working outside the region. For attractions, these normally reflect a person living outside the region and working or shopping in the region.

However, for IX trips, the researchers were surprised to learn that productions are balanced to attractions, which meant that although trip ends in the CBD increased, this resulted at the expense of trip ends in other locations.

Martin and McGuckin (1998) noted: "External station productions are trips whose home is outside of the region and external station attractions are trips whose home is within the region." Interestingly, the Charlottesville model appears to be organized a bit differently: a column labeled "IX productions" shows values greater than zero for all CBD zones but equal to zero for all external stations. A different column labeled "IX attractions" shows values of zero for all CBD zones yet greater than zero for all external stations. Examination of the script shows that the IX productions appear to be based on both the number of households in the area and the employment, whereas the attractions appear to be based on traffic counts. Further, the rate for productions is roughly 0.33 trips per household plus 0.724 trips per employee, such that for zones located in the CBD, most of the "IX productions" are based on employment, not households.

Thus, in order to generate approximately 12,752 trips, the attraction percentages shown in Table 6 had to be modified to account for how productions and attractions are balanced, which varied by trip purpose: for HBW, HBO, and NHB, productions guide the control total; for HBU, no balancing is performed; and for IX, attractions guide the control total. Accordingly, the researchers first increased university attractions from 0% to 7% to equal productions (which appeared reasonable since the CBD would attract some students from the nearby university); then set NHB attractions equal to NHB productions (which was a slight change from 33% to 32%); and then, recognizing that HBW and HBO attractions would be scaled to equal productions, scaled the attraction percentages for these purposes by the sum of the production percentages for these two categories. Thus, because HBW and HBO productions represent 21% of all productions, HBW attractions became 21%*25%/(25% + 42%) = 8% of all attractions and HBO attractions became 21%*42%/(25% + 42%) = 13%. The script was also modified to increase IX attractions by 1.02112 in order to allow an increase in 40% of IX productions. Although the nomenclature of the model differed from that in Martin and McGuckin (1998), this change allowed for productions (as defined in the model) to be attracted to IX attractions.

Table 7 shows that these changes resulted in an increase in total trip ends in the CBD and in the region. Some experiments showed that increasing the number of HBW attractions in the CBD can be done, but because of scaling to productions, this would result in some trips being taken away from other locations. With the modifications shown, the desired number of trip ends (or total trips) within the CBD was within 3% of the desired amount for this scenario.

Table 7. Trips Generated in Scenario 2d

Trip End Purpose	Productions (P)			Attractions (A)			P IX	A IX	P HBU	A HBU	Total P	Total A	Total Trips
	HBW	HBO	NHB	HBW	HBO	NHB							
Desired	638	2,040	4,081	2,805	4,846	4,081	5,101	0	893	893	12,752	12,624	12,688
Total[a]	641	2,040	4,083	650	2,033	4,083	5,106	5,101	893	893	12,763	12,760	12,761
CBD[a]	641	2,040	3,954	982	1,492	3,954	9,883	0	893	893	17,411	7,321	12,366

HBW = home-based work; HBO = home-based other; NHB = nonhome-based; IX = internal-external; HBU = home-based university.
[a] Observed trips in the model.

Modify the Trip Generation Script to Accommodate This Increase in Trips. Finally, the script was modified to reflect the additional trips that would result from the conversion of parking to some type of employment. The variable "ZI.3.ParkPLo" is the total number of trip ends resulting from the conversion of parking to another use. This method required modifying a total of 16 lines in two scripts, as shown in Appendix C. Attraction increases were applied to the University of Virginia (UVA), CBD, and urban areas, whereas rural areas were unchanged.

Summary

For Scenario 2, a total of 10 sub-scenarios were executed: a base doubly constrained gravity model (which was the same as that used in Scenario 1); a base singly constrained gravity model (which differed from that used in Scenario 1); and for each of these gravity model types, 4 scenarios: replace commuter parking with an empty DV trip for the drive alone mode only; replace commuter parking with an empty DV trip for drive alone and carpool modes only; replace commuter parking with an empty DV trip for all modes; and redevelop CBD parking lots with new residential and commercial uses.

Scenario 3: Evaluate Potential Shifts From or to Transit

The possibility had been raised that DVs could "support" transit use by helping users get from their origin to the transit service or from the transit service to the final destination (Polzin, 2016). (For instance, if DVs performed this function, they might reduce the discomfort associated with the portion of the trip prior to boarding the transit vehicle.) Polzin (2016) also suggested that DVs could adversely affect transit use, for example, noting that transit could possibly be restricted to high-volume rail uses. When executing travel demand models for a variety of urban areas, Rixey (2017) concluded that transit use could increase or decrease. Accordingly, two contrasting scenarios were developed for evaluating the potential of DVs to influence transit use: one scenario considered an increase, and the other considered a decrease. A third scenario examined how longer trips generally might affect the transportation model.

In executing these scenarios, within the mode portion of the model, the total number of person trips will differ slightly, by about 0.02%, depending on whether they are extracted from the "InitialTdist.mat" matrix at the beginning of the mode choice step or from the file "Mode

Summary.txt" at the end of the mode choice step. Examination of the mode choice script does not show a clear reason for this modest difference. However, a possibility is that with the several numerical manipulations in the script (e.g., the initial number of person trips is first divided into 0 car, 1+ car, and student households for each zone and then the logit equations for the mode choice step are applied), there is some rounding that causes the discrepancy. To avoid errors in comparison, the researchers consistently used the person trip percentages based on the conclusion of the mode choice step, i.e., the person trip percentages extracted from the file "Mode Summary.txt."

Potential Shifts From Other Modes to Transit (Scenario 3a)

Scenario 3a considered how DVs might solve the last-mile problem for transit, i.e., lead to an increase in transit use. Part of this increase in comfort may result from shared DVs eliminating the need to walk to the transit stop and providing greater comfort by removing the driving task (Levin, 2015). The Corradino Group (2009) explained that there are three distinct transit modes in the model: (1) walk to local bus, (2) walk to premium service, and (3) drive to best available service. This "premium service" does not exist in reality; the Corradino Group (2009) explained: "The premium mode used for transit is a place holder for any future premium service that may be introduced in Charlottesville." Thus, in practice, transit modes 2 and 3 have almost zero values in the base scenario. To examine how DVs could potentially complement transit, the researchers created a new mode that is a hybrid of modes 2 and 3 by performing two changes for the peak hour:

1. *"Walking to the bus" was replaced with "taking a shared DV*." In the model, walking time was replaced with the driving time and the cost of out-of-vehicle travel time was replaced with 65% of the cost of in-vehicle travel time based on a potential change in comfort suggested by Childress et al. (2015). In practice, as shown in Figure 11, two lines in the script were changed: walk time (shown as the variable "pkwktimeex") was replaced with driving time to best available transit ("pkwktimeBA") and the in-vehicle time parameter "HBWCIVT" was replaced with "HBWCIVT*0.65." The variable "pkwktimeBA" means "drive to best available transit," despite the fact that "wk" means "walk" in other variables.

2. *"Waiting for the bus" was eliminated*. The wait time was set to zero, which is why the variable "pkwktimeex" is multiplied by zero.

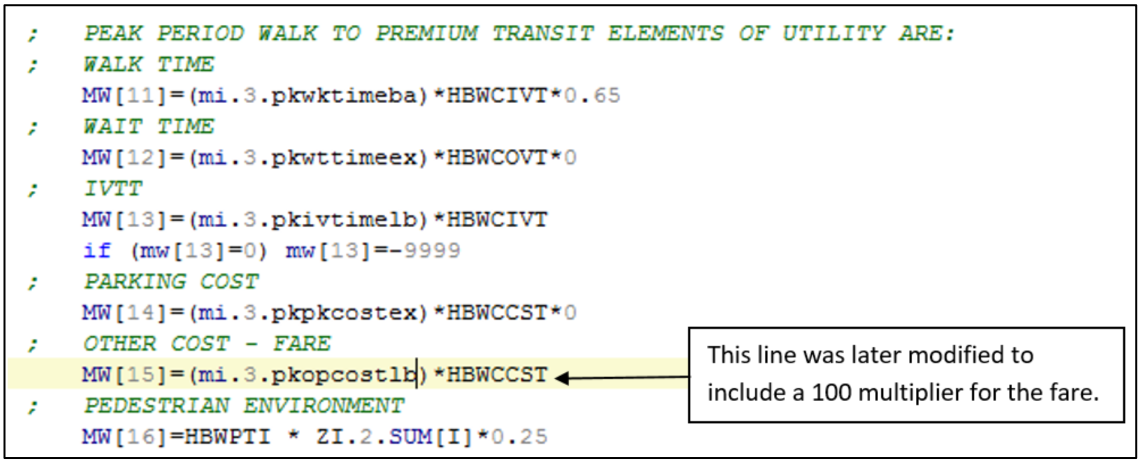
Although these represent the change in the mode conceptually, four additional changes were made to the script because of the nature of this particular model. The researchers' understanding of these variables was based on (1) examination of the model documentation (Corradino Group, 2009); (2) the model script; (3) calculations of the transit utility for three zone interchanges as shown in Appendix B; and (4) interactions with the TRP.

1. The variable for travel time in premium transit ("pkivtimeex") was replaced with the variable for travel time in local bus ("pkivtimelb").

2. The parking cost variable was set to zero, although the parking cost had been presumed to be zero in the original model.

3. The operating cost variable for local bus was used, where the variable “pkopcostex” was replaced with “pkopcostlb.”

4. For this particular scenario, after discussions with the TRP, a new base scenario was developed: local bus operating cost—i.e., the fare—was modified to be multiplied by 100 as shown by the line “MW[15]=(mi.3.pkopcostlb*100)*HBWCCST.” This made the utility function for walk to local bus comparable to the utility functions for walk to premium transit and drive to best available transit service, as discussed in Table 3.



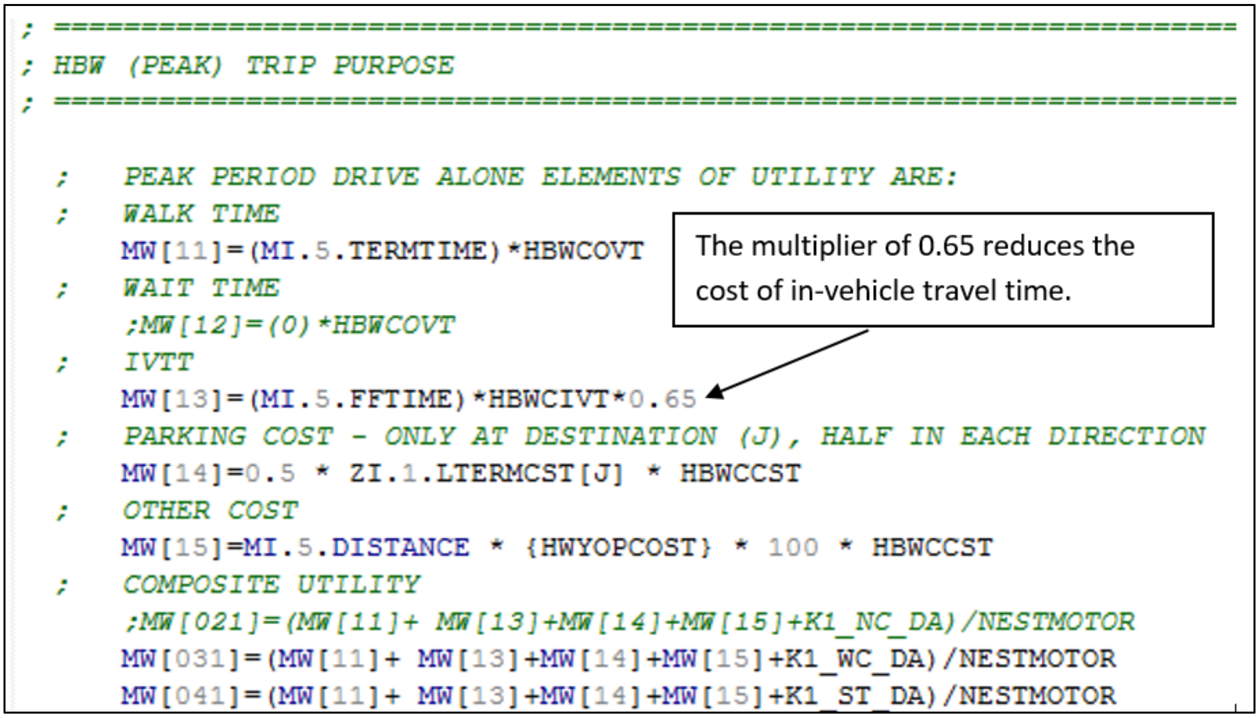
```
;    PEAK PERIOD WALK TO PREMIUM TRANSIT ELEMENTS OF UTILITY ARE:
;    WALK TIME
     MW[11]=(mi.3.pkwktimeba)*HBWCIVT*0.65
;    WAIT TIME
     MW[12]=(mi.3.pkwttimeex)*HBWCOVT*0
;    IVTT
     MW[13]=(mi.3.pkivtimelb)*HBWCIVT
     if (mw[13]=0) mw[13]=-9999
;    PARKING COST
     MW[14]=(mi.3.pkpkcostex)*HBWCCST*0
;    OTHER COST - FARE
     MW[15]=(mi.3.pkopcostlb)*HBWCCST
;    PEDESTRIAN ENVIRONMENT
     MW[16]=HBWPTI * ZI.2.SUM[I]*0.25
```

This line was later modified to include a 100 multiplier for the fare.

Figure 11. Initial Modifications to Implement Scenario 3a. Later, the fare was multiplied by 100 and a revised base scenario and a new version of Scenario 3a were developed.

Shifts From Transit to Other Modes (Scenario 3b)

Zhao and Kockelman (2017) suggested that by year 2020, connected vehicles may increase VMT for one particular region by 20%, owing to three factors: (1) “self-parking” of DVs (e.g., an increase in ZOVs as discussed in Scenario 2); (2) “door-to-door” service, some of which would result in a shift from existing transit modes (the focus of Scenario 3b); and (3) increased comfort for passengers of DVs. Therefore, within the same mode choice script (file “MCMAT00A.S”), the in-vehicle travel time was multiplied by 0.65 for three modes: drive alone, carpool 2, and carpool 3+ during the peak hour. As with Scenario 3a, the focus was on the peak hour, so only HBW trips had the utility function modified, as shown in Figure 12.



```
; ====================================================================
; HBW (PEAK) TRIP PURPOSE
; ====================================================================

  ;   PEAK PERIOD DRIVE ALONE ELEMENTS OF UTILITY ARE:
  ;   WALK TIME
      MW[11]=(MI.5.TERMTIME)*HBWCOVT
  ;   WAIT TIME
      ;MW[12]=(0)*HBWCOVT
  ;   IVTT
      MW[13]=(MI.5.FFTIME)*HBWCIVT*0.65
  ;   PARKING COST - ONLY AT DESTINATION (J), HALF IN EACH DIRECTION
      MW[14]=0.5 * ZI.1.LTERMCST[J] * HBWCCST
  ;   OTHER COST
      MW[15]=MI.5.DISTANCE * {HWYOPCOST} * 100 * HBWCCST
  ;   COMPOSITE UTILITY
      ;MW[021]=(MW[11]+ MW[13]+MW[14]+MW[15]+K1_NC_DA)/NESTMOTOR
      MW[031]=(MW[11]+ MW[13]+MW[14]+MW[15]+K1_WC_DA)/NESTMOTOR
      MW[041]=(MW[11]+ MW[13]+MW[14]+MW[15]+K1_ST_DA)/NESTMOTOR
```

The multiplier of 0.65 reduces the cost of in-vehicle travel time.

Figure 12. Example of Reducing the Cost of In-Vehicle Travel Time by 35%. A similar procedure was performed for the carpool 2 and carpool 3+ modes.

Potential Longer Trips (Scenario 3c)

Chakraborty (2017) suggested that DVs might alter behavior by allowing longer trips to be taken since the increased comfort would lower the value of travel time. For the singly constrained gravity model, the friction factors used in the trip distribution step were iteratively adjusted until the mean congested trip travel time had increased by 35%, a percentage suggested by Childress et al. (2015). Table 8 shows how the travel time changes for the free flow condition (which is used for the initial measure of impedance in the trip distribution step and applies to each trip purpose separately) and the overall congested MTT. For the singly constrained gravity model, a multiplier of 0.125 times the friction coefficient yielded a congested travel time (29.81 minutes) that was 35.01% longer than the base model congested time (22.08 minutes). This factor was derived iteratively: previous multipliers included 0.095 (yielding 30.35 minutes, which is a 37.5% trip length increase relative to the base congested time of 22.08 minutes); 0.105 (29.99 minutes, a 35.8% increase); 0.20 (28.95 minutes, a 31% increase); 0.14 (29.56 minutes, a 33.9% increase); and 0.12 (29.97 minutes, a 35.7% increase). For the doubly constrained model, when all friction factors are set to be equal (e.g., whether the value is 1 or 1,000), the congested MTT is 28.23 minutes, which is 35.1% higher than the base congested time of 20.89 minutes.

Table 8. Impact of Adjusted Impedances on Trip Length (minutes)

Trip Length Type	Trip Purpose	Doubly Constrained		Singly Constrained	
		Base Model	Revised Impedances[a]	Base Model	Revised Impedances[a]
Uncongested	HBW	17.58	19.02	10.15	11.41
	HBO	15.66	18.99	8.22	10.89
	NHB	14.24	18.2	7.05	10.04
	HBU	11.45	12.07	5.71	8.1
	HDORMU	11.49	11.9	5.11	7.55
	IX	21.93	24.59	16.65	19.94
Congested	All	20.89	28.23	22.08	29.81

HBW = home-based work; HBO = home-based other; NHB = nonhome-based; HBU = home-based university; HDORMU = home-based university dormitory; IX = internal-external.

[a] Multiplication of the original impedances by 0.125 yielded these mean trip times. For example, for HBW trips, the original impedance was $e^{-0.08001(\text{travel time})}$. For the revised impedance, this equation became $e^{-0.08001(\text{travel time})*0.125}$. Thus, as shown in Appendix C, the script was modified to read: “mw[21]=MI.2.FFTIME*(-0.08001*0.125).”

Summary

For Scenario 3, eight sub-scenarios were executed. With the revised utility function that included the 100 multiplier, there was a new base scenario and then Scenario 3a (shift from other modes to transit), Scenario 3b (shift from transit to other modes), and Scenario 3c (longer trips), with all models having singly and doubly constrained versions.

Scenario 4: Allow Nonfamilial Sharing of DVs

Scenario 4 concerns an increase in ZOV trips that might result from persons choosing to share DVs rather than purchase them outright. Whereas Scenarios 2 and 3 considered a DV that was restricted to a single household, it may be possible to share vehicles within a household or with others who live outside a household. Williams (2013) suggested that DVs may reduce car ownership and facilitate car-sharing, resulting in less time spent parking, more wear-and-tear on the vehicle, and higher fixed costs; in fact, 9 to 13 privately owned vehicles could be replaced by 1 shared DV.

Scenario 4 thus involves consideration of a subscription model where travelers pay for individual trips to a provider in lieu of owning a vehicle. Although such a subscription-based model may differ from a traditional ownership-based model in a number of ways, Scenario 4 considered just one potential difference: How might the increase in deadheading lead to an increase in VMT (and other outputs of interest such as emissions)? The amount of this ZOV VMT depends on the degree of matching between a leading trip’s destination and a following trip’s origin—with an infinitely high degree of matching such that these locations are identical, there would be no additional VMT.

Scenario 4a: A High Degree of Matching

If there is a high degree of matching such that ZOV trips are relatively short (e.g., beginning and terminating within the same zone), deadheading will generally not occur on the roadway network included in the model. An example is a trip that starts and stops in the same residential subdivision (e.g., within the same zone) (see Figure 13).

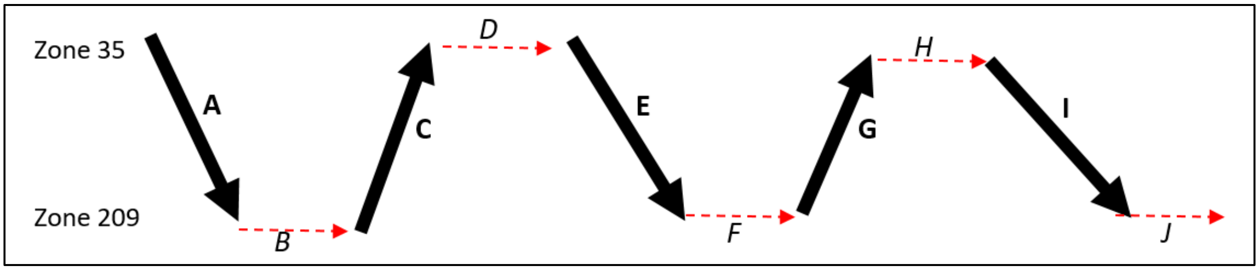


Figure 13. Example of Zero Occupant Vehicle Trips. The occupancies for interzonal trips A, C, E, G, and I are 1 person per vehicle. The occupancies for intrazonal trips *B, D, F, H,* and *J* (italicized) are 0.

The interpretation of this scenario is that because sharing occurs within each TAZ, the additional VMT is not on the observed roadway network (see Figure 13). Thus, trips B, D, F, H, and J are not on the network per se.

However, VMT still influences total emissions, as shown in Scenarios 4a-4c. For HBW trips, Equation 1 makes this trip length a function of individual zone size based on a review of Martin and McGuckin (1998). For example, for ZOV trips within Zone 209 versus those within Zone 35, a ZOV trip within Zone 209 has a length of 0.5(6.33)^(1/2) = 1.26 miles (since Zone 209 is relatively large with an area of 6.33 miles) whereas each ZOV trip within Zone 35 has a length of 0.5(0.11)^2 = 0.16 miles (since Zone 35, near the CBD, has a much smaller area of 0.11 miles).

0.5(Zone area)^0.5 (Number of HBW trips terminating in the zone) [Eq. 1]

To implement this approach, the number of vehicle trips for each zone based on the number of destinations from the origin-destination table may be tabulated. Table 9 illustrates these calculations for the simple two-zone system in Figure 13 where there are five trips between Zones 35 and 209 (which occur on the network) and an additional five ZOV trips that occur off the network. The three ZOV trips terminating in Zone 35 add roughly 0.49 VMT; by contrast, the two ZOV trips terminating in Zone 209 add roughly 2.51 VMT.

For Scenario 4a, the number of HBW vehicle trips just prior to Sequence 7 (trip assignment) was 129,300, although a different answer (112,359) based on the step just prior to trip assignment in Sequence 12. For consistency, the number of vehicle trips from the latter process was used, based on the file "modeout.mat," which meant that the number of vehicle trips for three modes (drive alone, carpool 2, and carpool 3+) needed to be exported and summed outside Cube software (which was used to execute the Charlottesville model).

Table 9. Example of Tabulating Zero Occupant Vehicle (ZOV) Vehicle Miles Traveled (VMT) for Figure 13

Description	Zone 35	Zone 209
On network trips starting in the zone	Trips A, E, I	Trips C, G
Off network trips ending in the zone	Trips B, F, J	Trips D, H
Zone area in miles	0.107	6.322
ZOV trip length in miles	0.163	1.257
Total off-network ZOV VMT	= 3 x 0.163	= 2 x 1.257
Total off-network ZOV VMT	0.49	2.51

Scenarios 4b and 4c: A Medium Degree or Low Degree of Matching

Scenarios 4c and 4b presumed that when one passenger departs the shared DV, the vehicle must then make a ZOV trip within a particular region in order to arrive at the origin for the next passenger. In contrast to Scenario 4a, Scenario 4c presumed a low degree of matching such that these regions are relatively large: the entire study area is split into 5 regions, consisting of roughly 50 TAZs per region. By contrast, Scenario 4b presumed a greater degree of matching than Scenario 4c (but less so than Scenario 4a) such that the regions were relatively small, with Scenario 4c splitting the area into 51 regions consisting of roughly 1 to 13 TAZs per region. As with Scenario 4a, Scenarios 4c and 4b considered only commuting trips (HBW) in order to forecast peak hour transportation system performance.

For Scenario 4c, a GIS analysis was used to develop these 5 regions where the 262 TAZs were converted from a vector format to a raster format. Using five seed zones and the Euclidean allocation tool, a raster consisting of 5 regions was established (Figure 14, *left*). The resultant raster of 5 regions was converted to a polygon format, and then a spatial join was performed between these 5 vectorized regions and the 262 TAZs such that each TAZ was associated with 1 of the 5 regions (Figure 14, *right*). Then, the number of HBW person trips in file "TGEN_PA.dbf" (i.e., 153,862.8) that terminated in each region was determined and, based on Equation 1, the trip length for a ZOV trip associated with each HBW trip end was determined.

For example, the doubly constrained model and the northwest region in Figure 14 can be considered. The zones in that region showed a total of 11,098 HBW person trip ends. Because that region has an area of 153,454,155 square meters (59.24 square miles), Equation 1 suggests that a ZOV trip that stayed within the region would have an average length of 3.849 miles (e.g., $0.5*(59.24)^{1/2} = 3.849$). Thus, ZOV trips for the region generate 29,653.4 trips*3.849 miles = 114,126 VMT, and the sum of the additional VMT from all regions yields 496,466 VMT, as shown in Table 10.

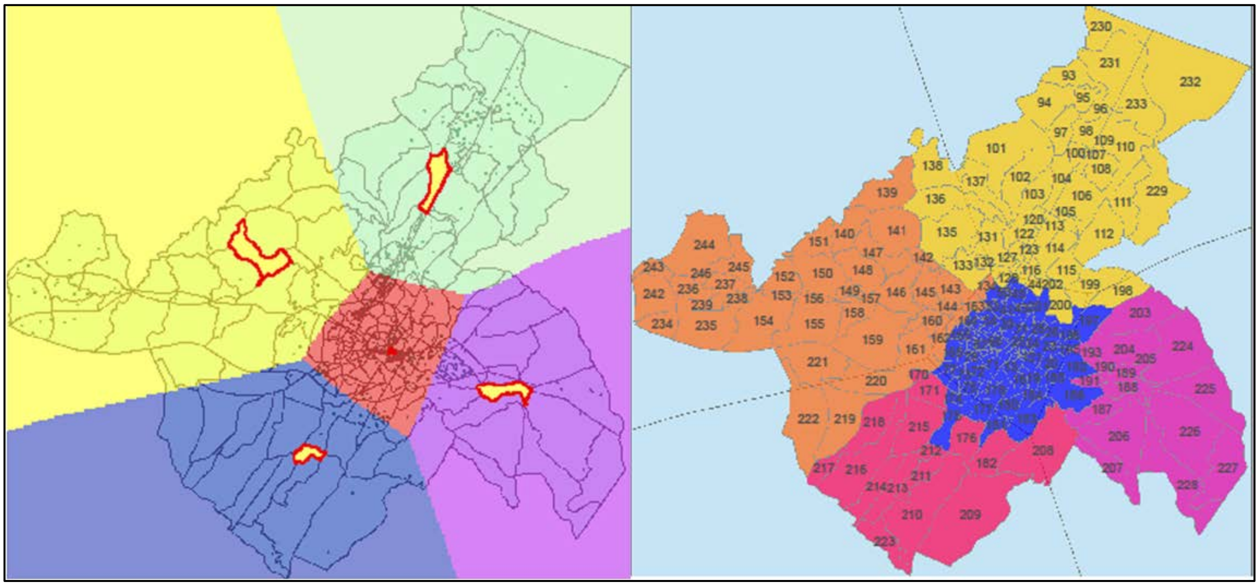


Figure 14. Implementation of Scenario 4c (a low degree of matching) With 5 Regions (*left*) and Association of Each TAZ With a Region (*right*). TAZ = transportation analysis zone.

Table 10. Summary of Vehicle Miles Traveled (VMT) From Zero Occupant Vehicle (ZOV) Trips Based on Low Degree of Matching for Doubly Constrained Gravity Model (Scenario 4c)

Region	Area (m^2)	Average ZOV Trip Length (mi)	Home-Based Work Destination Ends[a]	ZOV VMT[a]
Northwest	153,454,155	3.849	29,653	114,126
Northeast	170,076,017	4.052	50,371	204,089
Southeast	826,59,022	2.825	7,864	22,213
Southwest	86,261,173	2.886	5,785	16,692
Central	55,526,259	2.315	60,190	139,346
Total			153,863[b]	496,466

[a] All numbers are rounded to the nearest integer.
[b] The exact number as calculated by the researchers (153,862.8 person trips) is the total productions used in trip generation. There is a total of 153,863 person trips in the file "PDDST00A.PRN," which includes home-based work productions.

As noted previously, in the base case in year 2040, the total VMT is 6,829,605.34 for the doubly constrained gravity model. The estimated new VMT is thus 6,829,605.34 + 496,465.6419 = 7,326,070.642 VMT. Thus, in the trip generation script ("TGGEN00A.S"), as shown in Appendix C, a multiplier is used for the NHB trips such that the VMT generated by the model is roughly this amount. The researchers found that multiplying NHB trips by a factor of 1.685 gave a value within approximately 0.0011% of that amount (i.e., 7,325,221.93). A similar process was performed for the singly constrained gravity model: the researchers found that a multiplier of 1.608 yielded a VMT (7,399,473.59) that was within 0.01% of the desired VMT from the GIS analysis (i.e., 7,399,469.822).

The steps were repeated for a medium degree of matching (Scenario 4b), where it was presumed that there are only a few zones per ZOV matching region (Figure 15). As one might expect, with medium matching rather than low matching, the ZOV VMT is less and hence the multiplier for NHB trips is also less, with values of 1.22 and 1.173 for the doubly and singly constrained models, respectively.

Summary

For Scenario 4, 10 sub-scenarios were executed. Three concerned commuters: a high degree of matching of HBW vehicle trips where all ZOV VMT occurs off the network (Scenario 4a); a medium degree of matching of HBW trips (Scenario 4b); and a low degree of matching of HBW trips (Scenario 4c). In addition, 2 other scenarios were performed: a high degree of matching of all vehicle trips (Scenario 4d), and a high degree of sharing of vehicle trips that are carpool only (Scenario 4e).

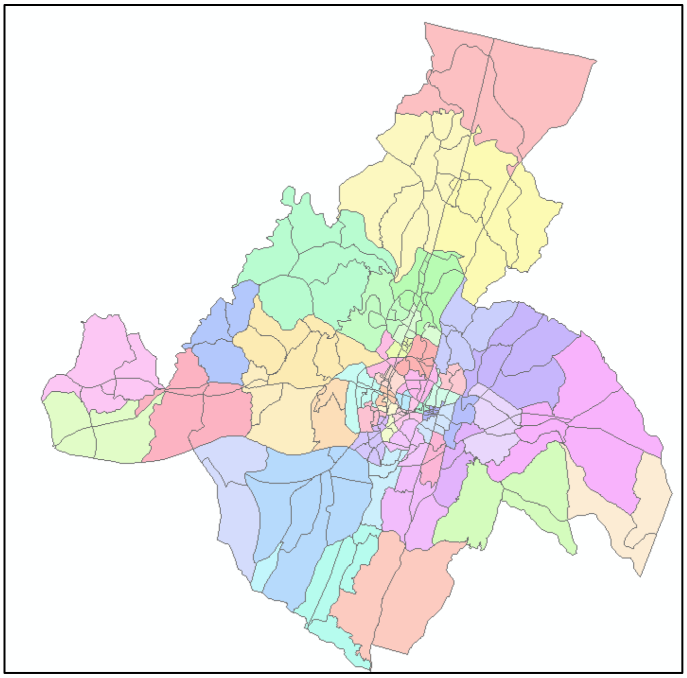


Figure 15. Catchment Area for Scenario 4b. The scenario presumes a medium degree of matching (hence 51 smaller regions rather than 5 large regions).

Scenario 5: Increase Travel by Age Groups With Traditionally Lower Vehicle Access

Overview

Scenario 5 asks: What would be the impact if persons who do not have access to a vehicle because they lack a driver's license could use a DV?" Scenario 5 contains eight sub-scenarios. Scenarios 5a and 5b concern persons age 65+ and persons age 13-17, respectively, and focus on nonwork trips only. Scenario 5c combines these two scenarios and includes persons age 18-64; for that age group only, the scenario considers both work and nonwork trips. Scenario 5d provides a comparison for all scenarios: What if the region's growth doubles the expected value for 2040? The doubling of growth is not attributed to DVs but rather is an example of an unforeseen shock that might affect the results of the travel demand model—and thus its change can be compared to those of the other scenarios that involve DVs.

Figure 16 shows the percentage of persons by age group who have or potentially have a driver's license or access to a DV based on roughly current year populations (U.S. Census Bureau, 2015b), forecast year data (Weldon Cooper Center, 2012), and rates of licensure by age group available from the literature (e.g., Miller et al., 2016; Zmud et al., 2016). For example, in year 2015, there were roughly 11,738 persons age 15-19 in the Albemarle-Charlottesville area. Because population growth should increase this age cohort from 11,738 to 15,153 by 2040, the number of licensed drivers would be expected to increase from 4,695 to 6,061, based on a 40% rate of licensure for this age group (Miller et al., 2016). If every person could have access to a vehicle, however (such that each person gets access to a licensed vehicle, even if he or she does not have a driver's license), then the number of licenses in this age group would increase from 6,061 (driver's licenses) to 15,153 (vehicle licenses). Figure 16 shows the impacts of the increase; the larger increases are at the upper and lower ends of the age spectrum.

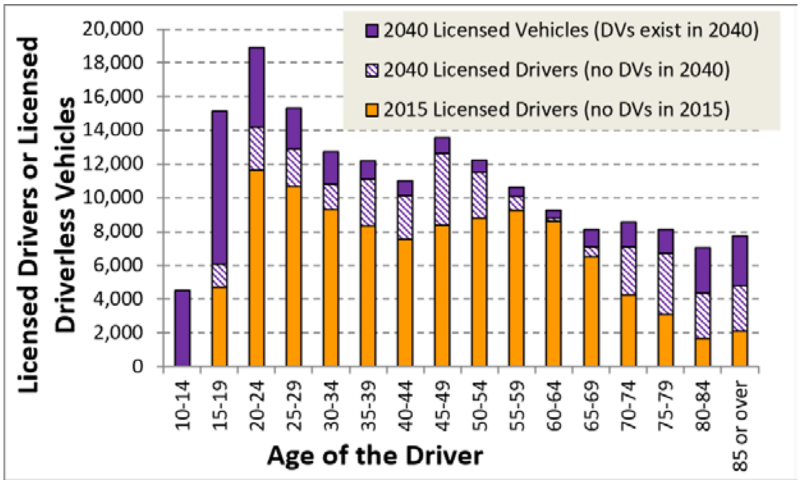


Figure 16. Potential Impacts of Population Growth and Technology on Number of Licensed Drivers and Licensed Driverless Vehicles in the Charlottesville Area. For example, for the age group 15-19 inclusive, the figure suggests that there were 4,695 licensed drivers in this age group in 2015. Without driverless vehicles, one would expect that because of population growth, there will be 6,061 licensed drivers in this category in 2040. If driverless vehicles were widely available in 2040 such that every person could have access to a licensed driverless vehicle, then at 1 per person there would be 15,153 licensed driverless vehicles for this age group in 2040. Drawn based on data from U.S. Census Bureau (2015b), Weldon Cooper Center for Public Service (2012), Miller et al. (2016), and Zmud et al. (2016).

One of the sources used for Scenario 5 was an interim report for NCHRP Project 20-102(1) (Zmud et al., 2016). *NCHRP Report 845* (Zmud et al., 2017) is the final report for this project. However, unlike the interim report, the final report does not cite the numerical information regarding rates of licensure and rates of disability as a function of age group. The information provided in the interim report (Zmud et al., 2016) was used for the development of Scenario 5, as shown in Appendix C.

Concepts for the Scenarios

As reported in Appendix B, the method for implementing Scenario 5a consisted of three main steps: (1) obtain current percentage of persons age 65+ in each Census block group; (2) reconcile geospatial errors that resulted when aligning Census geography with travel demand model geography; and (3) forecast the 2040 population age 65+ by zone. Those calculations suggest a potential increase of about 15.3% in HBO and NHB trips for persons age 65+.

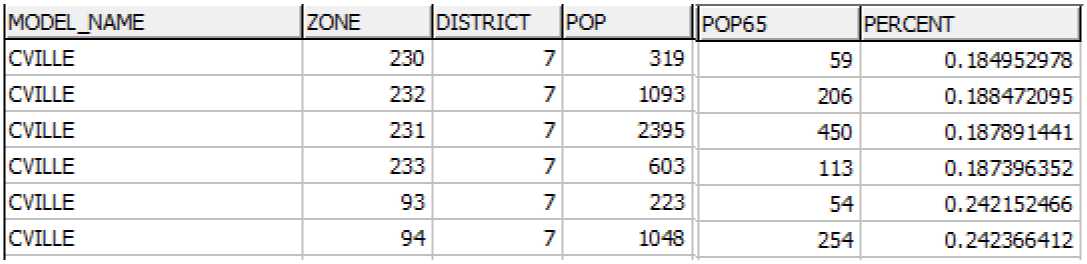
For Scenario 5b, an approach for estimating the additional trips because of younger persons (age 13-17) who previously could not travel was also developed where current populations for persons in that age range were obtained from the U.S. Census Bureau (2016). Because data were provided in the ranges of age 10-14 and 15-17, the researchers estimated the number of persons age 13-14 as 40% of the population age 10-14. This method provided an average percentage of persons age 13-17 by Census block group. Then, Census block groups and TAZs were aligned after an overlay in a GIS environment was performed and checked for errors, yielding a present day percentage of persons age 13-17 by TAZ. Although the percentage of persons age 13-17 will change between the present and 2040, the change is not as dramatic as with persons age 65+: this percentage is 6.66% at present (U.S. Census Bureau, 2015b) and will rise to 6.69% in 2040 (Weldon Cooper Center, 2012). Accordingly, the percentages of the population age 13-17 for each zone that were computed based on present-day populations were all increased by the ratio of 6.69%/6.66% = 1.003. Finally, the modified percentages were multiplied by the number of persons in each zone in 2040 in order to obtain a forecast of persons age 13-17 in each zone. For example, for Zone 161, with 369 persons, the percentage of persons in that zone forecast to be age 13-17 was 2.93% of 369—about 11 persons. Truong et al. (2017) suggested that persons age 13-17 could see an increase in trips of 11.12%; thus, a multiplier of 1.1112 was used for such persons for HBO and NHB trips. As was the case with Scenario 5a (persons age 65+), HBW trips were not increased.

For Scenario 5c, a similar procedure was considered for persons age 18-64, where approximately 14.8% of Virginians age 18-64 do not have a driver's license (Miller et al., 2016). Data from Truong et al. (2017), when adapted to Albemarle County and the City of Charlottesville data projections for 2040 (Weldon Cooper Center, 2012), suggested that an additional 3.67% of trips could be realized with the arrival of DVs; hence a weight of 1.0367 was used for all trip purposes—HBW, HBO, and NHB—with the judgment being that some of these persons were more likely to be in the workforce. These data were combined with those for Scenarios 5a and 5b.

Scenario 5d was implemented by doubling most socioeconomic variables for each zone in the file "LandUse_2040A.dbf": population, household, automobiles, total employment, retail employment, school enrollment, university employees, number of on-campus students, dormitory beds, off-campus students, and classroom seats. No changes were made to two other variables: acreage and zonal university parking. There is one additional parameter in the file titled "Academic E." After reviewing the model report and the Cube script, the researchers could not determine what this variable meant, and thus it was not altered.

Implementation of Scenarios

The number of persons age 65+ varies by zone (see Figure 17). For example, for Zone 230, the total population is 319 with about 18.5% (i.e., 59 or a proportion of 0.185) being age 65+. By contrast, the percentage of persons age 65+ in Zone 94 is about 24.2% (i.e., 254 of 1,048 persons). Then, in the trip generation step, the number of HBO and NHB productions is set equal to existing productions multiplied by (1 + 15.3%*the percentage of people age 65+ in each zone). In Zone 93, about 24.2% of the population is expected to see HBO and NHB trips increase by 15.3%. Thus, for that zone, which generated 361 HBO trips and 63 NHB trips, Figure 17 shows that the calculated increase in the number of HBO trips is 361*[(1 + 24.2%)*(15.3%)] = about 375 trips and the number of NHB trips is 63*[1 + (24.2%)*(15.3%)] = about 65 trips. The script was thus modified, as shown in Appendix C (Figure C5).

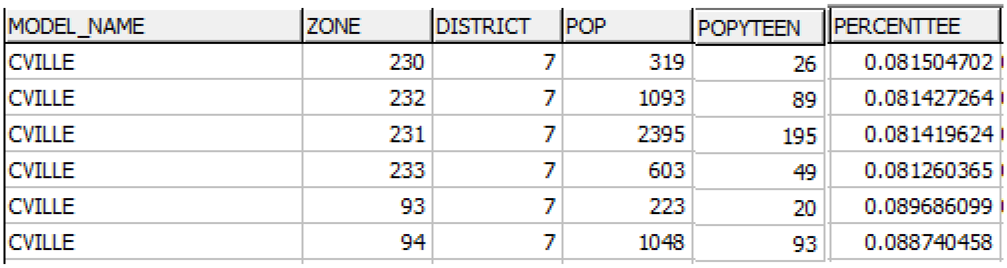


MODEL_NAME	ZONE	DISTRICT	POP	POP65	PERCENT
CVILLE	230	7	319	59	0.184952978
CVILLE	232	7	1093	206	0.188472095
CVILLE	231	7	2395	450	0.187891441
CVILLE	233	7	603	113	0.187396352
CVILLE	93	7	223	54	0.242152466
CVILLE	94	7	1048	254	0.242366412

Figure 17. New Landuse_2040A.dbf Table

A similar procedure was followed for Scenario 5b. For example, for Zone 93, about 9% of the population is expected to see HBO and NHB trips increase by 11.12%. Thus, for Zone 93, which generated 361 HBO trips and 63 NHB trips, the increased number of HBO trips is 361*[1 + (0.09)*(11.12%)] = about 364.6 trips and the number of NHB trips is 63*[1 + (0.09%) *(11.12%)] = about 63.63 trips (see Figure 18).

Finally, Scenario 5c increases trips for each of these age groups (see Figure C6 in Appendix C). Results were checked by hand and with the model; for example, for HBW, HBO, and NHB trips, the model gave 200.2, 386.4, and 67 for Scenario 5c; these numbers calculated by hand were 203.26, 386.043, and 67.35.



MODEL_NAME	ZONE	DISTRICT	POP	POPYTEEN	PERCENTTEE
CVILLE	230	7	319	26	0.081504702
CVILLE	232	7	1093	89	0.081427264
CVILLE	231	7	2395	195	0.081419624
CVILLE	233	7	603	49	0.081260365
CVILLE	93	7	223	20	0.089686099
CVILLE	94	7	1048	93	0.088740458

Figure 18. Modification to Trip Generation Script for Scenario 5b. HBO and NHB trips were increased by 11.12% to account for increased trips by travelers age 13-17. HBO = home-based other; NHB = nonhome-based.

Summary

For Scenario 5, therefore, eight scenarios were executed besides the base scenario. Six of these concerned additional travel by persons without a vehicle who can now access a DV: increased travel by persons age 65+; increased travel by persons age 13-17; and increased travel by all ages, with each scenario using the singly and doubly constrained model. The remaining two, one for the singly constrained model and for the doubly constrained model, represented a large increase in population and employment growth in 2040 relative to the expected 2040 values.

Scenario 6: Capacity Reduction, Induced Trips, Redevelopment, and Partial DV Adoption

This category of scenarios is a combined scenario that integrates elements from the previous scenarios. The resultant combined scenario was not created to provide a worst-case analysis: for a situation where congestion becomes great, for example, Scenario 5d, which greatly increases travel time, could be used. Rather, the combined scenario entails the situation where DVs are introduced but are not the dominant mode of transportation. Accordingly, capacity is reduced on some but not all facilities; parking in the CBD is reduced, thus allowing some new development in the CBD; and a change in behavior in terms of longer trips and additional trips occurs. The environmental impact of two options are examined: DVs being shared versus DVs not being shared. To execute this scenario, therefore, four key changes were made to the model:

1. *Capacity was reduced by 32% but only on three types of facilities: interstates, freeways, and major arterials.* For all other facilities, capacity was not altered. The

rationale was that for high-speed facilities, a greater margin of safety is required but that for lower speed facilities, capacity is unchanged. Thus, a modified version of Scenario 1a was used.

2. *Because DVs may induce additional travel by persons without a driver's license, the number of trips was increased*—but not by the same amount shown in Scenario 5c. Rather, to indicate a relatively low percentage of persons who might have a DV, a figure of 24.8% was selected based on Bansal and Kockelman (2017), who suggested that figure for year 2045 if certain events transpired, such as technology decreasing at a cost of about 5% annually. Thus, a modified version of Scenario 5c was used.

3. *A portion of parking in the CBD area (24.8%) was replaced with development.* The idea was that some developers see that greater value can be obtained by converting existing parking lots to parking, but not all parking lots are converted to other land uses. Thus, a modified version of Scenario 2d was used, with the 24.8% figure being selected based on Change 2.

4. *Because increased comfort of DVs makes longer trips feasible for some users, impedances were reduced.* For the singly constrained gravity model, friction factors were increased, and for the singly constrained gravity model, the magnitude of the coefficient c for travel time in the expression $e^{c\text{*time}}$ was reduced. However, the changes were not as large as those in Scenario 3c. For the singly constrained gravity model, for example, whereas Scenario 3c had reduced impedance by a factor of 0.125 (e.g., changing impedance from $e^{-c\text{*(travel time)}}$ to $e^{-c\text{*(travel time)*0.125}}$), this combined scenario only moderately altered the factor, using $e^{-c\text{*(travel time)*0.70}}$. The value of 0.70 was chosen because compared to a multiplier of 1.0, it raised VMT from 6,903,004.18 (the singly constrained gravity model base VMT) to 7,466,519.26, for an increase of 8.2%, which is roughly one-fourth (e.g., roughly 24.8%) of the increase sought in Scenario 3c where DVs increased travel time because of increased comfort. For the doubly constrained gravity model, the researchers modified the friction factors to increase VMT by a similar amount using first a linear approximation and later an exponential function. To start the linear approximation, the friction factor associated with 1 minute was left unchanged for each of the six trip purposes. These friction factors were 5996 (HBW), 5484 (HBO), 2723 (NHB), 126687 (HBU), 126687 (HDORMU), and 8187 (IX). Then, the friction factors were initially decreased in a linear fashion by the expression a*time until a trip length was obtained that was about 19% higher than the base trip length. Then, an exponential decay function of the form $e^{c\text{*time}}$ was fit to these values for each trip purpose and c was adjusted further until the VMT of 7,395,451.47 was obtained, which was 8.3% higher than the base VMT of 6,829,605.34. Thus, a modified version of Scenario 3c was used.

The model was executed based on the four key changes and became the "base case combined scenario." Then, two policies were contrasted, focusing on the peak hour and HBW trips. One policy was not to provide sharing of DVs, where owners of DVs sent their DV home rather than parking it at work. This scenario was similar to Scenario 2c except that a market penetration rate of 24.8%, rather than 100%, was used, with the script changes made in Figure C7 in Appendix C reflecting this option.

Then, after the changes in Figure C7 were removed, the other policy was to provide sharing of DVs relative to this new base case combined scenario, where there is a low degree of matching, as shown in Scenario 4 (e.g., with five regions). For each HBW vehicle trip from the base case combined scenario, a ZOV trip was added, where this ZOV trip was the average trip distance from Scenario 4c. The NHB VMT was increased until this additional VMT was obtained. For instance, for the doubly constrained gravity model, the difference in VMT between Scenario 6b (privately owned DVs) and Scenario 6c (shared DVs with a low degree of matching) was determined using the following five steps.

1. Execute the base case combined scenario, which yielded a VMT of 7,565,546.88.

2. Increase HBW person trips (using the method shown in Figure C7 where such an increase occurs after mode choice) by 24.8%, and execute the model. The end of this sub-step yields the results of the not-sharing alternative.

3. Remove the HBW person trips from the model in Step 2.

4. Add 24.8% of the induced HBW VMT from Scenario 4c. As stated previously, the methodology from Scenario 4c attributed an additional 496,466 new ZOV VMT from shared DVs. Thus, 24.8% (496,466) = 123,123.48 is added to obtain a new VMT such that 123,123.48 + 7,565,546.88 = 7,688,670.36 VMT.

5. Use an NHB multiplier to obtain approximately this new VMT. For the doubly constrained case, a multiplier of 1.1 yielded a VMT of 7,687,147.01, which was within 0.02% of the desired value of 7,688,670.36. The end of this sub-step yields the results of the sharing alternative.

Summary of Model Results for the Six Scenarios

Table 11 shows the key changes in the base scenarios throughout this effort and suggests that with legacy models such as those used in Charlottesville, there is a strong possibility that additional information will be learned as one delves more deeply into the model itself, and thus it may not always be the case that there is a single base scenario.

The results of the scenarios are presented in Tables 12 through 27. Tables 12 through 17 show the absolute results, and Tables 18 through 23 show the relative results.

Table 11. Summary of Base Scenarios

Type[a]	Scenario	Characteristics	VMT	VHT	MTT
Double	1, 2, 4, 5, 6	Make 3 changes that apply to all scenarios: • Adjust trip production rates to match documentation. • Incorporate fares into the mode choice step. • Add script to obtain mean trip time.	6,829,605.34	167,101.64	20.89
Double	3	Include a 100 multiplier for the local bus operating cost.	6,828,131.94	167,293.27	20.89
Single	1 only	Develop friction factors for the singly constrained gravity model based on an iterative procedure in accordance with Martin and McGuckin (1998).	7,688,831.98	219,496.25	24.57
Single	2, 4, 5, 6	Develop friction factors based on a simpler procedure noted in Cambridge Systematics, Inc., et al. (2012).	6,903,004.18	189,192.57	22.09
Single	3	Develop friction factors based on a simpler procedure noted in Cambridge Systematics, Inc., et al. (2012), and include a 100 multiplier for the local bus operating cost.	6,902,795.22	189,196.84	22.08

VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

[a] Double = doubly constrained gravity model; single = singly constrained gravity model.

Table 12. Results of Scenario 1: Change in Capacity[a]

Model Type	Results	Decrease 32%	Base Case	Increase 30%	Increase 100%
Doubly constrained	VMT	7,079,205.500	6,829,605.34	6,747,453.330	6,731,498.390
	VHT	244,207.840	167,101.64	153,157.980	145,056.520
	MTT	26.890	20.89	19.750	19.080
Singly constrained	VMT	8,187,508.82	7,688,831.98	7,543,089.10	7,473,970.15
	VHT	513,664.57	219,496.25	183,405.96	167,491.54
	MTT	47.18	24.57	21.76	20.45

VMT = vehicle miles traveled, VHT = vehicle hours traveled, MTT = mean trip time.

[a] Values are based on changing the capacity in the lookup table.

Table 13. Results of Scenario 2: Change in Parking Behavior

Model Type	Results	Base Case	Replace HBW Parking With ZOV Trips: Drive Alone Mode Only	Replace HBW Parking With ZOV Trips: Drive Alone and Carpool Modes Only	Replace HBW Parking With ZOV Trips: All Modes	Convert CBD Parking Lots to Other Uses
Doubly constrained	VMT	6,829,605.34	7,451,277.32	7,650,573.31	7,711,615.81	6,936,922.85
	VHT	167,101.64	193,853.79	203,012.84	206,501.98	170,977.63
	MTT	20.89	21.18	21.37	21.30	21.00
Singly constrained	VMT	6,903,004.18	7,554,723.44	7,769,168.08	7,825,552.84	7,033,312.45
	VHT	189,192.57	223,624.31	236,518.44	241,057.50	197,080.66
	MTT	22.09	22.89	23.24	22.90	22.45

HBW = home-based work; ZOV = zero occupant vehicle; CBD = central business district; VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

Table 14. Results of Scenario 3: Changes in Comfort Levels

Model Type	Results	Base Case	DVs Solve the Last Mile Problem for Transit	DVs Capture Transit Market Share	DVs Make Longer Trips More Appealing
Doubly constrained	VMT	6,828,131.94	6,814,366.98	6,826,759.97	8,576,827.18
	VHT	167,293.27	166,670.74	167,312.18	247,556.86
	MTT	20.89	20.91	20.89	28.23
Singly constrained	VMT	6,902,795.22	6,894,671.03	6,907,381.89	8,833,979.39
	VHT	189,196.84	188,745.23	189,195.26	284,238.86
	MTT	22.08	22.11	22.08	29.81

DVs = driverless vehicles; VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

Table 15. Results of Scenario 4: Shared DVs Increase Zero Occupant Vehicle Trips for HBW Only

Model Type	Results	Base Case	High Matching	Medium Matching	Low Matching
			Match is found in same TAZ	Match is found within nearby TAZs[a]	Match is found but may be several TAZs away[a]
Doubly constrained	VMT	6,829,605.34	No change except off-network VMT increases 33,910	6,988,626.15	7,325,221.93
	VHT	167,101.64		174,249.01	189,867.54
	MTT	20.89		20.83	20.790
Singly constrained	VMT	6,903,004.18	No change except off-network VMT increases 45,460	7,047,368.54	7,399,473.59
	VHT	189,192.57		196,171.89	215,029.12
	MTT	22.09		22.16	22.40

DVs = driverless vehicles; HBW = home-based work; TAZ = transportation analysis zone; VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

[a] Execution of values is based on multipliers of 1.22 (medium matching, doubly constrained), 1.173 (medium matching, singly constrained), 1.61 (low matching, doubly constrained), and 1.549 (low matching, singly constrained).

Table 16. Results of Scenario 5: Change in Travel Demand

Model Type	Results	Base Case	Additional Travel by Persons Age 65+	Additional Travel by Persons Age 13-17	Additional Travel by Persons of All Ages	Double Growth in the Region
Doubly constrained	VMT	6,829,605.34	6,883,749.25	6,840,372.56	6,946,501.10	9,476,552.78
	VHT	167,101.64	169,602.52	167,697.11	172,561.90	336,840.33
	MTT	20.89	20.88	20.91	20.92	26.99
Singly constrained	VMT	6,903,004.18	6,986,549.27	6,933,309.49	7,049,134.41	9,666,916.34
	VHT	189,192.57	193,210.56	190,194.98	196,484.38	408,361.48
	MTT	22.09	22.28	22.37	22.43	32.64

VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

Table 17. Results of Scenario 6: Reduced Capacity, Induced Trips, Redevelopment, and Partial DV Adoption

Model Type	Results	Base Case	New Combined Based Case	Private DVs[a]	Shared DVs: Low Degree of Matching[b]	Shared DVs: Medium Degree of Matching[c]
Doubly constrained	VMT	6,829,605.34	7,565,546.88	7,837,741.46	7,687,147.01	7,610,887.48
	VHT	167,101.64	231,041.01	251,854.36	239,630.86	235,742.65
	MTT	20.89	26.05	25.58	26.11	26.19
Singly constrained	VMT	6,903,004.18	7,583,825.30	7,891,612.76	7,705,895.08	7,623,948.66
	VHT	189,192.57	251,680.04	273,165.94	258,676.89	251,829.06
	MTT	22.09	27.02	26.79	27.21	27.08

DVs = driverless vehicles; VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

[a] Reflects new combined base case plus an increase in home-based work trips of 24.8%.

[b] Execution of the values is based on multipliers of 1.1 (doubly constrained) and 1.09 (singly constrained) in nonhome-based trips. This presumes a low degree of matching as per Figure 14 with zero occupant vehicle trips within small regions.

[c] Execution of values is based on multipliers of 1.05 (doubly constrained) and 1.015 (singly constrained) in nonhome-based trips. This presumes a medium degree of matching as per Figure 15 with zero occupant vehicle trips within larger regions.

Table 18. Relative Changes for Scenario 1: Change in Capacity[a]

Model Type	Results	Decrease 32%	Base Case	Increase 30%	Increase 100%
Doubly constrained	VMT	1.04[b]	1.00	0.99	0.99
	VHT	1.46	1.00	0.92	0.87
	MTT	1.29	1.00	0.95	0.91
Singly constrained	VMT	1.06	1.00	0.98	0.97
	VHT	2.34	1.00	0.84	0.76
	MTT	1.92	1.00	0.89	0.83

VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

[a] Values are based on changing the capacity in the lookup table.

[b] In this cell, for instance, the "1.04" indicates that decreasing capacity 32% increases VMT by 4%.

Table 19. Relative Changes for Scenario 2: Change in Parking Behavior

Model Type	Results	Base Case	Replace HBW Parking With ZOV Trips: Drive Alone Mode Only	Replace HBW Parking With ZOV Trips: Drive Alone and Carpool Modes Only	Replace HBW Parking With ZOV Trips: All Modes	Convert CBD Parking Lots to Other Uses
Doubly constrained	VMT	1.00	1.091	1.120	1.129	1.02
	VHT	1.00	1.160	1.215	1.236	1.02
	MTT	1.00	1.014	1.023	1.020	1.01
Singly constrained	VMT	1.00	1.094	1.125	1.134	1.02
	VHT	1.00	1.182	1.250	1.274	1.04
	MTT	1.00	1.036	1.052	1.037	1.02

HBW = home-based work; ZOV = zero occupant vehicle; CBD = central business district; VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

Table 20. Relative Changes for Scenario 3: Changes in Comfort Levels

Model Type	Results	Base Case	DVs Solve the Last Mile Problem for Transit	DVs Capture Transit's Market Share	DVs Make Longer Trips More Appealing
Doubly constrained	VMT	1.00[a]	0.9980	1.000	1.256
	VHT	1.00[a]	0.9963	1.000	1.480
	MTT	1.00[a]	1.0010	1.000	1.351
Singly constrained	VMT	1.00	0.9988	1.001	1.280
	VHT	1.00	0.9976	1.000	1.502
	MTT	1.00	1.0014	1.000	1.350

DVs = driverless vehicles; VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

[a] Reflects the base case where VMT = 6,828,131.94, VHT = 167,293.27, and MTT = 20.89.

Table 21. Relative Changes for Scenario 4: Shared DVs Increase Zero Occupant Vehicle Trips for Home-Based Work Trips Only

Model Type	Results	Base Case	Match Is Found in Same TAZ	Match Is Found Within Nearby TAZs	Match Is Found But May Be Several TAZs Away
Doubly constrained	VMT	6,829,605.34	No change except VMT increases 0.50%[a]	1.023	1.073
	VHT	167,101.64		1.043	1.136
	MTT	20.89		0.997	0.995
Singly constrained	VMT	6,903,004.18	No change except VMT increases 0.66%[a]	1.02	1.072
	VHT	189,192.57		1.04	1.14
	MTT	22.09		1.00	1.01

DVs = driverless vehicles; TAZ = transportation analysis zone; VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

[a] The off-network VMT was calculated by the researchers, and dividing this by the on-network VMT shown for the base case gives these percentages.

Table 22. Relative Changes for Scenario 5: Change in Travel Demand

Model Type	Results	Base Case	Additional Travel By Persons Age 65+	Additional Travel by Persons Age 13-17	Additional Travel by Persons of All Ages	Double Growth in the Region
Doubly constrained	VMT	1.000	1.008	1.002	1.017	1.388
	VHT	1.000	1.015	1.004	1.033	2.016
	MTT	1.000	1.000	1.001	1.001	1.292
Singly constrained	VMT	1.000	1.012	1.004	1.021	1.400
	VHT	1.000	1.021	1.005	1.039	2.158
	MTT	1.000	1.009	1.013	1.015	1.478

VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

Table 23. Relative Change for Combined Base Case Scenario (Scenario 6)

Model Type	Results	Base Case	New Combined Based Case	Private DVs	Shared DVs: Low Degree of Matching	Shared DVs: Medium Degree of Matching
Doubly constrained	VMT	1.000	1.108	1.148	1.126	1.114
	VHT	1.000	1.383	1.507	1.434	1.411
	MTT	1.000	1.247	1.225	1.250	1.254
Singly constrained	VMT	1.000	1.099	1.143	1.116	1.104
	VHT	1.000	1.330	1.444	1.367	1.331
	MTT	1.000	1.223	1.223	1.232	1.226

DVs = driverless vehicles; VMT = vehicle miles traveled; VHT = vehicle hours traveled; MTT = mean trip time.

DISCUSSION

Overview

The results presented in Tables 18 through 23 are interesting but are useful only to the extent that they inform concerns raised by stakeholders—that is, the value of a model derives from its ability to help planners inform stakeholders of the impacts of potential decisions (Meyer and Miller, 2013). With regard to the five local issues of interest cited by VAMPO attendees discussed previously that are potentially addressed by modifications to the regional model, execution of the model after incorporation of DVs suggested five insights for this particular region:

1. The impact of the transition period in which DVs might lead to a decrease in capacity is a significant concern.

2. There is substantial land available for conversion of parking lots, and in this particular location, the network appears poised to handle the traffic.

3. Under the best of conditions, DVs can only modestly strengthen the role of transit. There is a significant risk that DVs might reduce the mode share of nonmotorized vehicles.

4. ZOV trips may increase because of self-parking or unmatched trips, but the former has the potential to be much greater than the latter.

5. If vehicle types do not change, emissions will generally increase as greater vehicle travel occurs. However, for the doubly constrained model only, a capacity decrease may modestly reduce emissions.

Local Issue 1: Impact of a Transition Period in Which DVs Might Decrease Capacity

The initial concern regarding a capacity decrease during a transition period appears justified. A capacity reduction potentially increases VHT by 46% in the doubly constrained model or 146% in the singly constrained model and is particularly detrimental to some smaller facilities: the percentage of congested major collectors is more than doubled, increasing from 12% to 37% for the doubly constrained model or 34% to 72% for the doubly and singly constrained models, respectively. Table 18 (for Scenario 1) also shows that for this particular region, VHT is more sensitive to changes in demand or capacity than VMT, owing to the nonlinear exponent for the volume/capacity ratio in the volume delay function. However, this result is also somewhat specific to the use of the shortest travel time for the impedance function that is used in the gravity model: had the impedance function been based on distance, rather than travel time, VMT might have been more sensitive than VHT (Xiao, 2017).

One result was counterintuitive at the aggregate level: capacity increases were associated with VMT decreases (although decreases were modest). Table 24 suggests one explanation: 50% of interstate segments and almost 89% of major freeway segments were congested under the base case; thus, it might be the case that such facilities offer more direct routes that because of capacity increases became feasible for more motorists.

The singly constrained gravity model showed greater sensitivity to changes than the doubly constrained model: an increase in capacity of 30% reduced VHT to 92% of its value for the doubly constrained case but to 84% of its value for the singly constrained case. This is expected as the singly constrained gravity model relies to a greater extent on travel time, or any other measure of impedance, than does the doubly constrained model (Cambridge Systematics, 2014; VDOT, 2009).

As noted in the formulation of Scenario 1 in the "Methods" section, it is possible to alter capacity not in the lookup table but rather in the volume delay function. If the steps of trip distribution and trip assignment are applied only in sequence, increasing the capacity in a volume delay function that is used in the trip assignment step should affect the route chosen but not the locations of origins and destinations. However, because of multiple feedback loops within the model between trip distribution and trip assignment, changing the capacity in either step yields virtually identical results in terms of VMT, VHT, and MTT. That is, the relative changes in the top row of Table 18 (for the doubly constrained case) are identical except that for the 32% decrease in capacity, modification of the volume delay function yielded a 45% increase in VHT (rather than the 46% shown in Table 18) and an increase in MTT of 30% (rather than the 29% shown in Table 18). For the singly constrained case, all results were the same except for the drop in capacity, where modification to the volume delay function yielded a VHT increase of 130% (rather than the 134% shown in Table 18) and an MTT increase of 96% (rather than the 92% shown in Table 18).

Table 24. Impacts of Scenarios on Percentage of Congested Facilities[a]

Trip Distribution Approach	Capacity Change	Interstate	Freeway	Major Arterial	Minor Arterial	Major Collector	Minor Collector	Local Street
Doubly constrained gravity model	32% decrease	88.9[b]	97.5	77.7	71.5	36.9	30.3	15.0
	No change	54.2	73.4	44.2	40.8	12.1	11.2	3.5
	30% increase	0.0	29.1	19.8	24.6	9.4	5.4	0.9
	100% increase	0.0	0.0	7.9	6.0	1.5	0.6	0.0
Singly constrained gravity model	32% decrease	72.2	100.0	90.0	86.0	72.0	61.2	30.2
	No change	50.0	88.6	59.5	58.3	34.2	22.1	6.7
	30% increase	0.0	68.4	37.4	35.4	13.6	5.8	0.5
	100% increase	0.0	2.5	9.8	15.2	4.7	1.3	0.2

[a] For this region, a segment is defined as congested if its volume/capacity ratio exceeds 0.8.

[b] For example, the "88.9" shown in the third column, second row, indicates that a 32% decrease in capacity meant that 88.9% of interstate segments had a volume/capacity ratio > 0.8.

Local Issue 2: Impact of Converting CBD Parking Lots to Other Land Uses

For the doubly constrained model, Scenario 2d showed a modest increase in VMT (1.57%), VHT (2.32%), and MTT (0.53%), which was not surprising given that the CBD represents a relatively small portion of the regional model. The singly constrained formulation increased these percentages modestly to 1.89%, 4.17%, and 1.63%, respectively, and thus the doubly constrained model remains the focus of the discussion herein. What was surprising was that in the CBD, travel speeds were generally not affected substantially: although the increase in volumes led to speed decreases, these were relatively small and no larger than a drop of 5 mph. Mode splits did not change, which was not surprising given that travel speeds had not changed: no link in the CBD saw speeds decrease by less than 5 mph. Of the 191 links in the CBD, 1 had a speed increase of a bit less than 1.5 mph; 36 had speed increases of less than 1 mph; 126 had speed decreases of less than 1 mph; and 16 had speed decreases between 1 and 5 mph.

For this particular case, the model generally suggested that there could be substantial growth in demand, as shown by the off-street network. For Zones 33, 34, and 35, Figure 19 contrasts the relatively few streets that are part of the modeled network with the greater number of local streets that are not part of the modeled network. For example, whereas West Main Street was included, Hardy Drive was not. For Zones 33, 34, and 35, the additional centroid connector volumes were 2,366, 3,253, and 3,179, respectively (representing both directions), which are percentage increases of 107%, 30%, and 29%, respectively, over the base scenario. If these volumes were split evenly over the five north-south and east-west off-network facilities that are represented with dashed lines in Figure 19, this would be an additional 1,760 vehicles per hour on these facilities on a daily basis. If a capacity of 800 vehicles per hour is presumed (a value inferred from the capacity for the smallest type of on-network facility, described as “Local Only serves local traffic Local City/Subdivision Streets” [Corradino Group, 2009], during a peak hour, such movements could be accommodated by local streets. For example, with 10% of the volume occurring during the peak hour, the centroid connectors could add, in theory, roughly 176 extra vehicles if these were distributed equally among the five facilities.

That said, further exploration could be appropriate to determine if the increase in centroid volumes could affect the “livability” of the area: Ben-Joseph (1995) and Spack (2011) suggested that volumes of about roughly 1,000 vehicles per day can adversely affect a community. Further, examination of the volumes reported for the City of Charlottesville (VDOT, 2017b) raises the possibility that these new volumes could be relatively large compared to existing volumes; for example, although most of the streets shown in Figure 19 were not counted, a count is available for a section of Albemarle Street to the north of the area, where that count is 170 vehicles per day.

In sum, Scenario 2d does not suggest large regional changes in transportation performance, and it appears that the roadways could support this traffic volume. Further, in the process of developing Scenario 2d, it was observed that there was a sizeable amount of land presently dedicated to parking that if such parking was not needed in the future could conceivably be converted from parking to other uses. However, it is possible that greater attention may need to be paid to those living near the smaller off-network facilities that would have these local (off-network) trips.

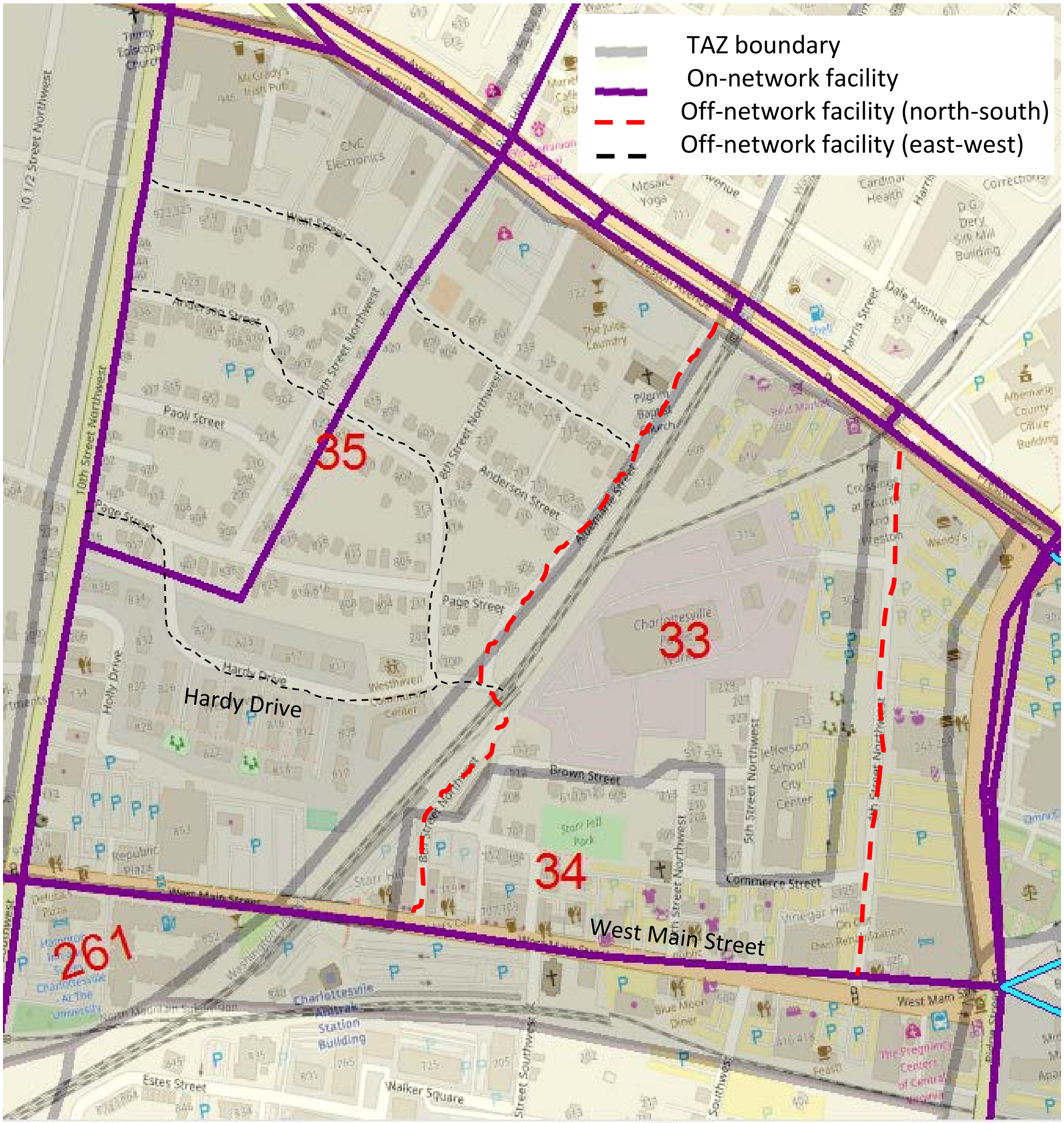


Figure 19. Contrast Between Off-Network and On-Network Facilities Supporting Zones 33, 34, and 35. TAZ = transportation analysis zone.

Local Issue 3: Impacts of DVs on Transit's Mode Share

Table 20 shows that under a scenario where DVs could increase market share by eliminating waiting time, there is almost an imperceptible impact on aggregate performance measures. With the increased mode share for transit, VMT and VHT on the transportation network drop, but the amount is negligible: VMT drops by about one-fifth of 1 percent for the doubly constrained model and about one-tenth of 1 percent for the singly constrained model.

VHT also drops by relatively small amounts: 0.37% and 0.24% for the doubly and singly constrained case, respectively. Generally, trips are transferred from the drive alone and carpool modes to transit, which explains why VMT and VHT decrease slightly in the aggregate. Further, although most of the additional transit trips are from the auto mode, about 9% are transfers from the active modes of bicycling and walking, as shown in Table 25. MTT increases by one-tenth of 1 percent for the doubly constrained case and slightly more for the singly constrained case.

However, at the disaggregate level, the impact is more pronounced. If DVs eliminate waiting time for transit and replace the walk time with a ride in a DV, DVs can increase mode share for transit by around 3 percentage points. The doubly constrained gravity model suggests a figure of 3.10%, raising transit's mode share from 0.26% to 3.36%, and the singly constrained gravity model suggests a figure of 2.71%, raising mode share from 0.28% to 2.99%. That said, this impact is "nuanced" (T. Donna Chen, personal communication, April 19, 2018). In absolute terms, a mode share change of 3 percentage points is relatively small, but in relative terms, it represents more than a 10-fold increase in transit ridership. With regard to how such an increase in transit demand would affect quality of service, more transit passengers could lead to several potential changes (e.g., more standing than sitting on the bus, greater service frequency, and more or fewer resources depending on how operating costs and revenue are affected).

Table 25 also shows that only about one-half of this increase comes from taking mode share from SOVs: the next biggest portion of this increase (about 1 percentage point) comes from carpool shifting to transit, and then about one-fourth of a percentage point of the increase is a shift from nonmotorized modes to transit.

Scenario 3 had a slightly different utility function than the other scenarios: for Scenario 3, the fare for the mode "walk to local bus" was modified to be multiplied by 100 for all three transit modes: walk to local bus, walk to premium transit, and drive to best available transit service. In the original model, however, this multiplier of 100 is not present for the fare of walk to local bus.

Table 25. Impact of Scenario 3a on Transit's Mode Share

	Gravity Model					
	Doubly Constrained			**Singly Constrained**		
Mode	**Base**	**Scenario 3a**	**Difference[a]**	**Base**	**Scenario 3a**	**Difference[a]**
Drive alone	87,553	85,123	-1.58%[a]	87,536	85,435	-1.37%
Carpool 2	38,176	36,856	-0.86%	38,264	37,114	-0.75%
Carpool 3+	18,721	18,121	-0.39%	18,951	18,431	-0.34%
Walk to local transit	397	4	-0.26%	424	7	-0.27%
Walk to premium transit	0	5,162	3.35%	0	4,589	2.98%
Drive to best available transit	5	4	0.00%	3	3	0.00%
Nonmotorized walk	4,298	4,051	-0.16%	4,143	3,899	-0.16%
Nonmotorized bicycle	4,746	4,576	-0.11%	4,580	4,425	-0.10%

[a] Change in absolute mode shares based on the file "Mode Summary.txt." For example, under the base scenario, drive alone had 87,553 trips of a total of 153,896, for a mode share of 56.89%. Under Scenario 3a, the mode share for drive alone dropped to 55.31%. The difference, 55.31% − 56.89% = -1.58%, is reported here.

Interestingly, comparable results are obtained in terms of the impact on mode share if the model is executed with the original utility function: DVs could increase transit's mode share by 2.97% (e.g., raising mode share from 0.39% to 3.36% for the doubly constrained gravity model) or 2.59% (e.g., raising mode share from 0.40% to 2.99% for the singly constrained gravity model). Another interpretation of these results is that the utility functions suggest that elimination of the fare alone—without any DV impacts—yields an increase of between roughly 0.12% or 0.13% of transit's mode share for HBW trips.

As expected, Scenario 3b reduced transit's mode share and increased the auto mode share. The changes in absolute shares were modest: as shown in Table 26, drive alone, carpool 2, and carpool 3+ increased their mode share from 93.86% to 94.14%. However, examination of the modes in greater detail shows a slight surprise: the greatest impact was on nonmotorized modes—even on a percentage basis relative to such modes, which is interesting in that nonmotorized modes have a larger mode share than transit. That is, more trips were lost to DVs from biking and walking than were lost to transit. For instance, the number of transit trips decreased slightly (an absolute change of 22 or 23 trips or 5.2% to 5.7% in total transit trips). However, the number of nonmotorized trips changed by about 20 times that amount (402 to 404 trips), with bicycle trips decreasing by 6.3% relative to total bicycle trips.

Table 26. Impact of Scenario 3b on Transit's Mode Share

Mode	Gravity Model					
	Doubly Constrained			Singly Constrained		
	Base	Scenario 3a	Difference[a]	Base	Scenario 3a	Difference[a]
Drive alone	87,553	87,772	0.14%	87,536	87,760	0.14%
Carpool 2	38,176	38,317	0.09%	38,264	38,403	0.09%
Carpool 3+	18,721	18,786	0.04%	18,951	19,016	0.04%
Walk to local transit	397	375	-0.01%	424	402	-0.01%
Walk to premium transit	0	0	0.00%	0	0	0.00%
Drive to best available transit	5	4	0.00%	3	3	0.00%
Nonmotorized walk	4,298	4,195	-0.07%	4,143	4,044	-0.06%
Nonmotorized bicycle	4,746	4,447	-0.19%	4,580	4,275	-0.20%

[a] Change in absolute mode shares based on the file "Mode Summary.txt." For example, drive alone's mode share increased from 56.89% to 57.03%, for an increase of 0.14%.

Local Issue 4: Impact of Zero Occupant Vehicles on Vehicle Miles Traveled

The number of ZOV trips may increase through DVs self-parking (if DVs are privately owned and the owner sends the vehicle back home or to a lower cost parking area) or through an empty DV traveling from one person's destination to another person's origin (if shared). The results in Tables 19 and 21 suggest that although both situations may increase VMT, the former could increase VMT much more than the latter.

If all commuters chose to send the DV home, under Scenario 2c, VMT would increase by 12.9% for the doubly constrained model. By contrast, with regard to the potential increase in VMT because of ZOVs resulting from DVs being shared, for the doubly constrained model, Table 21 (for Scenario 4) suggests that this increase in VMT could range from about 0.50% if DVs could be matched within the same zone (e.g., off-network VMT only), to 2.3% if matching occurred within a few zones, to roughly 7.26% if matching occurred across many zones, i.e., an almost worst-case matching scenario. The singly constrained gravity model yielded similar results: Scenario 2c (singly constrained) showed a possibility of all commuters sending their vehicle home (thereby increasing VMT by 13.4%) compared to the three cases of a very high degree of matching where all ZOV VMT occurred off the network (increasing VMT by 0.66%), a case of a medium degree of matching (where ZOV VMT increase by 2.1%), and a case of low matching (where ZOV VMT increases by 7.19%).

The larger VMT increases have real-world consequences; for example, Scenario 2c showed that the (roughly) 13% increases in VMT for the doubly and singly constrained gravity models could increase VHT by 23.6% or 27.4%, respectively. Thus, a key question with regard to DVs is the extent to which they will be shared (outside the household) versus used by multiple members of the household. Certainly, a doubling of all commute trips is likely a worst-case scenario that may not materialize. However, it is also conceivable that for members of a household who had different departure times and destinations, some doubling of trips as shown in Table 19 could occur.

Table 19 also shows the relative value of supporting other modes if a policy objective is to reduce an increase in VHT. If the substitution of additional trips for parking occurs only for commuters who drive alone, Scenario 2a showed that VHT increases about 16% (under the doubly constrained gravity model). If, however, existing carpool users also become DV owners (who then substitute two empty DV trips for parking their vehicle at work), Scenario 2b showed a VHT increase of 21.5%. If this occurs for all modes, VHT increases to 23.6%, as shown in Scenario 2c. In this particular instance, the impact on carpooling appears to be responsible for almost one-fourth of the increase in delay.

In contrast to the additional trips of Scenarios 2a, 2b, and 2c, Table 27 suggests that with a high degree of matching, even for all trips, the VMT by ZOVs would be about 2.5% of all VMT. This additional VMT would, of course, be smaller if it applied only to work-based trips.

Table 27. Additional Results of Scenario 4: Additional Off-Network VMT Resulting From ZOVs With a High Degree of Matching

Scenario	Description[a]	Doubly Constrained[b]	Singly Constrained[c]
4a	All internal vehicle trips, HBW purpose only	33,910	45,460
4d	All internal vehicle trips, all purposes	172,140	170,083
4e	Only carpooling internal vehicle trips, all purposes	51,242	49,237

VMT = vehicle miles traveled; ZOVs = zero occupant vehicles; HBW = home-based work.

[a] *Internal* refers to HBW, home-based other; nonhome-based and home-based university trips only and excludes internal-external, external-internal, and external-external trips. There were no home-based university dormitory trips in the model.

[b] For the base scenario where VMT = 6,829,605.34, vehicle hours traveled (VHT) = 167,101.64 and mean trip time (MTT) = 20.89.

[c] For the base scenario where VMT = 6,903,004.18, VHT = 189,192.57 and MTT = 22.09.

The combined scenario simulated two possible futures where DVs had many of the elements discussed previously, i.e., a potential capacity decrease during the transition period, conversion of the downtown parking lots to other land uses, and additional travel by persons without access to a vehicle—but also a situation where only a minority of vehicles were driverless. The difference in these two futures was that DVs were either privately owned or shared. A medium degree of matching for shared DVs increased VMT by 11.4% (doubly constrained gravity model) and 10.4% (singly constrained gravity model), and if vehicle emissions technologies were not to change, these changes in VMT and speed would lead to respective NO_x emissions increases of 2.94% and 5.03%. The results of a low degree of sharing increased NO_x emissions and VMT more; for the doubly constrained gravity model, VMT increased by 12.6% and NO_x emissions increased by 3.65%. Yet both of these futures where DVs are shared yielded a lesser environmental impact than if DVs were not shared: VMT and NO_x emissions increased by 14.8% and 5.65%, respectively. These results are consistent with the results obtained from the individual scenarios, although the difference between sharing and not sharing herein is not as great as the difference between Scenario 2c and Scenarios 4b and 4c. That said, the results suggested a public benefit for shared DVs.

As was the case with VMT and VHT in Scenarios 3a and 3b, the results for MTT in Scenarios 4b and 4c had an important nuance. Scenario 4b showed that MTT decreases relative to the base scenarios, which the researchers believe results because with the ZOV travel, there are additional shorter-distance trips, which lower MTT.

Local Issue 5: Impact on Emissions

VAMPO stakeholders had expressed an interest in how DVs might influence emissions. Table 28 generally shows that as VMT increases, so might NO_x emissions (chosen as a focus because they are a contributor to ground level ozone, which has affected other Virginia areas, although Charlottesville is presently an attainment area). It was not surprising that NO_x emissions increased (by 11.64%) for the doubly constrained gravity model, for example, when commuters chose not to share DVs but rather to send them home, thereby doubling trips between home and work. However, the changes in capacity (Scenario 1a) might have some surprising impacts on emissions: emissions increased for the singly constrained model (by 4.9%) but decreased for the doubly constrained model (by 2.5%). Depending on age and vehicle type, NO_x emissions tended to follow a parabolic curve shown in Figure ES1; for one set of assumptions, emissions rates were minimized at speeds of around 32 mph and maximized at very low and very high speeds (California Air Resources Board, 2013). Thus, an increase in speed on a facility might lead to a reduction or an increase in emissions depending on the facility's current speed, as shown in Figure ES1.

Examination of speeds by facility type provided an explanation for the case of the reduction in capacity for Scenario 1: for the doubly constrained model only, the reduced speeds on two classes of facilities—freeways and major collectors—on average corresponded to a lower NO_x emissions factor than was the case without the capacity reduction. For the singly constrained gravity model, although speeds also decreased for these two classes of facilities, the emissions factor associated with the speed corresponding to a reduction in capacity was lower than for the base scenario. Thus, although the relationship between the number of trips and VMT was fairly constant for these scenarios, the relationship between trips or VMT and emissions rates was not constant. If such capacity reductions were to occur, these results could help identify the types of facilities that should be improved if a reduction in NO_x emissions was a priority.

Table 28. Impact of Certain Scenarios on NO_x Emissions

Scenario No.	Abbreviated Description	Impact on NO_x Emissions: Doubly Constrained Model	Impact on NO_x Emissions: Singly Constrained Model
1a	Capacity reduced by 32%	-2.51%	4.87%
2a	Commuters chose not to park (drive alone only)	8.05%	8.76%
2b	Commuters chose not to park (drive alone and carpool)	10.76%	11.76%
2c	Commuters chose not to park (all modes)	11.64%	12.39%
2d	CBD parking lots converted to other uses	1.48%	1.67%
3c	Longer trips	21.65%	25.05%
4b	Sharing with a medium degree of matching	2.08%	1.90%
4c	Sharing with a low degree of matching	6.65%	6.63%
5a	Increase trips for persons age 65+[a]	0.70%	0.95%
5b	Increase trips for persons age 13-17[a]	0.10%	0.30%
5c	Increase trips for all persons regardless of age[a]	1.51%	1.95%
5d	Double population and employment	34.8%	38.32%
6a	New combined base scenario	2.29%	4.16%
6b	Combined base case DVs not shared	5.65%	8.51%
6c	Combined base case DVs shared (low matching)	3.65%	6.13%
6d	Combined base case DVs shared (medium matching)	2.94%	5.03%

CBD = central business district; DVs = driverless vehicles.

[a] Trip increases in Scenarios 5a, 5b, and 5c reflect proportions in those age groups for persons who do not have access to a vehicle but who could have access to a DV.

Other Potential Local Issues of Interest

It appears possible to modify the regional model to address local issues in addition to the five mentioned, depending on how the question is framed and what level of assumptions is required. Three such issues are mentioned here.

For the first issue, the incorporation of pickup and drop-off lanes at local businesses for DVs, may be used as an example (see Table 4). Although it is not feasible to incorporate directly the design of such lanes into regional travel demand modeling software, it may be possible to examine a related question: How would well-designed versus poorly designed pickup and drop-off lanes affect total travel time (e.g., VHT)? The modeling approach would be determined by whether related literature supported either of two propositions, both of which presume that poorly designed (or nonexistent) DV pickup/drop-off lanes affect the access time to a particular zone.

1. *If the difference in access time influenced a person's ultimate destination, this would be reflected by changing the zone's access time in the trip distribution step.* In that

sense, access time is treated as any other component of travel impedance and thus can be directly incorporated into the regional model.

2. *If the difference in access time did not influence a person's destination, the regional model itself would not be altered.* Instead, outside the model, the change in access time would be multiplied by the number of trips terminating in the appropriate zone and the result would be added to the modeled VHT.

Thus, although the model cannot determine how to design the pickup and drop-off lanes, the regional model may, with supporting literature, help determine the impact of such lanes being well designed or poorly designed.

The second and third issues (see Table 4), although not addressed in this report, could be partially addressed within the regional model structure provided additional behavioral insights were obtained from the literature. The second issue concerns parking pricing: if the utilities in the mode choice step were updated to reflect the cost of parking versus the cost of sending the DV home, it is conceivable that the model could support an analysis of how parking prices might affect the generation of ZOV trips (e.g., an expanded version of Scenarios 2a, 2b, and 2c). The third issue concerns growth outside existing areas: the regional model by itself cannot determine how high property taxes would need to climb to discourage additional growth outside the region, but it could support a modified version of Scenario 3c where one could determine the increase in population and employment (in new zones outside the study area) that would yield a mean commute time that the appropriate literature indicated was tolerable based on the higher level of comfort offered by DVs.

For all three of these issues, determination of the modeling approach would depend on a review of the literature or the collection of information from other sources to determine which behavioral assumptions were appropriate. For example, for the third issue, one possibility is that commute times (with a DV) might be 35% higher than with a conventional vehicle (Childress et al., 2015), but this percentage would be adjusted as additional findings from other locations became available.

CONCLUSIONS

- *There are several ways to alter existing travel demand models to address DV-related topics of interest to regional planners*. Examples include the following:

  — Alter the capacity in the capacity lookup table (to examine impacts of DVs having shorter headways that can increase capacity).

  — Adjust the friction factors or the travel impedance parameter (to examine how the increased comfort of DVs may lead to longer trip lengths).

  — Modify the utility function in the mode choice step (to examine how a system of shared DVs that reduced out-of-vehicle waiting time could affect transit use).

- — Increase trip generation rates for certain zones based on forecast change in population by age group (to examine how increased access to DVs might affect travel by persons without access to a vehicle, such as teens without a driver's license).

- — Increase trips in the origin-destination vehicle matrix that follows the mode choice step (to examine the impact of privately owned DVs being sent home empty rather than parked for the day at the place of employment).

- — In conjunction with a separate GIS-based analysis, increase NHB trips (to examine the impact of shared DVs traveling from the leading person's destination to the following person's origin).

- *For the purposes of discussing DVs, scenario planning can generate useful discussion even if the model inputs are uncertain, and this discussion may proceed in a qualitative or quantitative manner.*

  - — As a qualitative example, when this work began, staff at the Charlottesville Model Design Workshop in March 2017 indicated that they were interested in knowing how DVs might affect parking. Because the parking-related scenario had not been developed at that time, the research team put together an outreach exercise showing the degree to which parking might be affected if DVs led to a doubling of all trips. Despite this model input (doubling all trips) being different from a later model input (doubling only commute trips), the VAMPO participants in the June 2017 outreach exercise were able to provide areas of concern that were later used to refine model scenarios.

  - — As a quantitative example, uncertainty in the utility function did not seem to affect the results dramatically provided the model was executed in a consistent manner. For example, for the question "what would the impact be if DVs eliminated waiting time for transit and also reduced the walk time," the answer based on the doubly constrained model is that DVs could increase transit's mode share by either 3.10% (e.g., raising mode share from 0.26% to 3.36% as shown for Scenario 3a) or 2.97% (e.g., raising mode share from 0.39% to 3.36% as shown when the original utility functions were used for Scenario 3a). A similar pattern holds for the singly constrained gravity model: DVs could increase transit's mode share by either 2.59% or 2.71%, depending on whether the utility function includes the "100" multiplier for local bus. In sum, based on the model, it appears that DVs have the potential to raise transit's mode share by about 3 percentage points under a scenario where the waiting time is eliminated and the out-of-vehicle waiting time is replaced by driving a DV, which, in turn, has a 35% reduction in discomfort compared to driving to the stop in a conventional vehicle.

- *Some, but not all, policy-related questions can be examined by the regional model, and those that can be examined have varying levels of difficulty.* Table 4 showed that although some issues of interest to stakeholders are not easily addressed with the model (e.g., curbside access management), other macroscopic questions (e.g., the impact of DVs affecting capacity) are feasible within the modeling structure. Then, the effort required to implement the issues that are feasible will vary (meaning that one can start with the simplest changes first). For example, only a few person hours were required to modify the capacity in the lookup table, with most of that time being used for conversions between the various database formats. By contrast, knowledge of the proprietary scripting language was necessary in order to increase trips for the population age 65+, and both scripting and calibration procedures were required to develop an appropriate singly constrained gravity model.

- *The regional model may be used to prioritize areas of concern to local stakeholders*. For this region in particular, incorporation of DVs led to the following observations in response to concerns identified by VAMPO attendees.

  - The model suggests that if parking is not needed, there is substantial land development opportunity in downtown areas. Scenario 2d suggested that parking garages and lots in the downtown area, not including street parking, have roughly 3.4 million square feet of redevelopment potential in the downtown area—and the model suggests that the existing transportation network may be able to accommodate this development.

  - Concerns about the transition period during which the use of DVs might result in a reduction in capacity are justified. VHT was estimated to increase by 45% for the doubly constrained gravity model. By contrast, the model showed that another potential concern—the impact of additional travel by persons who had not had access to a vehicle—had a far less detrimental impact on performance: VHT was estimated to increase by only about 1%.

  - The impact of DVs being shared versus not shared is substantial. Considering the commute trip (e.g., HBW purpose) only, if DVs are not shared, for the doubly constrained gravity model VMT increases by 12.91%, whereas sharing of DVs increases VMT by 2.33% to 7.26% depending on whether a moderate degree of matching occurs (e.g., the termination of the first person’s trip and the origin of the second person’s trip is a few TAZs apart) or a low degree of matching occurs (e.g., the DV must traverse many zones). A high degree of matching among shared DVs would increase VMT by only one-half of a percentage point.

  - The impact on other modes is not substantial in absolute terms but is substantial in relative terms. A transit-favorable scenario suggested DVs can modestly increase transit’s mode share from a current value of roughly one-fourth of 1% to more than 3%. Although this range is small in absolute terms, in the model it reflects a 12-fold increase in transit’s mode share. Further, with transit’s mode share in the model being relatively low, the mode share appeared unlikely to drop substantially; however, a competing scenario where DVs offer increased comfort and hence willingness to travel could reduce nonmotorized mode share by about one-fourth of 1 percentage point.

  - If vehicle types do not change, emissions may increase, but the increases will be higher for nonshared DVs than for the case of induced travel by persons who do not have access to a vehicle. The worst-case scenario of commuters choosing to send DVs back home to park increases NOx emissions by 11.64%—and this increase results just from a change in behavior for a single purpose (the HBW) trip. By contrast, an increase in DV use by persons who do not have access to a vehicle is estimated to increase NOx emissions by 1.51%.

- *Socioeconomic parameters, i.e., population and employment, continue to be of critical importance for the model.* Of all the results presented here, the most dramatic change in absolute percentages resulted from a population and employment increase of 100%: Scenario 5d showed that VMT and VHT increased by 39% to 40% and 102% to 116%, respectively. The ranges reflect the use of the doubly constrained or singly constrained gravity model.

- *The aggregate performance measures may mask important distinctions in more detailed performance measures.* The researchers had initially expected to focus on three aggregate measures of performance: VHT, VMT, and MTT. However, for some scenarios, differences in these measures were slight yet the scenario demonstrated an impact in other areas. Notably, for example, although the transit-favorable scenario (Scenario 3a) showed a drop of about 0.20% in VMT or 0.37% in VHT, the mode shift—an increase in transit's mode share from 0.26% to 3.36%—was far more dramatic. Other modal shifts were also of interest: in Scenario 3b, which asked a question opposite to that of Scenario 3a (i.e., what if the increased attractiveness of DVs led them to take market share from transit), although the number of transit trips decreased slightly, the number of nonmotorized trips decreased by about 20 times that amount.

RECOMMENDATIONS

1. *VDOT's Transportation and Mobility Planning Division (TMPD) should consider adding material regarding ways to incorporate DVs in VDOT's Travel Demand Modeling Policies and Procedures manual (Cambridge Systematics, 2014) when it is next updated. A proposed draft of that material is shown in Table 29, although this may be modified as appropriate by the TRP or others performing the update.* This manual provides guidance for calibrating travel demand models (led by VDOT) and then applying such models to alternative scenarios (led by MPOs). The portion of the manual that is most relevant to this recommendation refers to the development of alternative scenarios of interest to MPOs. For example, because MPOs are often interested in alternative land development scenarios, the manual offers guidance on how MPOs may incorporate those scenarios into the model. This recommendation is to update the appropriate sections of the manual to include guidance for considering DVs as part of such scenarios. As is the case with land use alternatives, this guidance does not require MPOs to perform these alternatives but rather provides information regarding how to incorporate them. If this recommendation is accepted, it may be implemented when the manual is next updated. In the past, the manual has been periodically updated: Version 1.22 was published in 2007 (VDOT, 2007); Version 1.30 was available in 2009 (VDOT, 2009); and Version 2.0 became available in 2014 (Cambridge Systematics, 2014).

Table 29. Proposed Additions to VDOT's *Travel Demand Modeling Policies and Procedures* Manual

Section (Title)	Excerpt of Current Text[a]	Potential Additional Text[b]
2.1 (Purpose and Need for Modeling in Transportation Planning Analysis)	[Lists examples such as] "Evaluation of the effects of transportation and planning policies (such as pricing and land use)."	[Add this example] "Evaluation of potential demand and supply impacts of new technologies, such as driverless vehicles."
2.4.2 (Major Revisions)	"The major difference between major revisions and model development is that major revisions do not result in significant changes to the model structure."	"For example, some of the ways to incorporate driverless vehicles into alternatives scenarios, such as changing capacities and altering parameters for the waiting time, do not entail a major revision in the model structure. Others, such as adding a new mode, may constitute such a major revision."[c]
4.1.3 (Transportation Networks)	"Networks for other scenarios, such as Vision Long-Range Plan (VLRP) and interim years other than those prepared for by air quality conformity, may be prepared but are not required."	"For example, for a scenario with driverless vehicles, a new scenario network might entail any combination of the following: • Altered capacities in the capacity lookup table for all or some functional classes[b] • Altered parameters for the utility function for some or all transit and highway modes • Altered population and employment values to reflect new development • Altered friction factors or impedance parameters to reflect greater ease of travel."
	"An example of a fictitious capacity lookup table is shown in Table 4.11." [The table shows that in the central business district, freeways have a capacity of 1,600]	"For example, if literature suggests that driverless vehicles might increase the capacity of freeways by 30%, then an alternative scenario to include the arrival of such vehicles would increase the capacity of freeways in the CBD from 1,600 veh/hr/lane to 2,080 veh/hr/lane"
4.1.2 (Land Use / Socioeconomic Data)	"Local agencies are responsible for the base-year and forecast land use data necessary for travel demand forecasting."	"Local agencies may wish to consider multiple forecasts for land use data. For example, to consider driverless vehicles, an agency might wish to have an additional scenario where parking lots in the CBD are converted to other land uses."
5.1.1 (Trip Purposes)	"Home-based school (HBSc) travel also is unique in terms of travel modes (since most students are too young to drive and some are so young that they require escorting)."	"It may be appropriate to increase certain types of trips in modeling alternative scenarios if new technologies will provide greater access to vehicles than is presently the case. For example, a scenario might increase the number of HBSc trips by vehicle for persons age 13-17 to account for high school students who do not have access to a vehicle but who can travel unescorted."
6.1.4 (Singly versus Doubly Constrained Models)	"There is no consensus on best practice concerning whether it is always better to have a singly constrained or doubly constrained trip distribution model "	"MPOs may wish to execute the model twice—once using the doubly constrained gravity method and once using the singly constrained gravity method—to determine if the impacts of driverless vehicles vary substantially between these two methods."

Section (Title)	Excerpt of Current Text[a]	Potential Additional Text[b]
9.1.2 (Modes)	"Auto can be segmented into single-occupant vehicles (SOV) and high-occupancy vehicle (HOV) . . ."	"and zero occupant vehicle [ZOV] if the model considers either (1) the replacement of parking with ZOV trips or (2) shared driverless vehicles. The latter can be implemented by increasing NHB trips on the network or may be an off-network calculation."
13.2.2 (Long- and Short-Range Transportation Planning)	"This often involves scenario analysis, where groups of projects are analyzed together to determine their cumulative impacts over the long term."	"Scenario analysis may also include consideration of alternative futures. For example, one scenario might presume no major changes in vehicle technology, and another scenario might presume driverless vehicles by year 2040."
13.2.4 (Evaluation of Transportation Improvements and Infrastructure Investments)	"There are some types of projects for which models may not be as well suited for analysis [and then examples are listed]."	For example, evaluating the needed increase in curbside access required by large numbers of driverless vehicles at a particular commercial location is better addressed through microscopic models than through regional travel demand models.

[a] From VDOT's *Travel Demand Modeling Policies and Procedures* manual (Cambridge Systematics, 2014).
[b] Proposed additional text would follow the sentence in the second column.
[c] For examples of ways to revise a legacy model, see Table ES1.

IMPLEMENTATION AND BENEFITS

Implementation

The direction taken in this study differed from a strict focus on modeling: the goal was not to devise a demand model that captured all elements of DVs but rather to devise a model that addressed just a few topics of interest to local decision-makers, which here pertained to capacity, parking decisions, greater access for a subset of the population with limited mobility, and emissions. In that sense, the information in Tables 18 through 23 (for the six scenarios) suggested that the most productive steps for regions with limited budgets and staff in considering DVs might be to identify a few policy concerns and then look at simple changes to the model that could provide insights into those concerns. To implement these steps, the study recommended providing guidance in VDOT's *Travel Demand Modeling Policies and Procedures* manual (Cambridge Systematics, 2014).

The head of TMPD's Travel Demand Modeling Section will consider the suggested revisions (see Table 29) when the manual is next updated. The word "consider" is used for two reasons. First, although it is expected that the manual will be updated, it is not yet known when that will occur. Second, it was reported at the project's executive review meeting on May 11, 2018, that some of the concepts identified in Table 29 are already being used in other models and that some of the other concepts identified in Table 29 are being considered on a test basis. It is thus possible that as experience is acquired with other models, information will be obtained that supports, refutes, or modifies the continued use of the concepts.

Benefits

Virginia’s transportation planning process seeks to identify potential problems, where VDOT seeks to work “with decision makers and citizens to reach consensus on solutions to those problems” (VDOT, 2014). The travel demand model supports this mission and can be used to “evaluate transportation systems or policies” (Cambridge Systematics, 2014). The chief benefit of implementing the modifications in Table 29 is that they offer the entities responsible for executing the travel demand model a relatively low-cost method for incorporating potential impacts of DVs into the regional model, with some sacrifice in precision. Agencies can thus execute a wide variety of scenarios (as done in this study), assess the results, and then focus on a couple of scenarios that are of greatest importance in greater detail.

One way to quantify the potential benefit of implementing this recommendation is thus to compare the costs of executing the travel demand model without being able to use these low-cost methods versus with being able to use these low-cost methods. A hypothetical situation in which an agency’s chief concern is the impact of DVs on VHT in two decades may be used as an example. In this situation, the agency is interested in knowing how three possible actions might affect the regional model: capacity enhancements, greater investment in transit, and encouragement of land use policies such as zoning.

For the case study region examined in this study, implementation of these three alternatives might require an estimated 16 to 44 hours of work once the analyst is familiar with the model and the region. Capacity changes require altering a single lookup table; the time requirement is due primarily to determining the values to which capacities should be changed (for an estimated 1 to 4 hours of effort). The mode shift to transit requires understanding the model script, and hence some additional study (of roughly 10 to 20 hours) may be required to alter the utility function, although the actual coding changes are minor. Implementation of land use policies can require the greatest effort if a detailed study is done (as per Scenario 2d); however, a simpler modification of socioeconomic data (e.g., increase population and employment in the CBD) could greatly reduce this time to an estimated 5 to 20 hours. (For locations other than the case study region, these time estimates could be higher or lower depending on the complexity of the model, the quality of model documentation, and the analyst’s familiarity with the model.)

If the MPO obtained the same results as given in this study, where alterations in capacity greatly affected VHT (Scenario 1a) yet alterations to transit (Scenario 3a) and land development (Scenario 2d) did not affect VHT substantially, the MPO might then choose to focus on just one of these scenarios (Scenario 1a) in greater detail. The researchers do not have detailed cost information regarding the number of hours a firm or internal staff might require to do a more detailed scenario. However, a publicly available response to a request for proposals to perform some modeling-related work in the Missoula, Montana, area (LSA Associates, Inc., 2010) indicated that some types of optional enhancements to the model could require 33 to 114 hours of staff time. If a more detailed analysis coincided with the lower end of this range, the cost for the more detailed analysis might be about 50 hours.

Thus, with implementation of the study recommendation, the MPO might spend a total of roughly 44 hours (at a screening level) and another 50 hours (studying one scenario in detail), for a total of 94 hours. Without implementation of the study recommendation, the MPO might spend a total of 150 hours (studying each of the three scenarios in detail at 50 hours each). Thus, there might be a savings of roughly 150 − 94 = 54 person hours.

The benefits calculated as described are tenuous. If further work at the national level suggests that the use of DVs will not materialize for many decades, implementing the study recommendation would have no benefit. The time estimates given are also highly dependent on the model. For instance, under a scenario where the model was fully documented and/or the model developer was available to perform these scenarios, the screening shown in Table 29 might not be necessary. That said, this exercise suggests that a potential time savings can result if staff can modify the regional model to address scenarios of interest to stakeholders.

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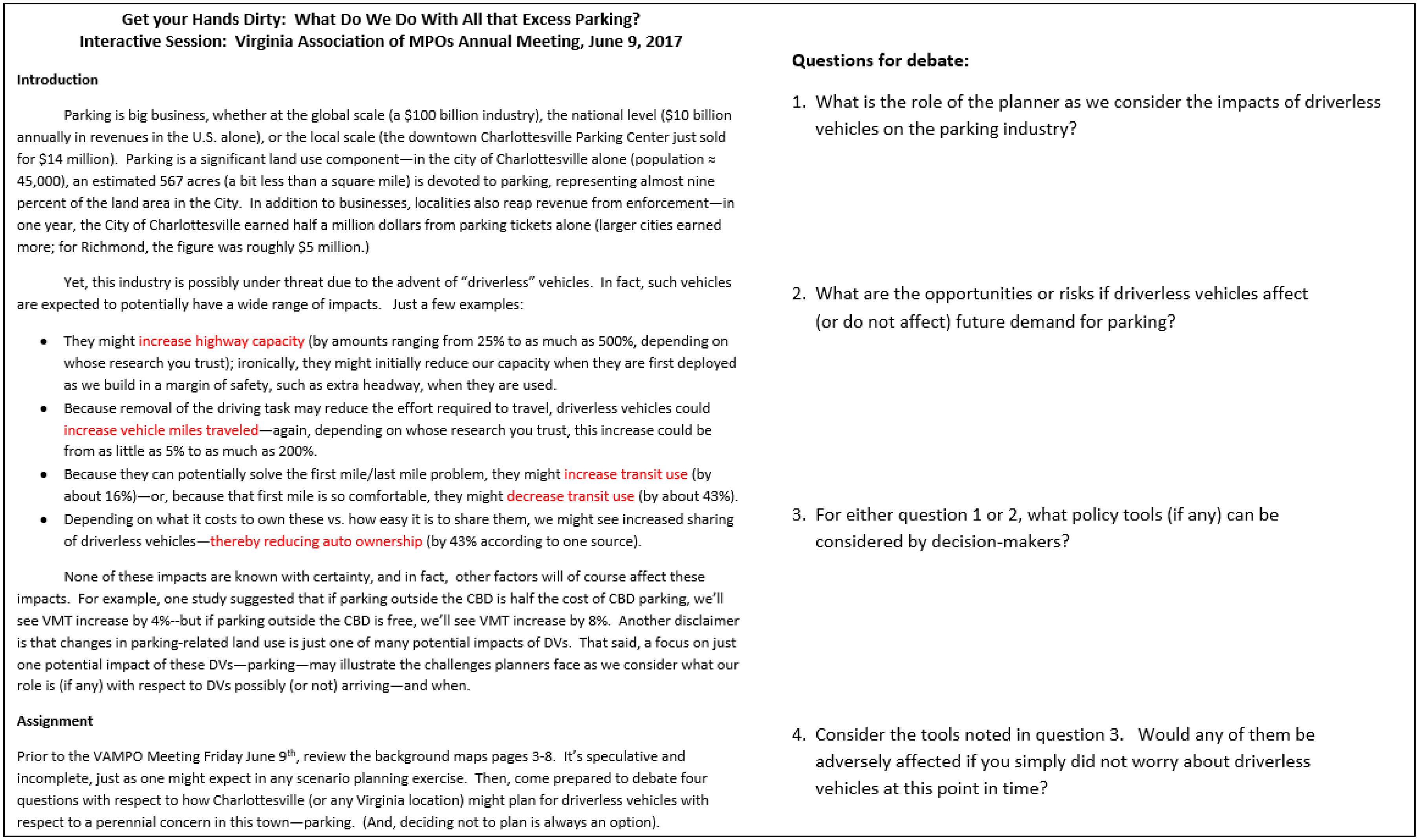
APPENDIX A

EXCERPT OF MATERIAL PROVIDED TO VAMPO ATTENDEES[a]



Get your Hands Dirty: What Do We Do With All that Excess Parking?
Interactive Session: Virginia Association of MPOs Annual Meeting, June 9, 2017

Introduction

Parking is big business, whether at the global scale (a $100 billion industry), the national level ($10 billion annually in revenues in the U.S. alone), or the local scale (the downtown Charlottesville Parking Center just sold for $14 million). Parking is a significant land use component—in the city of Charlottesville alone (population ≈ 45,000), an estimated 567 acres (a bit less than a square mile) is devoted to parking, representing almost nine percent of the land area in the City. In addition to businesses, localities also reap revenue from enforcement—in one year, the City of Charlottesville earned half a million dollars from parking tickets alone (larger cities earned more; for Richmond, the figure was roughly $5 million.)

Yet, this industry is possibly under threat due to the advent of "driverless" vehicles. In fact, such vehicles are expected to potentially have a wide range of impacts. Just a few examples:

- They might increase highway capacity (by amounts ranging from 25% to as much as 500%, depending on whose research you trust); ironically, they might initially reduce our capacity when they are first deployed as we build in a margin of safety, such as extra headway, when they are used.
- Because removal of the driving task may reduce the effort required to travel, driverless vehicles could increase vehicle miles traveled—again, depending on whose research you trust, this increase could be from as little as 5% to as much as 200%.
- Because they can potentially solve the first mile/last mile problem, they might increase transit use (by about 16%)—or, because that first mile is so comfortable, they might decrease transit use (by about 43%).
- Depending on what it costs to own these vs. how easy it is to share them, we might see increased sharing of driverless vehicles—thereby reducing auto ownership (by 43% according to one source).

None of these impacts are known with certainty, and in fact, other factors will of course affect these impacts. For example, one study suggested that if parking outside the CBD is half the cost of CBD parking, we'll see VMT increase by 4%--but if parking outside the CBD is free, we'll see VMT increase by 8%. Another disclaimer is that changes in parking-related land use is just one of many potential impacts of DVs. That said, a focus on just one potential impact of these DVs—parking—may illustrate the challenges planners face as we consider what our role is (if any) with respect to DVs possibly (or not) arriving—and when.

Assignment

Prior to the VAMPO Meeting Friday June 9th, review the background maps pages 3-8. It's speculative and incomplete, just as one might expect in any scenario planning exercise. Then, come prepared to debate four questions with respect to how Charlottesville (or any Virginia location) might plan for driverless vehicles with respect to a perennial concern in this town—parking. (And, deciding not to plan is always an option).

Questions for debate:

1. What is the role of the planner as we consider the impacts of driverless vehicles on the parking industry?
2. What are the opportunities or risks if driverless vehicles affect (or do not affect) future demand for parking?
3. For either question 1 or 2, what policy tools (if any) can be considered by decision-makers?
4. Consider the tools noted in question 3. Would any of them be adversely affected if you simply did not worry about driverless vehicles at this point in time?

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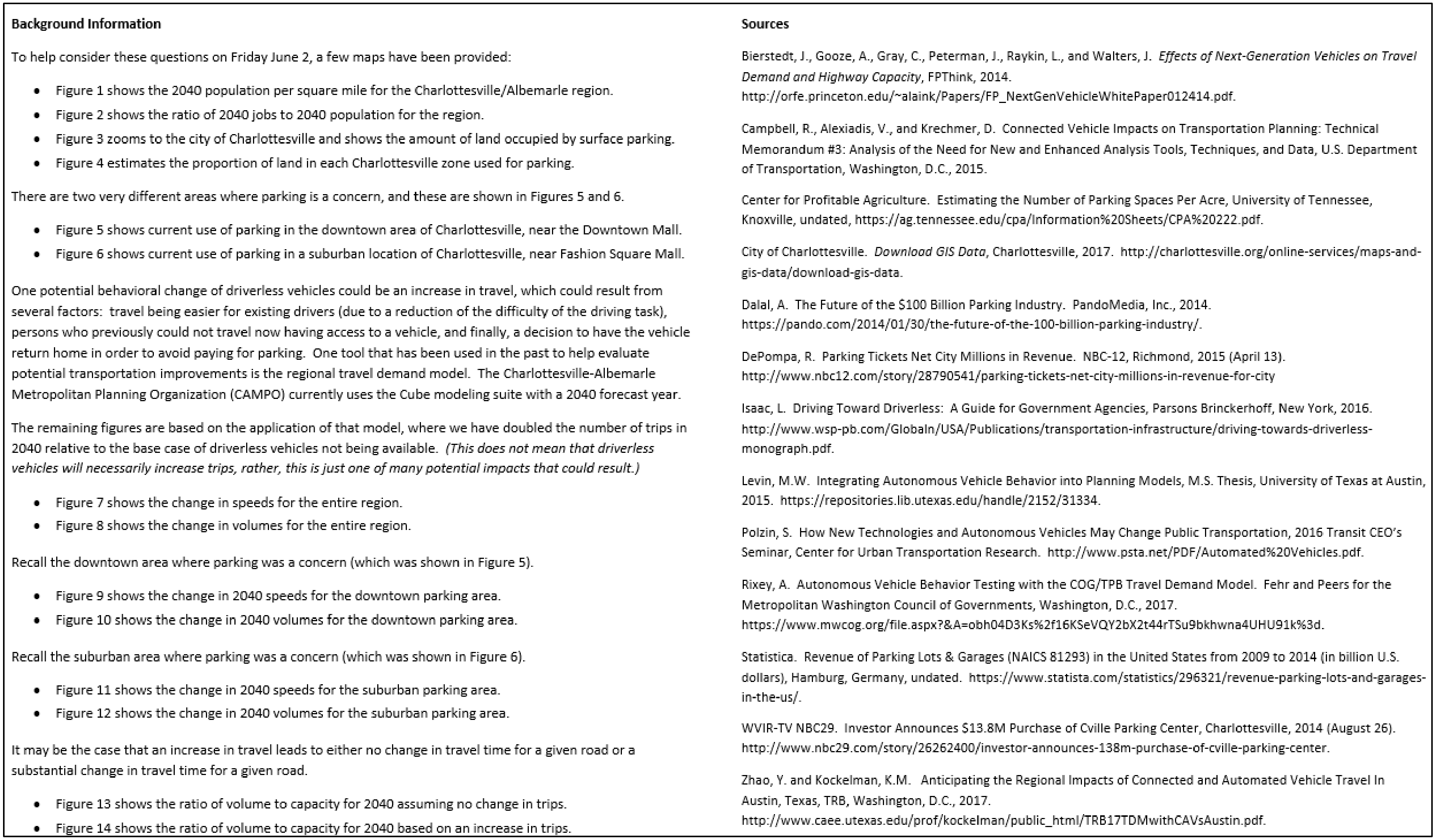
[a] The alignment of the "Questions for debate" was altered slightly to enhance readability. The red font was in the original material provided to attendees.



Background Information

To help consider these questions on Friday June 2, a few maps have been provided:

- Figure 1 shows the 2040 population per square mile for the Charlottesville/Albemarle region.
- Figure 2 shows the ratio of 2040 jobs to 2040 population for the region.
- Figure 3 zooms to the city of Charlottesville and shows the amount of land occupied by surface parking.
- Figure 4 estimates the proportion of land in each Charlottesville zone used for parking.

There are two very different areas where parking is a concern, and these are shown in Figures 5 and 6.

- Figure 5 shows current use of parking in the downtown area of Charlottesville, near the Downtown Mall.
- Figure 6 shows current use of parking in a suburban location of Charlottesville, near Fashion Square Mall.

One potential behavioral change of driverless vehicles could be an increase in travel, which could result from several factors: travel being easier for existing drivers (due to a reduction of the difficulty of the driving task), persons who previously could not travel now having access to a vehicle, and finally, a decision to have the vehicle return home in order to avoid paying for parking. One tool that has been used in the past to help evaluate potential transportation improvements is the regional travel demand model. The Charlottesville-Albemarle Metropolitan Planning Organization (CAMPO) currently uses the Cube modeling suite with a 2040 forecast year.

The remaining figures are based on the application of that model, where we have doubled the number of trips in 2040 relative to the base case of driverless vehicles not being available. *(This does not mean that driverless vehicles will necessarily increase trips, rather, this is just one of many potential impacts that could result.)*

- Figure 7 shows the change in speeds for the entire region.
- Figure 8 shows the change in volumes for the entire region.

Recall the downtown area where parking was a concern (which was shown in Figure 5).

- Figure 9 shows the change in 2040 speeds for the downtown parking area.
- Figure 10 shows the change in 2040 volumes for the downtown parking area.

Recall the suburban area where parking was a concern (which was shown in Figure 6).

- Figure 11 shows the change in 2040 speeds for the suburban parking area.
- Figure 12 shows the change in 2040 volumes for the suburban parking area.

It may be the case that an increase in travel leads to either no change in travel time for a given road or a substantial change in travel time for a given road.

- Figure 13 shows the ratio of volume to capacity for 2040 assuming no change in trips.
- Figure 14 shows the ratio of volume to capacity for 2040 based on an increase in trips.

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[Figures 1-14 cited are available from the authors. Figures 13 and 14 are shown as Figure 1 in this report.]

APPENDIX B

DERIVATION OF SOCIOECONOMIC DATA FOR PERSONS AGE 65+ (SCENARIO 5a)

Estimation of Persons Age 65+ By Zone

Zmud et al. (2016) indicated that age is one factor that influences the ability to drive, noting that starting at age 50, the proportion of persons who no longer drive increases as a function of aging. Accordingly, the researchers sought to estimate of the number of persons age 65+ for each TAZ, where the estimate would be consistent with the projection of total population used in the base 2040 travel demand model. Three main steps were used to obtain the estimate: (1) obtain the current proportion of persons age 65+ in each Census block group, (2) align the Census geography with the travel demand model geography, and (3) forecast the 2040 population age 65+ by zone.

Obtain Current Proportion of Persons Age 65+ in Each Census Block Group

The first step was to obtain current populations of persons age 65+ by Census block group from the most recent 5-year dataset available (U.S. Census Bureau, 2016). For each Census block group, the percentage of persons age 65+ was determined by summing the male and female persons in the six age categories for age 65+ (e.g., age 65-66, age 67-69, and so forth) and dividing by the total population of the block group. This method provided an average percentage of persons age 65+ by Census block group.

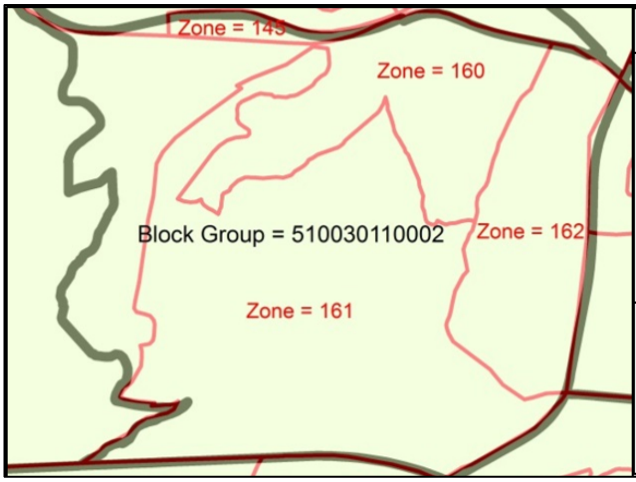
Align Census Geography With Travel Demand Model Geography

For the second step, although the effort described in Modification 6 (Figure 6) comprised most of the work required to align the zones from the travel demand model and those from the U.S. Census Bureau (2015a), additional processing was needed in order to overlay the zones from the travel demand model with the Census block groups. The general approach was to use the “Feature to Point” tool in ArcGIS, which in this particular case generated a centroid for each TAZ. Then, the zones were reviewed for errors; for example, in a few cases the centroid might be outside an irregular shaped zone, and in other cases there were sliver polygons resulting from the geoprocessing. Finally, the centroid of each TAZ (a point feature) could be easily associated with a Census block group (a polygon) such that each zone had a percentage of persons age 65+.

Forecast the 2040 Population Age 65+ by Zone

For the third step, the percentage of persons age 65+ is not expected to remain constant. For Charlottesville and Albemarle as a whole, the number of persons age 65+ based on 2015 data was 22,523 (of a total population of 152,300); that is, about 14.8% of the population was age 65+ (U.S. Census Bureau, 2015b). For year 2040, this percentage is forecast to rise to 19.5%; that is, with a total population forecast of 203,359, the forecast number of persons age 65+ is 39,656 (Weldon Cooper Center, 2012). Accordingly, the percentage populations for each zone that were computed based on current populations were all increased by the ratio of 19.5%/14.8% = 1.32.

Finally, the modified percentages were multiplied by the number of persons in each zone in 2040 in order to obtain a forecast of persons age 65+ in each zone. For example, Figure B1 shows how a forecast value of 274 persons age 65+ was obtained for TAZ 161: the present day percentage is 56% (which should increase by a factor of 1.32 to 74%), and given that the 2040 total population of that zone is 369, the number of persons age 65+ is expected to be 74% of 369, which is 274.



Entity	Quantity	Value
Census block group	Total population 2015	975
	Persons age 65+ (2015)	549
	Percent persons age 65+ (2015)	56%
	Forecast increase in percentage (2040)	132%
Zone 161	Total population (2040)	369
	Percent persons age 65+ (2040)	74%
	Persons age 65+ (2040)	274

Figure B1. Computation of Persons Age 65+ in TAZ 161, Situated Inside Census Block Group 510030110002

Estimation of Extra Trips by Persons Age 65+

The literature (Truong et al., 2017; Zmud et al., 2016) suggested that with DVs, persons who currently cannot drive because of their age might take advantage of such vehicles, leading to an increase in trips. Three different approaches using 2040 population forecasts for persons age 65+ in Charlottesville and Albemarle (Weldon Cooper Center, 2012) suggested that this increase in trips could be 12.9%, 14.4%, or 18.6%. For this scenario, an average value of 15.3% was used for two trip purposes: HBO and NHB.

Derivation of the Percentages of 14.4% and 18.6%

One approach to considering how DVs might affect travel is to compare licensure rates by age group. Calculations specific to Virginia reported by Miller et al. (2016) indicated that as of 2012, approximately 82% of persons age 65+ had a driver's license. If it is assumed that the remaining persons age 65+ without a driver's license would use DVs, and if it is further assumed that trip characteristics for such persons were similar to those for other drivers, an 18% increase in trips might be expected. A variation of this approach would be to consider national (not Virginia specific) rates of licensure for specific age groups reported by Zmud et al. (2016), which are 91.4% for persons age 60-69; 83.0% for persons age 70-79; and 61.7% for persons age 80+. If it is assumed that the rate of licensure for persons age 65-69 and persons age 60-64 (i.e., 91.4%) is the same, a weighted average for the Charlottesville-Albemarle region for 2040 would be a 23% increase in trips. That is, in 2040, among all persons age 65+, the distribution is expected to be as follows: a proportion of 0.21 is forecast for age 65-69; a proportion of 0.42 is forecast for age 70-79; and a proportion of 0.37 is forecast to be 80+. A weighted average would thus be 91.4%*(0.21) + 83.0%*(0.42) + 61.7%*(0.37) = 76.8% of such persons having a driver's license, meaning that 23.2% of such persons would not have a license.

However, both estimates—the 18% figure and the 23.2% figure—are possibly high given that they presume all persons without a driver's license would like to travel and that persons age 65+ take the same number of trips as younger persons. Data from the 2009 National Household Travel Survey used by Lynott and Figueiredo (2011) suggest that whereas persons age 16-49 average 4.0 trips per day, persons age 65+ average 3.2 trips per day—a 20% lower figure. Reducing the aforementioned averages of 18% and 23.2% by 20% suggests an increase in trips for persons age 65+ of 14.4% and 18.6%, respectively.

Derivation of the Percentage of 12.9%

A lower estimate the increase in trips attributable to persons age 65+ is available from Truong et al. (2017), who suggested that autonomous vehicles would increase the number of trips by 5.13% for persons age 65-74 and by 18.48% for by persons age 75+. As was the case with the aforementioned calculations, Truong et al. (2017) considered the effects of age on licensure, which is influenced by the presence of disabilities, and trip generation; in addition, they considered modal shifts and auto occupancy rates. The number of persons in these age groups is not expected to be identical in 2040; for example, in the Charlottesville-Albemarle region, the number of persons age 65-74 is forecast to be 16,704 (about 42% of the total population age 65+) and the number of persons age 75+ is forecast to be 22,950 (about 58% of the total population age 65+). Accordingly, if the results of Truong et al. (2017) were to be applicable for the Charlottesville-Albemarle region, the aggregate number of trips by persons age 65+ would be expected to increase by a weighted average of 5.13%(0.42) + 18.48%(0.58), or about 12.9%.

Other Potential Percentages Not Used Here

To be clear, these figures are variable. It is possible, for example, that the 20% difference in trips for persons age 65+ and persons age 16-49 reported by Lynott and Figueiredo (2011) is strikingly similar to the proportion of trips nationally that are usually attributed to the HBW trip purpose of 15% (Cambridge Systematics, Inc., et al., 2012). Accordingly, it might be appropriate to increase the 15.3% figure used in these scenarios by a factor of roughly 15% (e.g., to a value of 17.6%) with the idea that it would only be applicable to the nonwork trips (i.e., HBO and NHB). That said, the use of the 15.3% estimate appears to be a reasonable order of magnitude approximation for determining the impact of trips generated by persons age 65+. Accordingly, the 15.3% increase in HBO and NHB trips was used to generate Scenario 5b.

APPENDIX C

KEY SCRIPTS USED IN THE SCENARIOS

In all scripts shown in Appendix C, a semicolon (;) precedes any comment, which is text that is not to executed by the software but which is intended to clarify the action being done by the script. Blank lines are not required but are an indication of separate tasks being executed by the script. For instance, there is a blank line between the establishment of the trip impedances and then the use of the trip impedances to distribute trips by purpose. Except for the first script shown below (implementing a singly constrained gravity model), most of the scripts were not created anew for this project but instead were modifications to existing scripts, and key changes that were made (to existing scripts) are highlighted in red font. The lines of the scripts are in 10-point font. (Following the development of the draft report, it was pointed out to the researchers that there are some locations where there is a space before the equals sign and in some cases there is no space. Because the scripts were working in their present form, the researchers did not modify these spacings.) Figures C3 through C7 show screenshots of the editor used to modify the scripts. The editor automatically adds certain colors that have various specific meanings, such as green for a comment or blue for a matrix.

Script for Implementing a Singly Constrained Gravity Model (all Scenarios)

```
;Establish the location of the print file which records how the script was executed
RUN PGM=MATRIX
PRNFILE="{CATALOG_DIR}\OUTPUT\{SCENARIO_FULLNAME}\Logs\PDDST00A.PRN"

;Establish the input and output files
FILEI MATI[2] = "{CATALOG_DIR}\OUTPUT\{SCENARIO_FULLNAME}\FFTIME.MAT"
FILEI ZDATI[1] = "{CATALOG_DIR}\Output\{Scenario_FullName}\TGEN_PA.DBF"
FILEO MATO[1] = "{CATALOG_DIR}\Output\{Scenario_fullname}\InitialTdist.MAT", mo=1-5,
name=HBW,HBO,NHB,HBU,HDORMU
FILEO MATO[2] = "{CATALOG_DIR}\Output\{Scenario_fullname}\EITdist.MAT,"
 MO=6, NAME=IX

;Create arrays
PARAMETERS
   zones = {Total Zones}
   maxiters ={AITERS}
   ARRAY HBWpersonTrips = ZONES
   ARRAY HBOpersonTrips = ZONES
   ARRAY NHBpersonTrips = ZONES
   ARRAY HBUpersonTrips = ZONES
   ARRAY HDORMUpersonTrips = ZONES
   ARRAY IXpersonTrips=ZONES
;Establish productions

JLOOP
      HBWpersonTrips[I]=ZI.1.HBW_P
      HBOpersonTrips[I]=ZI.1.HBO_P
      NHBpersonTrips[I]=zi.1.nhb_p
      HBUpersonTrips[I]=zi.1.HBUP
      HDORMUpersonTrips[I]=zi.1.HDORMUP
      IXpersonTrips[I]=zi.1.IX_P
```

```
ENDJLOOP

;Create trip impedances
mw[30]=MI.2.FFTIME
mw[21]=MI.2.FFTIME*(-0.04259)            ;Can replace with -0.08001
mw[22]=MI.2.FFTIME*(-0.09881)            ;Can replace with -0.18959
mw[23]=MI.2.FFTIME*(-0.18995)            ;Can replace with -0.22559
mw[24]=MI.2.FFTIME*(-0.10779)            ;Can replace with -0.20830
mw[25]=MI.2.FFTIME*(-0.10779)            ;Can replace with -0.20830
mw[26]=MI.2.FFTIME*(-0.10516)            ;Can replace with -0.20004

;Distribution for home-based work trips
XCHOICE,
ALTERNATIVES=ALL,
DEMAND=HBWpersonTrips[I],
UTILITIESMW=21,
ODEMANDMW=1,
DESTSPLIT=TOTAL All, INCLUDE=1-{Internal Zones},
STARTMW=99
FREQUENCY VALUEMW=1 BASEMW=30, RANGE=0-50

;Distribution for home-based other  trips
XCHOICE,
ALTERNATIVES=ALL,
DEMAND=HBOpersonTrips[I],
UTILITIESMW=22,
ODEMANDMW=2,
DESTSPLIT=TOTAL All, INCLUDE=1-{Internal Zones},
STARTMW=99
FREQUENCY VALUEMW=2 BASEMW=30, RANGE=0-50

;Distribution for nonhome-based  trips
XCHOICE,
ALTERNATIVES=ALL,
DEMAND=NHBpersonTrips[I],
UTILITIESMW=23,
ODEMANDMW=3,
DESTSPLIT=TOTAL All, INCLUDE=1-{Internal Zones},
STARTMW=99
FREQUENCY VALUEMW=3 BASEMW=30, RANGE=0-50

;Distribution for non-dormitory university tripsXCHOICE,
ALTERNATIVES=ALL,
DEMAND=HBUpersonTrips[I],
UTILITIESMW=24,
ODEMANDMW=4,
DESTSPLIT=TOTAL All, INCLUDE=1-{Internal Zones},
STARTMW=99
FREQUENCY VALUEMW=4 BASEMW=30, RANGE=0-50

;Distribution for dormitory university tripsXCHOICE,
ALTERNATIVES=ALL,
DEMAND=HDORMUpersonTrips[I],
UTILITIESMW=25,
ODEMANDMW=5,
DESTSPLIT=TOTAL All, INCLUDE=1-{Internal Zones},
```

```
STARTMW=99
FREQUENCY VALUEMW=5 BASEMW=30, RANGE=0-50

;Distribution for internal-external tripsXCHOICE,
ALTERNATIVES=All,
DEMAND=IXpersonTrips[I],
UTILITIESMW=26,
ODEMANDMW=6,
;DESTSPLIT=TOTAL All, INCLUDE=1-{Internal Zones}, EXCLUDE = 1-265,
DESTSPLIT=TOTAL All, EXCLUDE = 1-265,
STARTMW=99
FREQUENCY VALUEMW=6 BASEMW=30, RANGE=0-50

; end of the program
ENDRUN
```

Script for Obtaining a Congested Trip Length Frequency Distribution

The lines shown here yield the MTT as required by the file “CVMAT00A.S” in Sequence 13.

```
RUN PGM=MATRIX PRNFILE="{CATALOG_DIR}\Output\{Scenario_FullName}\totaltrip length.prn"
MSG='Average trip Length'
FILEO MATO[1] = "{CATALOG_DIR}\Output\{Scenario_FullName}\Total triplength.MAT", mo=3 name ='total
trip length'
FILEI MATI[1] =
"{CATALOG_DIR}\OUTPUT\{SCENARIO_FULLNAME}\FBCONGTIMESOV{Year}.MAT"
mw[1]=mi.1.3
FILEI MATI[2] =
"{CATALOG_DIR}\OUTPUT\{SCENARIO_FULLNAME}\CVFINALVEHTRIPS{Year}.DAT"
mw[2]=mi.2.5
mw[3]=mw[1]*mw[2]
FREQUENCY VALUEMW=2  BASEMW=1,  RANGE=1-100
ENDRUN
```

For Scenarios 2a, 2b, and 2c only, because the number of vehicles on the network changed substantially right before the assignment step, two manual steps were performed after the model had been executed. These steps did not require further modification to the script for obtaining a congested trip length frequency distribution but were performed in order to update the matrix of zone-to-zone travel times. In sum, after the model has been executed in its entirety, the first step is to open file “PAHWY00B.S” (which is in pre-assignment Sequence 7), replace the file “CombVol2040.NET” in the script with the file “LoadedNet2040A.NET,” and then execute the sequence titled “Highway.” This first step provides an updated matrix of zone-to-zone congested travel times. The second step is to execute Sequence 13 (titled “Average Trip Length”). With the completion of the second step, the output file “TotalTripLength.prn” provides the MTT.

Implementation of Scenarios 2a, 2b, and 2c

Role of a 24-Hour Model Versus a Time-of-Day Model

The Charlottesville model uses a single 24-hour period. Right before the 24-hour volumes from the vehicle trip table are assigned to the network, the model divides the hourly capacity by 0.10 to obtain a 24-hour capacity and calculates the ratio of the 24-hour volume divided by this new capacity. In terms of the volume/capacity ratio for each link, this is mathematically equivalent to presuming that 10% of the 24-hour trips occur during the peak hour and dividing the resultant hourly volume by the original hourly capacity.

Accordingly, for incorporating additional ZOV trips in Scenarios 2a, 2b, and 2c, in which the commuter sends the empty vehicle back home (in the morning) and then requests the empty vehicle to return to work (in the evening), the approach presented in the body of the report in Figure 9 is appropriate. Figure C1 modifies Figure 9 slightly to reflect a simplified situation where there are 200 productions in Zone A and 200 corresponding attractions in Zone B for a person trip production attraction matrix for HBW trips by the mode of SOV. As shown in Figure C1(d), the result for this 24-hour period, assuming each person sends their DV home during the day, is a total of 200 trips from Zone A to Zone B and vice-versa.

Person	A	B	Total
A	0	200	200
B	0	0	0
Total	0	200	

(a)

Person.T	A	B	Total
A	0	0	0
B	200	0	200
Total	200	0	

(b)

Vehicle	A	B	Total
A	0	100	100
B	100	0	100
Total	100	100	

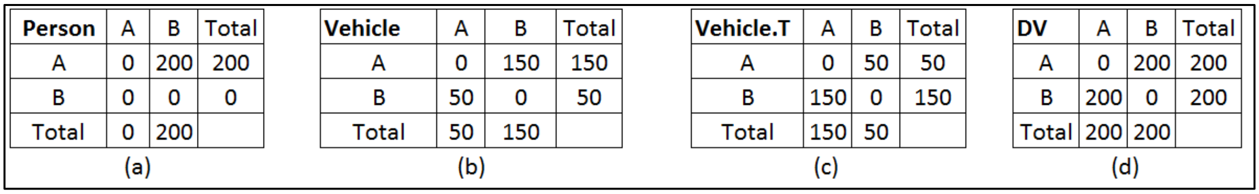
(c)

DV	A	B	Total
A	0	200	200
B	200	0	200
Total	200	200	

(d)

Figure C1. Steps to Model Commuters Sending an Empty DV Home Rather Than Parking It at Work for a Region With Only a 24-Hour Model: (a) production-attraction person matrix; (b) transposed production-attraction person matrix; (c) origin-destination vehicle matrix; (d) origin-destination vehicle matrix that includes additional trips by empty DVs. DV = driverless vehicle; Person.T = the transpose of the matrix defined by Person.

However, some regions in Virginia have a time-of-day model, where there might be, for example, different production attraction person matrices for different times of day. In that case, time-of-day factors (Martin and McGuckin, 1998) might be used to convert these production-attraction person matrices to origin-destination vehicle matrices. During the morning peak, such factors would reflect most HBW productions as origins and most HBW attractions as destinations (but not all, in order to account for reverse commuters, night shift work, and so forth). Figure C2(b) shows the resultant origin-destination vehicle trip matrix that might result from a simplified time-of-day factor that presumed 75% of HBW trips during the morning peak period had the origin at the production end and the destination at the attraction end. In order to reflect the fact that each of these morning trips might then be followed by a DV that reversed the trip order, the matrix would be transposed, as shown in Figure C2(c). The sum of these two matrices, Figure C2(d) would be the vehicles assigned to the network assuming there was a single morning peak period. Although Figure C2(d) is identical to Figure C1(d), the distinction presented here matters for areas that have a time-of-day model, as such areas may need to add a transposed matrix—that is, they may need to incorporate Figure C1(c) into the script.



Person	A	B	Total
A	0	200	200
B	0	0	0
Total	0	200	

(a)

Vehicle	A	B	Total
A	0	150	150
B	50	0	50
Total	50	150	

(b)

Vehicle.T	A	B	Total
A	0	50	50
B	150	0	150
Total	150	50	

(c)

DV	A	B	Total
A	0	200	200
B	200	0	200
Total	200	200	

(d)

Figure C2. Steps to Model Morning Commuters Sending an Empty DV Home Rather Than Parking It at Work for a Region With a Time-of-Day Model: (a) production-attraction person matrix; (b) transposed production-attraction person matrix; (c) origin-destination vehicle matrix; (d) origin-destination vehicle matrix that includes additional trips by empty DVs. DV = driverless vehicle; Vehicle.T = transpose of the matrix defined by Vehicle.

For the Charlottesville model, implementation of Scenarios 2a, 2b, and 2c required modifications to the script "MCMAT00C.S," which follows the mode choice step and determines the vehicles that will be loaded onto the network.

Script for Adding ZOV Trips for Driving Modes (Scenarios 2a and 2b)

For Scenario 2a, multiply the sum of the original and transposed matrix for HBW drive alone trips by 2:

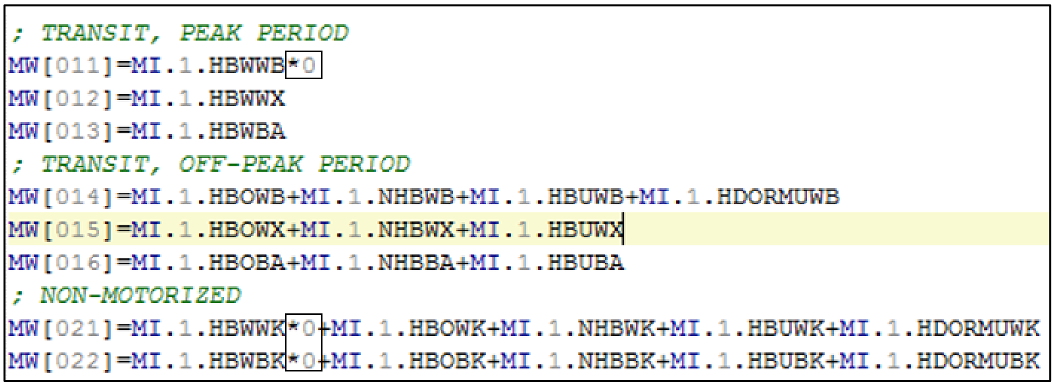
```
MW[1]=(2*(MI.1.HBWDA+MI.1.HBWDA.T)/1.0+…
```

For Scenario 2b, make the same change and then multiply the sum of the original and transposed matrix for HBW carpool 2 and carpool 3+ trips by 2:

```
MW[2]=(2*(MI.1.HBWCP+MI.1.HBWCP.T)/2.0+…
MW[3]=(2*(MI.1.HBWCX+MI.1.HBWCX.T)/{HBW3P}+
```

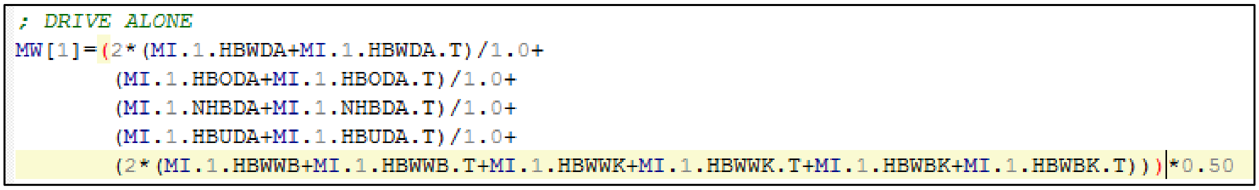
Script for Adding ZOV Trips for All Modes (Scenario 2c)

For Scenario 2c, after making the same changes for Scenarios 2a and 2b, in the same script eliminate the HBW trips that are made by biking, walking, or transit (see Figure C3) by multiplying such trips by zero. Then, as shown in Figure C4, modify the script to reflect that each of these trips becomes a drive alone trip.



```
; TRANSIT, PEAK PERIOD
MW[011]=MI.1.HBWWB*0
MW[012]=MI.1.HBWWX
MW[013]=MI.1.HBWBA
; TRANSIT, OFF-PEAK PERIOD
MW[014]=MI.1.HBOWB+MI.1.NHBWB+MI.1.HBUWB+MI.1.HDORMUWB
MW[015]=MI.1.HBOWX+MI.1.NHBWX+MI.1.HBUWX
MW[016]=MI.1.HBOBA+MI.1.NHBBA+MI.1.HBUBA
; NON-MOTORIZED
MW[021]=MI.1.HBWWK*0+MI.1.HBOWK+MI.1.NHBWK+MI.1.HBUWK+MI.1.HDORMUWK
MW[022]=MI.1.HBWBK*0+MI.1.HBOBK+MI.1.NHBBK+MI.1.HBUBK+MI.1.HDORMUBK
```

Figure C3. Eliminating Commute Trips by Transit, Biking, and Walking. The different colors in the figure were not created by the researchers. Rather, when using the editor, these colors appear automatically. Of greatest interest is the green color, which indicates a comment (e.g., a statement not executed by the software) as signified by a semicolon.



```
; DRIVE ALONE
MW[1]=(2*(MI.1.HBWDA+MI.1.HBWDA.T)/1.0+
        (MI.1.HBODA+MI.1.HBODA.T)/1.0+
        (MI.1.NHBDA+MI.1.NHBDA.T)/1.0+
        (MI.1.HBUDA+MI.1.HBUDA.T)/1.0+
        (2*(MI.1.HBWWB+MI.1.HBWWB.T+MI.1.HBWWK+MI.1.HBWWK.T+MI.1.HBWBK+MI.1.HBWBK.T)))*0.50
```

Figure C4. Replacing Transit, Bike, and Walk Trips With DV Trips. The red parentheses indicate that the entire expression was multiplied by 0.5.

Script for Implementing Conversion of Parking Lots to Other Uses (Scenario 2d)

Notice that the file “Landuse_2040A.dbf” is ZI.2 in the first script but ZI.3 in the second script. The red font shown herein indicates material added by the researchers in order to implement Scenario 2d. The empty spaces between lines are not required but were in the original scripts and intended to improve readability. The semicolon (;) indicates a comment (e.g., text that explains what the script is doing; such text is not executed by the software).

```
;In the file APPLICATIONS\TGMAT00F.S

        HBUP = 2.996*ZI.2.OffC_Stu*{HBO-TF}+ZI.2.ParkPLo*0.07; was 0.10
        HBUA = 1.375*ZI.2.Total_park*{HBO-TF}+ZI.2.ParkPLo*0.07; was 0.00

;In the file APPLICATIONS\TGGEN00A.S
        pix=0.331*zi.3.HH + 0.724*(zi.3.TOTEMP + zi.3.EMPLOYEE_P)+ZI.3.ParkPLo*0.40
        aix=zi.4.COUNT * zi.4.IXPCT+ZI.3.ParkPLo*0
        ; Balance attractions to productions
         a[4]=aix*1.02112

 if(zi.2.atype=1-2)

 phbw=_rates_city(1,1)* zi.1.h1V0+ _rates_city(1,2)* zi.1.H1V1 + _rates_city(1,3)* zi.1.H1V2 +
    _rates_city(1,4)* zi.1.H2V0 + _rates_city(1,5)* zi.1.H2V1 + _rates_city(1,6)* zi.1.H2V2 +
    _rates_city(1,7)* zi.1.H3V0 + _rates_city(1,8)* zi.1.H3V1 + _rates_city(1,9)* zi.1.H3V2 +
    _rates_city(1,10)* zi.1.H4V0 + _rates_city(1,11)* zi.1.H4V1 + _rates_city(1,12)* zi.1.H4V2
+ZI.3.ParkPLo*0.05

 phbo=_rates_city(2,1)* zi.1.h1V0+ _rates_city(2,2)* zi.1.H1V1 + _rates_city(2,3)* zi.1.H1V2 +
    _rates_city(2,4)* zi.1.H2V0 + _rates_city(2,5)* zi.1.H2V1 + _rates_city(2,6)* zi.1.H2V2 +
    _rates_city(2,7)* zi.1.H3V0 + _rates_city(2,8)* zi.1.H3V1 + _rates_city(2,9)* zi.1.H3V2 +
    _rates_city(2,10)* zi.1.H4V0 + _rates_city(2,11)* zi.1.H4V1 + _rates_city(2,12)* zi.1.H4V2
+ZI.3.ParkPLo*0.16

 pnhb=_rates_city(3,1)* zi.1.h1V0+ _rates_city(3,2)* zi.1.H1V1 + _rates_city(3,3)* zi.1.H1V2 +
    _rates_city(3,4)* zi.1.H2V0 + _rates_city(3,5)* zi.1.H2V1 + _rates_city(3,6)* zi.1.H2V2 +
    _rates_city(3,7)* zi.1.H3V0 + _rates_city(3,8)* zi.1.H3V1 + _rates_city(3,9)* zi.1.H3V2 +
    _rates_city(3,10)* zi.1.H4V0 + _rates_city(3,11)* zi.1.H4V1 + _rates_city(3,12)* zi.1.H4V2
+ZI.3.ParkPLo*0.32

;------------------------------------------------------------------
;
 if(i=55,58-62,68,80-92,163,165-169,251-256,258-260)          ; Attractions for UVA
   ahbw=ATTRRATES(3,1)*zi.1.temp+ZI.3.ParkPLo*0.08
   ahbo=ATTRRATES(1,5)*zi.1.ret + ATTRRATES(2,5)*nonretail +
ATTRRATES(4,5)*zi.1.hhx+ZI.3.ParkPLo*0.13
```

```
    anhb=ATTRRATES(1,9)*zi.1.ret + ATTRRATES(2,9)*nonretail +
ATTRRATES(4,9)*zi.1.hhx+ZI.3.ParkPLo*0.32
    flag=1
   ;print list=' UVA ',i(6),j(6),ahbw(8.2),zi.1.temp(6),ahbo(9.2),zi.1.ret(6),nonretail(6),zi.1.hhx(6)


  ELSEif(zi.2.atype=1 & flag=0)                              ;  Attractions for CBD
    ahbw=ATTRRATES(3,2)*zi.1.temp+ZI.3.ParkPLo*0.08
    ahbo=ATTRRATES(1,6)*zi.1.ret + ATTRRATES(2,6)*nonretail +
ATTRRATES(4,6)*zi.1.hhx+ZI.3.ParkPLo*0.13
    anhb=ATTRRATES(1,10)*zi.1.ret + ATTRRATES(2,10)*nonretail +
ATTRRATES(4,10)*zi.1.hhx+ZI.3.ParkPLo*0.32


  elseif(zi.2.atype=2-5 & flag=0)                      ;  Attractions for Urban
    ahbw=ATTRRATES(3,3)*zi.1.temp+ZI.3.ParkPLo*0.08
    ahbo=ATTRRATES(1,7)*zi.1.ret + ATTRRATES(2,7)*nonretail + ATTRRATES(4,7)*zi.1.hhx +
ATTRRATES(5,7)*zi.1.school+ZI.3.ParkPLo*0.13
    anhb=ATTRRATES(1,11)*zi.1.ret + ATTRRATES(2,11)*nonretail + ATTRRATES(4,11)*zi.1.hhx +
ATTRRATES(5,11)*zi.1.school+ZI.3.ParkPLo*0.32
```

Script for Increasing NHB Trips to Simulate ZOV Trips (Scenarios 4b and 4c)

In the file "TGGEN00A.S," a multiplier is used to increase NHB trips. For example, for the doubly constrained case with five regions (e.g., Scenario 4c), a multiplier of 1.61 was needed for the singly constrained model and a multiplier of 1.685 was needed for the doubly constrained model. Thus, the script was modified in two places (one for the city zones and one for the county zones) as indicated in red font (and the case below shows the doubly constrained case).

```
pnhb=(_rates_city(3,1)* zi.1.h1V0+ _rates_city(3,2)* zi.1.H1V1 + _rates_city(3,3)* zi.1.H1V2 +
        _rates_city(3,4)* zi.1.H2V0 + _rates_city(3,5)* zi.1.H2V1 + _rates_city(3,6)* zi.1.H2V2 +
        _rates_city(3,7)* zi.1.H3V0 + _rates_city(3,8)* zi.1.H3V1 + _rates_city(3,9)* zi.1.H3V2 +
        _rates_city(3,10)* zi.1.H4V0 + _rates_city(3,11)* zi.1.H4V1 + _rates_city(3,12)* zi.1.H4V2)*1.685

pnhb=(_rates_county(3,1)* zi.1.h1V0+ _rates_county(3,2)* zi.1.h1V1+ _rates_county(3,3)* zi.1.H1V2 +
        _rates_county(3,4)* zi.1.H2V0 + _rates_county(3,5)* zi.1.H2V1 + _rates_county(3,6)* zi.1.H2V2 +
        _rates_county(3,7)* zi.1.H3V0 + _rates_county(3,8)* zi.1.H3V1 + _rates_county(3,9)* zi.1.H3V2 +
        _rates_county(3,10)* zi.1.H4V0 + _rates_county(3,11)* zi.1.H4V1 +
        _rates_county(3,12)* zi.1.H4V2+ZI.3)*1.685
```

Scripts for Implementing More Trips by Persons Age 65+, 13-17, and 20-64 (Scenario 5)

Figure C5 shows the modification to the script for additional trips by persons age 65+ where for each zone the number of HBO and NHB trips is increased by the percentage of persons age 65+ (zi.3.percent) multiplied by 15.3%. Suppose, for example, a zone generated 100 HBO trips and had 50% of its population age 65+. Figure C5 would increase the number of HBO trips by a factor of (0.50*0.153 + 1) = 1.0765.

Scenarios 5b and 5c followed a similar approach. For example, as shown in Figure C6, Scenario 5c increased HBW trips by a factor of 3.67% multiplied by the percentage of persons age 18-64 (variable zi.3.Percent186). Further, Scenario 5c also increased nonwork trips (e.g., HBO and NHB) for all three age groups, where the percentage of persons age 65+, age 13-17, and age 18-64 are represented by the variables zi.3.Percent65, zi.3.PercentTee, and zi.3.Percent186, respectively.

Script for Implementing a Congested Travel Time Increase of 35% (Scenario 3c)

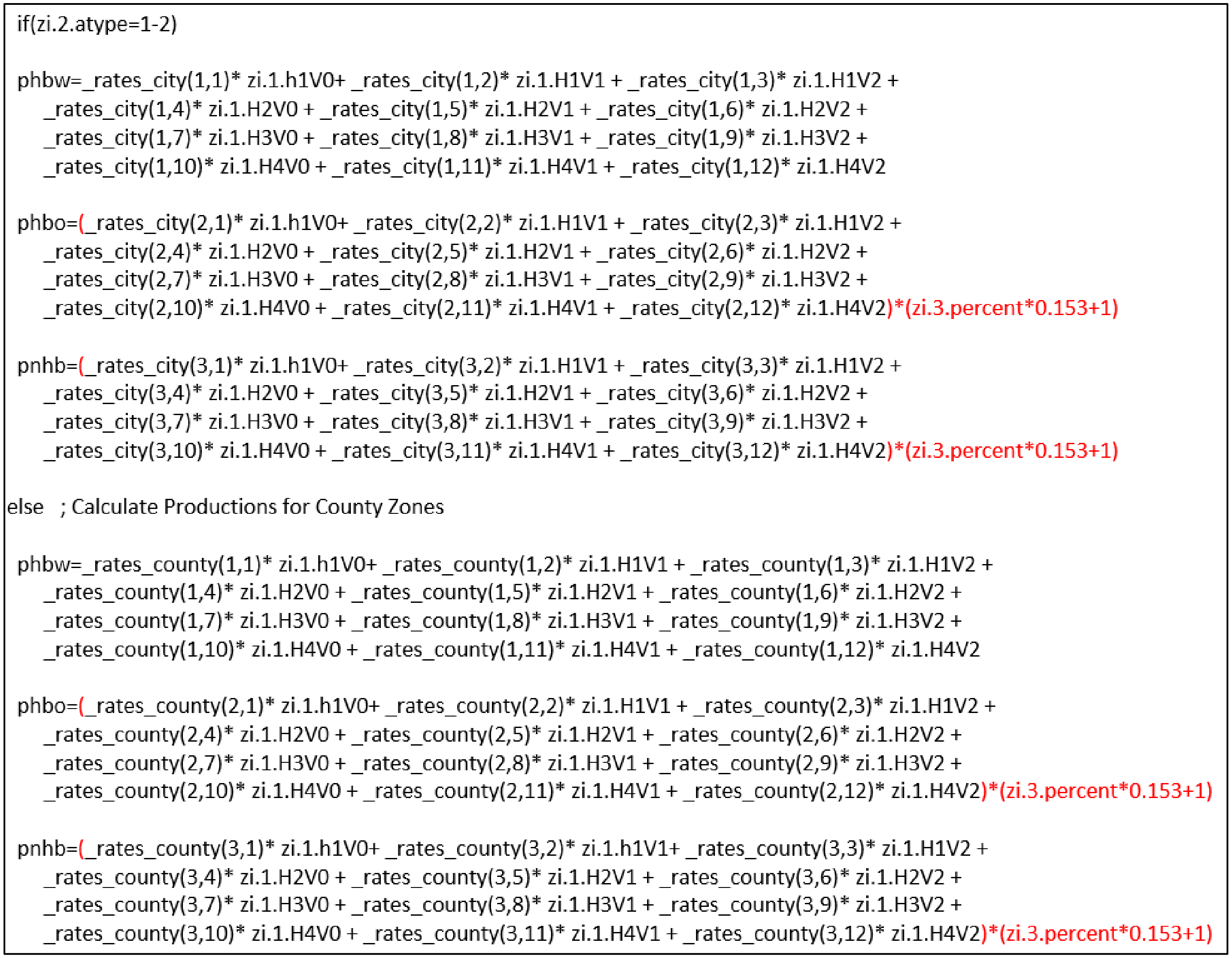
The multiplier 0.125 is used in these lines because with the impedances modified in this manner, the congested travel time rises from 22.08 to 29.81, an increase of 35%.

```
mw[21]=MI.2.FFTIME*(-0.08001*0.125)
mw[22]=MI.2.FFTIME*(-0.18959*0.125)
mw[23]=MI.2.FFTIME*(-0.22559*0.125)
mw[24]=MI.2.FFTIME*(-0.2083*0.125)
mw[25]=MI.2.FFTIME*(-0.2083*0.125)
mw[26]=MI.2.FFTIME*(-0.20004*0.125)
```

Script for Implementing the Combined Scenario (Scenario 6)

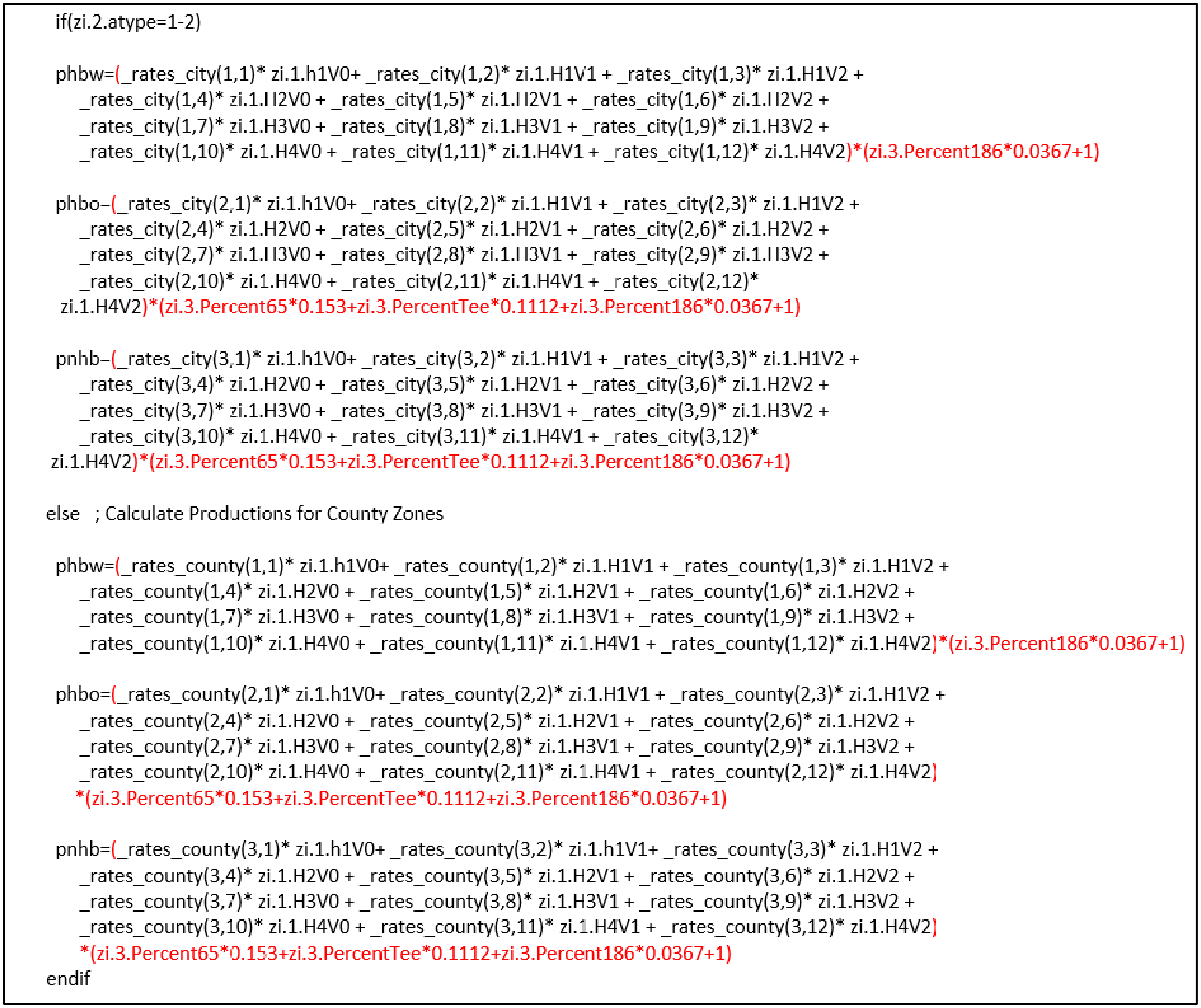
This portion of the script converts parking lots in the CBD to other land uses (with the ParkPLo variable) and increases trips for persons without access to a vehicle (hence the variables Percent186, PercentTee, and Percent65) in the "TGGEN00A.S" file. The red font indicates the changes needed to implement Scenario 6.

```
 if(zi.2.atype=1-2)

  phbw=((_rates_city(1,1)* zi.1.h1V0+ _rates_city(1,2)* zi.1.H1V1 + _rates_city(1,3)* zi.1.H1V2 +
      _rates_city(1,4)* zi.1.H2V0 + _rates_city(1,5)* zi.1.H2V1 + _rates_city(1,6)* zi.1.H2V2 +
      _rates_city(1,7)* zi.1.H3V0 + _rates_city(1,8)* zi.1.H3V1 + _rates_city(1,9)* zi.1.H3V2 +
      _rates_city(1,10)* zi.1.H4V0 + _rates_city(1,11)* zi.1.H4V1 + _rates_city(1,12)*
zi.1.H4V2+ZI.3.ParkPLo*0.05*0.248)*(zi.3.Percent186*0.0367*0.248+1))

  phbo=(_rates_city(2,1)* zi.1.h1V0+ _rates_city(2,2)* zi.1.H1V1 + _rates_city(2,3)* zi.1.H1V2 +
      _rates_city(2,4)* zi.1.H2V0 + _rates_city(2,5)* zi.1.H2V1 + _rates_city(2,6)* zi.1.H2V2 +
      _rates_city(2,7)* zi.1.H3V0 + _rates_city(2,8)* zi.1.H3V1 + _rates_city(2,9)* zi.1.H3V2 +
      _rates_city(2,10)* zi.1.H4V0 + _rates_city(2,11)* zi.1.H4V1 +
_rates_city(2,12)*zi.1.H4V2+ZI.3.ParkPLo*0.16*0.248)*(zi.3.Percent65*0.153*0.248+zi.3.PercentTee*0.1112*0.2
48+zi.3.Percent186*0.0367*0.248+1)

  pnhb=(_rates_city(3,1)* zi.1.h1V0+ _rates_city(3,2)* zi.1.H1V1 + _rates_city(3,3)* zi.1.H1V2 +
      _rates_city(3,4)* zi.1.H2V0 + _rates_city(3,5)* zi.1.H2V1 + _rates_city(3,6)* zi.1.H2V2 +
      _rates_city(3,7)* zi.1.H3V0 + _rates_city(3,8)* zi.1.H3V1 + _rates_city(3,9)* zi.1.H3V2 +
      _rates_city(3,10)* zi.1.H4V0 + _rates_city(3,11)* zi.1.H4V1 +
_rates_city(3,12)*zi.1.H4V2+ZI.3.ParkPLo*0.32*0.248)*(zi.3.Percent65*0.153*0.248+zi.3.PercentTee*0.1112*0.2
48+zi.3.Percent186*0.0367*0.248+1)

else   ; Calculate Productions for County Zones
  phbw=((_rates_county(1,1)* zi.1.h1V0+ _rates_county(1,2)* zi.1.H1V1 + _rates_county(1,3)* zi.1.H1V2 +
      _rates_county(1,4)* zi.1.H2V0 + _rates_county(1,5)* zi.1.H2V1 + _rates_county(1,6)* zi.1.H2V2 +
      _rates_county(1,7)* zi.1.H3V0 + _rates_county(1,8)* zi.1.H3V1 + _rates_county(1,9)* zi.1.H3V2 +
      _rates_county(1,10)* zi.1.H4V0 + _rates_county(1,11)* zi.1.H4V1 + _rates_county(1,12)*
zi.1.H4V2)*(zi.3.Percent186*0.0367*0.248+1))
```



```
 if(zi.2.atype=1-2)

 phbw=_rates_city(1,1)* zi.1.h1V0+ _rates_city(1,2)* zi.1.H1V1 + _rates_city(1,3)* zi.1.H1V2 +
     _rates_city(1,4)* zi.1.H2V0 + _rates_city(1,5)* zi.1.H2V1 + _rates_city(1,6)* zi.1.H2V2 +
     _rates_city(1,7)* zi.1.H3V0 + _rates_city(1,8)* zi.1.H3V1 + _rates_city(1,9)* zi.1.H3V2 +
     _rates_city(1,10)* zi.1.H4V0 + _rates_city(1,11)* zi.1.H4V1 + _rates_city(1,12)* zi.1.H4V2

 phbo=(_rates_city(2,1)* zi.1.h1V0+ _rates_city(2,2)* zi.1.H1V1 + _rates_city(2,3)* zi.1.H1V2 +
     _rates_city(2,4)* zi.1.H2V0 + _rates_city(2,5)* zi.1.H2V1 + _rates_city(2,6)* zi.1.H2V2 +
     _rates_city(2,7)* zi.1.H3V0 + _rates_city(2,8)* zi.1.H3V1 + _rates_city(2,9)* zi.1.H3V2 +
     _rates_city(2,10)* zi.1.H4V0 + _rates_city(2,11)* zi.1.H4V1 + _rates_city(2,12)* zi.1.H4V2)*(zi.3.percent*0.153+1)

 pnhb=(_rates_city(3,1)* zi.1.h1V0+ _rates_city(3,2)* zi.1.H1V1 + _rates_city(3,3)* zi.1.H1V2 +
     _rates_city(3,4)* zi.1.H2V0 + _rates_city(3,5)* zi.1.H2V1 + _rates_city(3,6)* zi.1.H2V2 +
     _rates_city(3,7)* zi.1.H3V0 + _rates_city(3,8)* zi.1.H3V1 + _rates_city(3,9)* zi.1.H3V2 +
     _rates_city(3,10)* zi.1.H4V0 + _rates_city(3,11)* zi.1.H4V1 + _rates_city(3,12)* zi.1.H4V2)*(zi.3.percent*0.153+1)

else   ; Calculate Productions for County Zones

 phbw=_rates_county(1,1)* zi.1.h1V0+ _rates_county(1,2)* zi.1.H1V1 + _rates_county(1,3)* zi.1.H1V2 +
     _rates_county(1,4)* zi.1.H2V0 + _rates_county(1,5)* zi.1.H2V1 + _rates_county(1,6)* zi.1.H2V2 +
     _rates_county(1,7)* zi.1.H3V0 + _rates_county(1,8)* zi.1.H3V1 + _rates_county(1,9)* zi.1.H3V2 +
     _rates_county(1,10)* zi.1.H4V0 + _rates_county(1,11)* zi.1.H4V1 + _rates_county(1,12)* zi.1.H4V2

 phbo=(_rates_county(2,1)* zi.1.h1V0+ _rates_county(2,2)* zi.1.H1V1 + _rates_county(2,3)* zi.1.H1V2 +
     _rates_county(2,4)* zi.1.H2V0 + _rates_county(2,5)* zi.1.H2V1 + _rates_county(2,6)* zi.1.H2V2 +
     _rates_county(2,7)* zi.1.H3V0 + _rates_county(2,8)* zi.1.H3V1 + _rates_county(2,9)* zi.1.H3V2 +
     _rates_county(2,10)* zi.1.H4V0 + _rates_county(2,11)* zi.1.H4V1 + _rates_county(2,12)* zi.1.H4V2)*(zi.3.percent*0.153+1)

 pnhb=(_rates_county(3,1)* zi.1.h1V0+ _rates_county(3,2)* zi.1.h1V1+ _rates_county(3,3)* zi.1.H1V2 +
     _rates_county(3,4)* zi.1.H2V0 + _rates_county(3,5)* zi.1.H2V1 + _rates_county(3,6)* zi.1.H2V2 +
     _rates_county(3,7)* zi.1.H3V0 + _rates_county(3,8)* zi.1.H3V1 + _rates_county(3,9)* zi.1.H3V2 +
     _rates_county(3,10)* zi.1.H4V0 + _rates_county(3,11)* zi.1.H4V1 + _rates_county(3,12)* zi.1.H4V2)*(zi.3.percent*0.153+1)
```

Figure C5. Modification to the Trip Generation Script for Scenario 5a, Where HBO and NHB Trips Are Increased by 15.3% to Account for Increased Trips by Travelers Age 65+. HBO = home-based other; NHB = nonhome-based. Drawn based on a screen capture of the script.



```
   if(zi.2.atype=1-2)

   phbw=(_rates_city(1,1)* zi.1.h1V0+ _rates_city(1,2)* zi.1.H1V1 + _rates_city(1,3)* zi.1.H1V2 +
     _rates_city(1,4)* zi.1.H2V0 + _rates_city(1,5)* zi.1.H2V1 + _rates_city(1,6)* zi.1.H2V2 +
     _rates_city(1,7)* zi.1.H3V0 + _rates_city(1,8)* zi.1.H3V1 + _rates_city(1,9)* zi.1.H3V2 +
     _rates_city(1,10)* zi.1.H4V0 + _rates_city(1,11)* zi.1.H4V1 + _rates_city(1,12)* zi.1.H4V2)*(zi.3.Percent186*0.0367+1)

   phbo=(_rates_city(2,1)* zi.1.h1V0+ _rates_city(2,2)* zi.1.H1V1 + _rates_city(2,3)* zi.1.H1V2 +
     _rates_city(2,4)* zi.1.H2V0 + _rates_city(2,5)* zi.1.H2V1 + _rates_city(2,6)* zi.1.H2V2 +
     _rates_city(2,7)* zi.1.H3V0 + _rates_city(2,8)* zi.1.H3V1 + _rates_city(2,9)* zi.1.H3V2 +
     _rates_city(2,10)* zi.1.H4V0 + _rates_city(2,11)* zi.1.H4V1 + _rates_city(2,12)*
   zi.1.H4V2)*(zi.3.Percent65*0.153+zi.3.PercentTee*0.1112+zi.3.Percent186*0.0367+1)

   pnhb=(_rates_city(3,1)* zi.1.h1V0+ _rates_city(3,2)* zi.1.H1V1 + _rates_city(3,3)* zi.1.H1V2 +
     _rates_city(3,4)* zi.1.H2V0 + _rates_city(3,5)* zi.1.H2V1 + _rates_city(3,6)* zi.1.H2V2 +
     _rates_city(3,7)* zi.1.H3V0 + _rates_city(3,8)* zi.1.H3V1 + _rates_city(3,9)* zi.1.H3V2 +
     _rates_city(3,10)* zi.1.H4V0 + _rates_city(3,11)* zi.1.H4V1 + _rates_city(3,12)*
  zi.1.H4V2)*(zi.3.Percent65*0.153+zi.3.PercentTee*0.1112+zi.3.Percent186*0.0367+1)

  else   ; Calculate Productions for County Zones

   phbw=(_rates_county(1,1)* zi.1.h1V0+ _rates_county(1,2)* zi.1.H1V1 + _rates_county(1,3)* zi.1.H1V2 +
     _rates_county(1,4)* zi.1.H2V0 + _rates_county(1,5)* zi.1.H2V1 + _rates_county(1,6)* zi.1.H2V2 +
     _rates_county(1,7)* zi.1.H3V0 + _rates_county(1,8)* zi.1.H3V1 + _rates_county(1,9)* zi.1.H3V2 +
     _rates_county(1,10)* zi.1.H4V0 + _rates_county(1,11)* zi.1.H4V1 + _rates_county(1,12)* zi.1.H4V2)*(zi.3.Percent186*0.0367+1)

   phbo=(_rates_county(2,1)* zi.1.h1V0+ _rates_county(2,2)* zi.1.H1V1 + _rates_county(2,3)* zi.1.H1V2 +
     _rates_county(2,4)* zi.1.H2V0 + _rates_county(2,5)* zi.1.H2V1 + _rates_county(2,6)* zi.1.H2V2 +
     _rates_county(2,7)* zi.1.H3V0 + _rates_county(2,8)* zi.1.H3V1 + _rates_county(2,9)* zi.1.H3V2 +
     _rates_county(2,10)* zi.1.H4V0 + _rates_county(2,11)* zi.1.H4V1 + _rates_county(2,12)* zi.1.H4V2)
     *(zi.3.Percent65*0.153+zi.3.PercentTee*0.1112+zi.3.Percent186*0.0367+1)

   pnhb=(_rates_county(3,1)* zi.1.h1V0+ _rates_county(3,2)* zi.1.h1V1+ _rates_county(3,3)* zi.1.H1V2 +
     _rates_county(3,4)* zi.1.H2V0 + _rates_county(3,5)* zi.1.H2V1 + _rates_county(3,6)* zi.1.H2V2 +
     _rates_county(3,7)* zi.1.H3V0 + _rates_county(3,8)* zi.1.H3V1 + _rates_county(3,9)* zi.1.H3V2 +
     _rates_county(3,10)* zi.1.H4V0 + _rates_county(3,11)* zi.1.H4V1 + _rates_county(3,12)* zi.1.H4V2)
     *(zi.3.Percent65*0.153+zi.3.PercentTee*0.1112+zi.3.Percent186*0.0367+1)
  endif
```

Figure C6. Modification to the Trip Generation Script for Scenario 5c. Drawn based on a screen capture of the script.

```
 phbo=(_rates_county(2,1)* zi.1.h1V0+ _rates_county(2,2)* zi.1.H1V1 + _rates_county(2,3)* zi.1.H1V2 +
     _rates_county(2,4)* zi.1.H2V0 + _rates_county(2,5)* zi.1.H2V1 + _rates_county(2,6)* zi.1.H2V2 +
     _rates_county(2,7)* zi.1.H3V0 + _rates_county(2,8)* zi.1.H3V1 + _rates_county(2,9)* zi.1.H3V2 +
     _rates_county(2,10)* zi.1.H4V0 + _rates_county(2,11)* zi.1.H4V1 + _rates_county(2,12)*
zi.1.H4V2)*(zi.3.Percent65*0.153*0.248+zi.3.PercentTee*0.1112*0.248+zi.3.Percent186*0.0367*0.248+1)


 pnhb=(_rates_county(3,1)* zi.1.h1V0+ _rates_county(3,2)* zi.1.h1V1+ _rates_county(3,3)* zi.1.H1V2 +
     _rates_county(3,4)* zi.1.H2V0 + _rates_county(3,5)* zi.1.H2V1 + _rates_county(3,6)* zi.1.H2V2 +
     _rates_county(3,7)* zi.1.H3V0 + _rates_county(3,8)* zi.1.H3V1 + _rates_county(3,9)* zi.1.H3V2 +
     _rates_county(3,10)* zi.1.H4V0 + _rates_county(3,11)* zi.1.H4V1 + _rates_county(3,12)*
zi.1.H4V2)*(zi.3.Percent65*0.153*0.248+zi.3.PercentTee*0.1112*0.248+zi.3.Percent186*0.0367*0.248+1)


;-------------------------------------------------------------------
;
 if(i=55,58-62,68,80-92,163,165-169,251-256,258-260)              ;  Attractions for UVA
   ahbw=ATTRRATES(3,1)*zi.1.temp+ZI.3.ParkPLo*0.08

   ahbo=ATTRRATES(1,5)*zi.1.ret + ATTRRATES(2,5)*nonretail +
ATTRRATES(4,5)*zi.1.hhx+ZI.3.ParkPLo*0.13*0.248
   anhb=ATTRRATES(1,9)*zi.1.ret + ATTRRATES(2,9)*nonretail +
ATTRRATES(4,9)*zi.1.hhx+ZI.3.ParkPLo*0.32*0.248

   flag=1
  ;print list=' UVA ',i(6),j(6),ahbw(8.2),zi.1.temp(6),ahbo(9.2),zi.1.ret(6),nonretail(6),zi.1.hhx(6)


 ELSEif(zi.2.atype=1 & flag=0)                              ;  Attractions for CBD
   ahbw=ATTRRATES(3,2)*zi.1.temp+ZI.3.ParkPLo*0.08*0.248
   ahbo=ATTRRATES(1,6)*zi.1.ret + ATTRRATES(2,6)*nonretail +
ATTRRATES(4,6)*zi.1.hhx+ZI.3.ParkPLo*0.13*0.248
   anhb=ATTRRATES(1,10)*zi.1.ret + ATTRRATES(2,10)*nonretail +
ATTRRATES(4,10)*zi.1.hhx+ZI.3.ParkPLo*0.32*0.248


 elseif(zi.2.atype=2-5 & flag=0)                     ;  Attractions for Urban
   ahbw=ATTRRATES(3,3)*zi.1.temp+ZI.3.ParkPLo*0.08*0.248
   ahbo=ATTRRATES(1,7)*zi.1.ret + ATTRRATES(2,7)*nonretail + ATTRRATES(4,7)*zi.1.hhx +
ATTRRATES(5,7)*zi.1.school+ZI.3.ParkPLo*0.13*0.248
   anhb=ATTRRATES(1,11)*zi.1.ret + ATTRRATES(2,11)*nonretail + ATTRRATES(4,11)*zi.1.hhx +
ATTRRATES(5,11)*zi.1.school+ZI.3.ParkPLo*0.32*0.248


;----------------------------
; Calculate External Trips
;----------------------------
pix=0.331*zi.3.HH + 0.724*(zi.3.TOTEMP + zi.3.EMPLOYEE_P)+ZI.3.ParkPLo*0.40*0.248              ;
Production for external trips (internal zone --> external zone)
aix=zi.4.COUNT * zi.4.IXPCT+ZI.3.ParkPLo*0.0000*0.248                              ; Attraction for external
trips (external zone --> internal zone)


; Balance attractions to productions
 p[1]=phbw*1.0
 p[2]=phbo*1.0
```

```
p[3]=pnhb
p[4]=pix
a[1]=ahbw
a[2]=ahbo
a[3]=anhb
a[4]=aix*(1+0.02112*0.248)
```

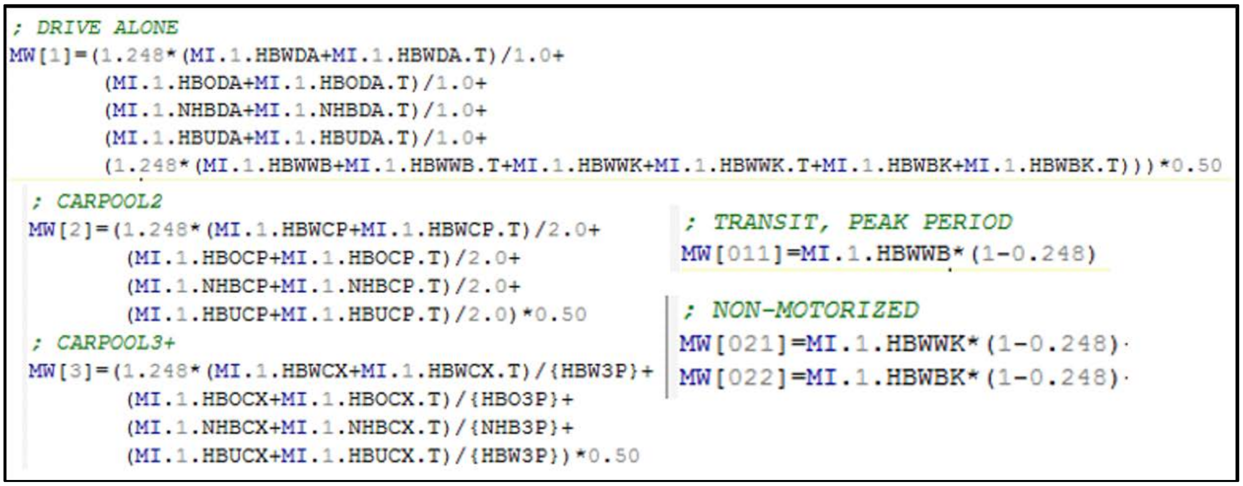
These changes occur in “TGMAT00F.S”:

```
HBUP = 2.996*ZI.2.OffC_Stu*{HBO-TF}+ZI.2.ParkPLo*0.07*0.248    ; home-based university PRODS from off-
campus (students); old production rate = 2.996
HBUA = 1.375*ZI.2.Total_park*{HBO-TF}+ ZI.2.ParkPLo*0.07*0.248    ; home-based university ATTRSS from
off-campus(parking spaces); old attraction rate = 1.375
```

This portion of the script reduces the impedance for the singly constrained gravity model. For the doubly constrained gravity model, no changes are necessary in the script, although new friction factors are used.

```
mw[30]=MI.2.FFTIME
mw[21]=MI.2.FFTIME*(-0.08001*0.7)
mw[22]=MI.2.FFTIME*(-0.18959*0.7)
mw[23]=MI.2.FFTIME*(-0.22559*0.7)
mw[24]=MI.2.FFTIME*(-0.2083*0.7)
mw[25]=MI.2.FFTIME*(-0.2083*0.7)
mw[26]=MI.2.FFTIME*(-0.20004*0.7)
```

This portion of the script is performed only for the case of not sharing (e.g., Scenario 6b). Similar to Scenario 2c, the file “MCMAT00C.S,” which follows mode choice, is altered. The difference between Scenario 6b and Scenario 2c, however, for this particular file is that rather than all HBW vehicle trips being doubled, such trips are increased by 24.8%—and rather than all transit, bike, and walk trips being eliminated, they are reduced by 24.8%. These changes are shown in Figure C7.



```
; DRIVE ALONE
MW[1]=(1.248*(MI.1.HBWDA+MI.1.HBWDA.T)/1.0+
        (MI.1.HBODA+MI.1.HBODA.T)/1.0+
        (MI.1.NHBDA+MI.1.NHBDA.T)/1.0+
        (MI.1.HBUDA+MI.1.HBUDA.T)/1.0+
        (1.248*(MI.1.HBWWB+MI.1.HBWWB.T+MI.1.HBWWK+MI.1.HBWWK.T+MI.1.HBWBK+MI.1.HBWBK.T)))*0.50
```

```
; CARPOOL2
MW[2]=(1.248*(MI.1.HBWCP+MI.1.HBWCP.T)/2.0+
        (MI.1.HBOCP+MI.1.HBOCP.T)/2.0+
        (MI.1.NHBCP+MI.1.NHBCP.T)/2.0+
        (MI.1.HBUCP+MI.1.HBUCP.T)/2.0)*0.50
; CARPOOL3+
MW[3]=(1.248*(MI.1.HBWCX+MI.1.HBWCX.T)/{HBW3P}+
        (MI.1.HBOCX+MI.1.HBOCX.T)/{HBO3P}+
        (MI.1.NHBCX+MI.1.NHBCX.T)/{NHB3P}+
        (MI.1.HBUCX+MI.1.HBUCX.T)/{HBW3P})*0.50
```

```
; TRANSIT, PEAK PERIOD
MW[011]=MI.1.HBWWB*(1-0.248)

; NON-MOTORIZED
MW[021]=MI.1.HBWWK*(1-0.248)
MW[022]=MI.1.HBWBK*(1-0.248)
```

Figure C7. Implementation of Scenario 6b. The different colors shown in the figure were not created by the researchers. Rather, when using the editor, these colors appear automatically, such as the green color, which indicates a comment. In Scenario 2c, the number 1.248, which appears in lines 2, 6, 8, and 13 in the left side of the figure had a value of 2, and the expression (1-0.248), which appears 3 times in the right side of the figure, had a value of 0.

This portion of the script is performed only for the case of sharing. The NHB multiplier is adjusted for the case of a low degree of matching of shared vehicles (for the doubly constrained gravity model) which is Scenario 6c as follows in two places in TGGEN00A.S:

```
 if(zi.2.atype=1-2)

 pnhb=((_rates_city(3,1)* zi.1.h1V0+ _rates_city(3,2)* zi.1.H1V1 + _rates_city(3,3)* zi.1.H1V2 +
     _rates_city(3,4)* zi.1.H2V0 + _rates_city(3,5)* zi.1.H2V1 + _rates_city(3,6)* zi.1.H2V2 +
     _rates_city(3,7)* zi.1.H3V0 + _rates_city(3,8)* zi.1.H3V1 + _rates_city(3,9)* zi.1.H3V2 +
     _rates_city(3,10)* zi.1.H4V0 + _rates_city(3,11)* zi.1.H4V1 +
_rates_city(3,12)*zi.1.H4V2+ZI.3.ParkPLo*0.32*0.248)*(zi.3.Percent65*0.153*0.248+zi.3.PercentTee*0.1112*0.2
48+zi.3.Percent186*0.0367*0.248+1))*1.1
```

```
pnhb=((_rates_county(3,1)* zi.1.h1V0+ _rates_county(3,2)* zi.1.h1V1+ _rates_county(3,3)* zi.1.H1V2 +
     _rates_county(3,4)* zi.1.H2V0 + _rates_county(3,5)* zi.1.H2V1 + _rates_county(3,6)* zi.1.H2V2 +
     _rates_county(3,7)* zi.1.H3V0 + _rates_county(3,8)* zi.1.H3V1 + _rates_county(3,9)* zi.1.H3V2 +
     _rates_county(3,10)* zi.1.H4V0 + _rates_county(3,11)* zi.1.H4V1 + _rates_county(3,12)*
zi.1.H4V2)*(zi.3.Percent65*0.153*0.248+zi.3.PercentTee*0.1112*0.248+zi.3.Percent186*0.0367*0.248+1))*1.1
```

Implementation of Scenarios 4d and 4e

The last two rows of Table 27 show two scenarios that were similar to Scenario 4a but with two simple modifications. For Scenario 4d, the process was applied to all vehicle trips, regardless of purpose, except for XX trips and IX trips; for this reason, the file “CVFINALVEHTRIPS2040.DAT” was used with modes of drive alone, carpool 2, and carpool 3+, where the matrices were exported and summed, similar to what was done for Scenario 4a. Scenario 4e considered the fact that ZOVs might tend to be used to different degrees by persons who drive alone versus carpool and thus examined what might occur if only persons who currently carpool use a DV; thus, only carpool 2 and carpool 3+ matrices were used.

APPENDIX D

EXAMPLE OF VALIDATION

Because they were using a model developed by others (Corradino Group, 2009), the researchers sought to ensure that they had not inadvertently misunderstood the model results or added errors when developing scenarios. Examples of steps necessary to understand the model and confirm results are provided in this appendix.

Example of Understanding the Overall Model

For the base scenario, it was possible to confirm that person trips and vehicle trips from the model matched expected values. In sum, Table D1 suggested that there should be approximately 772,132 vehicle trips after all seven purposes (HBW, HBO, NHB, HBU, HDORMU, IX/XI, and XX). The total volumes on all centroid connectors—including internal zones and external stations—summed to 1,529,438 vehicle trip ends. As shown in Figure D1, in recognition that a single trip (e.g., from Zone 1 to Zone 50) takes two trip ends, the traffic assignment as shown in the file "LoadedNet2040A_BaseValues.net" reflects 1,529,438/2 = 764,719 vehicle trips. Further, the values were reasonable for individual zones: for example, for Zone 1, there were 3,539 productions and 4,557 attractions after balancing, as shown in the files "TGEN_PA.DBF" and (for productions) "InitialTdist.MAT." Conversion of these to an origin-destination table would be expected to yield an average of roughly 4,048 person trip origins and destinations. If 77% of such person trips became vehicle trips, 3,177 vehicle trip origins and destinations would be expected. A similar number is shown for Zone 1 in the file "CVFINALVEHTRIPS2040.DAT" (3,280.9 vehicle trip origins and destinations), and in "LoadedNet2040A_.net," the number of vehicle trip ends is comparable (i.e., within 0.2%): the single connector shows 3,285.82 vehicle trip ends entering Zone 1 and the same number of vehicle trip ends leaving Zone 1.

The researchers used Table D1 to confirm that the results they were obtaining for the base case were as expected without gross errors. For example, the Corradino Group (2009) reported that for the base model, after productions for the five internal trip purposes (HBW, HBO, NHB, students living off campus, and students living in dorms were summed and then divided by the total number of households, a trip generation rate of 9.31 trips per household was obtained. Performing the same type of exercise with the 2040 base case data showed 772,557 person trips (e.g., the sum of the first five rows of Table D1) divided by the 82,105.68 households yielded 9.41 trips per household. It was also possible to replicate the calculations for the conversion of person trips to vehicle trips; for example, the 772,132 vehicle trips shown in Table D1) can be subdivided into vehicle trips for the different trip purposes. Table D1 thus explains a bit of the sensitivity of the model; for example, alteration of behaviors or conditions that affect only commuting are affecting only 14.9% of all person trips after those trips that pass through the area are considered.

Table D1. Summary of Trips for the Base Case (Doubly Constrained Gravity Model)[a]

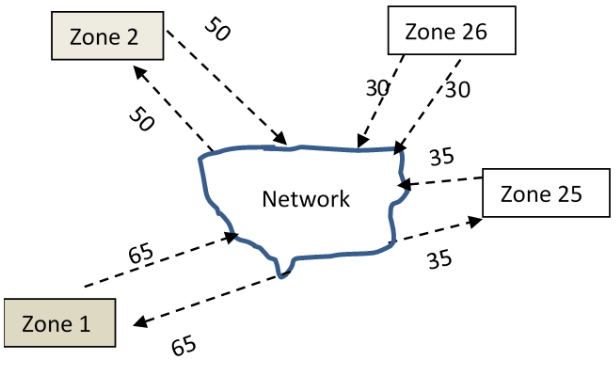
Quantity	Purpose	Drive Alone	Carpool 2	Carpool 3+	Walk to Bus	Drive to Bus	Walk	Bike	File or Derivation
Person trips	HBW	87,460	38,115	18,694	600	4.3	4,283	4,739	Modeout.mat
	HBO	102,129	143,136	52,802	837	0.3	16,692	2,660	Modeout.mat
	NHB	145,788	42,855	9,198	35	0.0	706	1,174	Modeout.mat
	HBUHBU	35,285	3,970	2,762	12,343	7.3	13,633	1,646	Modeout.mat
	HDORMU				4,878		15,504	10,624	Modeout.mat
	Internal person	772,557							InitialTdist.mat, TGEN_PA.DBF
	XX	20,244							ProcEXT_2040A.MAT
	IX	241,609							IX_OD.MAT[b]
	Total person	1,034,410							Internal person + XX + IX
Vehicle trips	HBW	87,460	19,058	5,842		4.3			Divide person trips by 2 (for CP2). Divide person trips by 3.2 (for CP3) except HBO (use 3.3)
	HBO	102,129	71,568	16,000		0.3			
	NHB	145,788	21,427	2,874		0.0			
	HBU	35,285	1,985	863		7.3			
	HDORMU								No vehicle trips
	Internal vehicle	370,662	114,038	25,580					Vehicles.mat
	XX	20,244							ProcEXT_2040A.MAT
	IX	241,609							IX_OD.MAT[b]
	External vehicle	261,853							Vehicles.mat, ODVehTrips 2040.MAT
	All vehicle	772,132							CVFINALVEHTRIPS2040.DAT
Trips of interest	Peak transit				600	4.3			TRANSIT.MAT
	Off peak transit				18,091	7.6			TRANSIT.MAT
	Transit				18,704				TRANSIT.MAT
	Nonmotorized						50,817	20,843	NONMOTOR.MAT
	Person	632,515	228,076	83,456	18,692	12	50,817	20,843	Sum person trips by mode[c]

HBW = home-based work; HBO = home-based other; NHB = nonhome-based; HBU = home-based university; HDORMU = Home-based university dormitory; XX = external-external; IX = internal-external.

[a] Base case doubly constrained gravity model with values of 6,829,605.34 (VMT), 167,101.65 (VHT), and 20.89 (MTT).

[b] The file “EITdist.MAT” reflects IX trips, comes from trip generation, and feeds IX_OD.MAT (with 241,585.46 trips).

[c] The file “InitialTdist.MAT” reflects (772,732) internal person trips and is within 0.02% of the sum of HBW, HBO, NHB, HBU, and HDORMU person trips (772,557) shown in this table. The file “TGEN_PA.DBF” (772,724 person trips) is within roughly 0.02% of this figure of 772,557.



Zone	1 (CBD)	2 (CBD)	25	26	Total
1	0	50	10	5	65
2	50	0	0	0	50
25	10	0	0	25	35
26	5	0	25	0	30
Total	65	50	35	30	180

Sum of centroid volumes:	360
Sum of trips:	180
Sum of CBD centroid volumes:	230
Sum of CBD trips:	130

Figure D1. Origin-Destination Table and Centroid Volumes for a Simple 4-Zone System. CBD = central business district.

For Scenario 2d, with regard to the additional 12,752 person trips that were anticipated from the conversion of parking lots that resulted from execution of the model for Scenario 2d, the researchers were initially surprised that these trips did not increase VMT, VHT, and MTT in the regional model by a substantial amount and thus sought to confirm that these trips had been incorporated into the script correctly. For the CBD zones, it was generally the case that 77% of person trips became vehicle trips (with the other person trips using carpool, transit, and nonmotorized modes). Accordingly, the 12,752 person trips (e.g., 12,752 productions and 12,752 attractions for a total of 25,504 person trip ends) produced by the CBD should have yielded roughly 77% of 25,504, or 19,638, vehicle trip ends. For the base scenario, the vehicle trip table CVFINALVEHTRIPS2040DAT showed that roughly 7.1% of vehicle trips remained with the CBD. Because, contrary to Figure D1, only a small percentage of CBD trips remained within the CBD, one would expect the total additional volume on the CBD connectors to be slightly lower than 100% of 19,638, e.g., perhaps (100% - 7.1%)(19,638) = 18,263 vehicle trip ends. Accordingly, the CBD centroid connectors in the model were identified (e.g., for Zones 1-11, 33-35, 66, and 261), and for those connectors, the difference in volumes between the base scenario and Scenario 2d was summed. For these connectors that difference was 22,631 vehicle trip ends based on the file "link.dbf." This suggested that the number of vehicle trip ends was reasonable.