TRAVEL BEHAVIOR, EMISSIONS, & LAND USE CORRELATION ANALYSIS IN THE CENTRAL PUGET SOUND

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16. ABSTRACT

A growing body of research documents that land use relates with travel mode choice, distances and time spent traveling, and household level vehicle emissions. However, to date little work has been done at a sufficiently disaggregate scale to gain an understanding of how local governments should alter their land use policies and plans to reduce vehicle use and encourage transit and non-motorized forms of travel. This study of the four county Central Puget Sound region links parcel level land use data with travel data collected from the Puget Sound Household Travel Survey (PSHTS).

The primary aim of the study is to describe how measures of land use mix, density, and street connectivity where people live and work influences their trip making patterns including trip chaining and mode choice for home based work trips, home based non-work trips, and mid day trips from work. Land use measures are developed within one kilometer of the household and employment trip ends in the survey. Tour based models are developed to estimate the relative utility of travel across available modes when controlling for level of service, regional accessibility to employment, and socio-demographic factors.

A secondary aim of the project is to estimate the linkages between land use and household generation of Oxides of Nitrogen and Volatile Organic Compounds that are precursors to the formation of harmful ozone. Emissions are estimated based on modeled speeds for AM, PM, and off peak travel at the trip link level and then aggregated to the household level. Household emissions are then correlated with land use patterns where people live when controlling for socio-demographic factors. An exploratory analysis was also conducted as part of this work to estimate how land use patterns where people work influences their modal choice and engagement in TDM programs offered by employers. The project relied on the Commute Trip Reduction Database from WSDOT. However, it was found that additional development of these data is necessary before this type of analysis can be done.

Results are presented that document how much of an increase in the utilization of specific modes of travel for work and non-work travel would likely accrue from specific types of land use changes, and from changes to travel cost and travel time.

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GLOSSARY OF ACRONYMS

CTR	Commute Trip Reduction
FHWA	Federal Highways Administration
GIS	geographic information system software
HBO	home-based other (origin=home, destination=non-work)
HBW	home-based work (origin=home, destination=work)
HC	hydrocarbons, also known as VOC (ground level ozone precursor)
LOS	level of service
LUTAQH	King County Land Use Transportation, Air Quality, and Health Study
MNL	multinomial logit
NAAQS	National Ambient Air Quality Standards
NOx	oxides of nitrogen (ground level ozone precursor)
NRD	net residential density (number of housing units per residential acre)
PEF	Pedestrian Environment Factors
PSCAA	Puget Sound Clean Air Agency
PSHTS	Puget Sound Household Travel Survey
PSRC	Puget Sound Regional Council
PSTP	Puget Sound Transportation Panel
SIP	State Implementation Plan (for NAAQS emission achievement)
TAZ	traffic analysis zone
TCSP	Transportation, Community and System Preservation (FHWA grant program)
TDM	travel demand management
VHT	vehicle hours traveled
VMT	vehicle miles traveled
VOC	volatile organic compounds, also know as HC (ground level ozone precursor)
WOW	work other work (origin=work, destination=non-home)

EXECUTIVE SUMMARY

Findings from this study inform how land use and transportation investment policies, plans, and actions can impact travel patterns and household level vehicle emissions in the Central Puget Sound Region. The results add unique information to the growing base of research that documents how travel and activity patterns are related with the design of the built environment.

The study correlates travel and vehicle emissions with the land use patterns where the (approximately) 12,000 participants in the 1999 Puget Sound Household Travel Survey[1] live and work. Detailed land use measures were developed in a geographic information system (GIS) for the area within a one kilometer "road network" distance (as opposed to a crow-fly, or straight line distance) from residential and employment locations, including:

- Measures of land use mix, or proximity between different types of destinations (e.g. live, work, shop, food, entertainment)
- Levels of street connectivity, or degree to which participants live and work in grid or cul-de-sac environments and can travel between destinations in a direct path
- Levels of residential density, or compactness of land use

The study performed a statistical correlation analysis of the effect of these land use variables on the relative utility (real or perceived benefit) of different travel modes - walking, biking, using transit, carpooling, and driving alone. The research approach to the analysis was unique in a number of ways:

- **The use of parcel-level land use data** allowed a more detailed look at how land use impacts travel behavior and emissions. Most studies that have been done in the region previously used census block or tract data, spatial units that are really too large to capture the variations in land use patterns that occur at a much smaller scale (about a 1 km radius or less around origins and destinations).
- **The use of a tour-based modeling approach**, where individual trips are linked together into trip chains, or "tours." Activity and tour-based

[1] Conducted by the Puget Sound Regional Council (PSRC)

modeling is predicated on the concept that people's mode choice is conditioned on all of the activities that take place within a tour. Thus the knowledge that the traveler has to stop, for example, to pick up a child on the way to and from work will affect the decision on mode for the initial trip to work. Statistical models were developed for three types of tours: home-based work tours, home-based non-work tours, and mid day 'subtours' from the place of employment. This approach more accurately simulates how decisions about travel are actually made, and how different land use measures, as the independent variables, impact simple (one destination) or complex (multi-destination) travel patterns for work and non-work related travel.

- **The use of link-based emissions analysis –** this detailed approach to modeling calculated speed sensitive emissions rates (HC, NOx) for every link of every trip taken in the PSRC Household Survey based on time of day and facility type.

The research also controlled for household and mode specific cost and levels of service characteristics. This framework adds a high degree of specificity to the previous body of research on land use – transportation interaction, both regionally and nationally. As in previous studies, the research controls for socio-demographic characteristics.

SUMMARY OF FINDINGS

The findings suggest that area residents make travel choice decisions based on several factors, the most important being time. A number of land use variables were also found to be statistically significant for all trip types modeled. Most interestingly, the choice to chain trips together into tours was highly correlated to the land use characteristics near where residents live and work. This study adds to our understanding of how the design of communities where we live influences our travel choices, and highlights the importance of land use patterns where we work. Findings show that work environments influence not only mid-day travel choices, but also a traveler's basic decision to use a specific mode when traveling to and from work. Participants that work in places with nearby shops and services were consequently found to not only walk more for their mid-day trips from work, but were also are less likely to drive to work. A summary of major findings follow:

1) **Time Matters Most** – The value an individual places on time was found to be highly significant in understanding how he or she makes trade-offs between various travel modes. For a mode to be viable, in terms of time, it is important that it compete favorably with the time required to accomplish a specific trip objective using a personal automobile. Thus, while walking for travel purposes often requires a substantial time commitment on the part of the traveler, increased proximity between uses resulting from mixed use, density, and street connectivity can overcome the fact that walking and biking are slow. This is more reasonable for shorter home based non-work tours and mid day tours from work. Time was an extremely important predictor of transit use as well. The analysis showed transit riders to be more sensitive to changes in travel time than to cost of transit fares, with wait time much more "costly" than in-vehicle time. Travel between many destinations in the region takes 2-3 times as long on transit than driving. The results suggest that a considerable growth in transit ridership could be achieved through more competitive travel times on transit. This is not a new concept, and suggests the importance of continuing to pursue the development of dedicated rights-of-way for regional transit travel. However, mode choice is largely "driven" by relative travel time *across all modes*. Primarily, reductions in vehicle travel time (which would occur in cases of increased capacity) were found to be associated with less transit use, walking, and biking, as shorter vehicle times increase the relative attractiveness of auto travel.
2) **Trip Chaining** - Land use patterns (in particular, the presence of shops and services and the presence of an interconnected street network) were found to be highly correlated with trip chaining patterns (the complexity, distance, and number of trips linked together into a 'tour'). Land use was found to be a stronger predictor of trip chaining patterns than demographic factors. Typically,

demographics correlate more strongly than land use to travel behavior, but it is likely that the detailed research approach, based on parcel-level land use data and a tour-based modeling framework, allowed new relationships to emerge.

3) **Work Environments and Travel Choice** -- Working in a walkable environment was associated with reduced auto use for the trip to and from work and increased walking for mid-day trips. Although not modeled in this analysis, these results suggest that transit and pedestrian-supportive land use patterns where we live and work enhance the viability transportation demand management strategies, such as encouraging modal shifts to transit transit, carpooling, or vanpool programs.
4) **The Supportive Role of Density** -- In this analysis, residential density did not correlate significantly with travel choice once travel time, travel cost, and other land use measures such as land use mix, street connectivity, and retail floor area ratio were entered into the models. Nevertheless, density plays an important indirect role in establishing walkable, transit supportive environments. Higher residential densities are needed to create the market for the shops and services that make places more walkable -- and are also necessary to make transit a viable modal option.
5) **The Importance of Retail Site Design** – The design of retail centers plays a critical role in shaping travel choice. Results show that people that live and / or work in places with less land devoted to surface parking, and where store entrances are closer to the curb are more likely to walk and take transit.
6) **Land Use, Air Quality and Physical Activity (2 birds / 1 stone)** - Increased levels of mixed use development, retail density, and street connectivity were associated with (1) lower per capita emissions and; (2) increased tendency to walk. This finding means that, through policy, planning and investment decisions that support walkable, compact, mixed-use environments, health benefits can be realized both through lower levels of emissions and higher levels of physical activity. Supporting evidence through the King County Land Use, Transportation, Air Quality, and Health study (LUTAQH)[2] shows that communities with

[2] See: http://www.metrokc.gov/kcdot/tp/ortp/lutaqh/execsummary092705.pdf

increased levels of active transportation (walk and biking) also have lower obesity rates.

DISCUSSION OF FINDINGS

Trip Chaining

This section provides a more detailed discussion of the findings related to trip chaining (trip tours). As noted above, land use was found to be more significantly correlated to trip chaining than socio-demographic and cost related factors; a result unique to land use and travel behavior research. Results further indicated that people living in areas with higher intersection density and a mix of office, residential, and retail land uses tend to make tours with fewer stops and with stops closer to home. These same people will also tend to make more home-based tours, resulting in more short, simple tours instead of fewer long, complex tours. This type of behavior can be related to mode choice – these short tours are easier to make by walk or bike modes. It is important to note that the findings do not imply that the number of destinations visited near home declines with connectivity or mix. Rather, the results suggest that the number and fraction of stops on a per tour basis declines due to simpler tour patterns.

It has been argued that this type of travel pattern (higher numbers of short, simple tours) may be associated with increased air pollution due to cold starts activity (Crane 2000). However, the results presented in this study suggest that the longer vehicle trips associated with lower levels of density, mix, and connectivity overwhelm the impact that higher trip generation rates may have on emissions – even when taking into account emissions from cold starts. This result is consistent with earlier research on land use, travel and vehicle emissions in the Central Puget Sound Region funded by the Washington State Department of Ecology.

Socio-economic factors were also found to be correlated with the choice to take simple or complex tours for non-work purposes. More vehicles per driver was associated with more complex non-work tour trip chains with more stops, and fewer stops near to home. Higher incomes and being over 50 were both associated with fewer stops close to home (these people also tend to be more likely to drive and less likely to walk). People in single-person households tended to make more stops close to home.

In the non-work tour model, driving alone and shared ride were found to increase with the ratio of available automobiles to drivers in a household, and if the tour includes a shopping stop (simple tours) or picking up/dropping off someone (multi-stop tour). As would be expected, households without automobiles (by default) had higher levels of transit use and walking. The analysis also indicated that generally, the more physical exertion a mode requires, the less likely older people were to use it. People over 50 years old were less likely to use transit as well. One interesting result is that biking and walking were more likely when the tour included a social or recreational purpose.

Modeling Travel Choice

The following section describes in detail the findings for each of the three tour models - home based non-work tours, home based work tours, and work based sub-tours (taken mid day from work). As part of this project, demand elasticities were calculated for each of the land use, time and cost variables found to be significant in the models. Demand elasticities provide a basis for understanding how changes in land use, time, and cost affects demand for specific modes of travel, and are included in the discussion below. Results presented may seem to be modest in terms of the amount of change in travel mode choice relative to a 10 percent change in a given land use policy. However, considerable variations in land use exist throughout the region, and what can be achieved in newly developing areas could have a proportionately greater impact. For example, if the residential area north of Redmond Town Center is compared to Upper Queen Anne Hill (as is done in more detail in Chapters 3 and 4), Queen Anne has an intersection density that is *50 percent* greater than Redmond's. A two percent increase in walking associated with a 10 percent increase in intersection density would translate into a 10 percent increase in walking associated with a 50 percent increase in intersection density -- all else being equal.

Table 1 summarizes an extensive set of variables that were developed for the study and indicates which factors were significant in explaining mode choice for simple and / or complex tours and specific aspects of each of the three tour types.

Table 1: Tour Models' Variables

Variable	Home Based Non-Work Tours	Home Based Work Tours	Mid-Day Work Based Sub Tours
Time and cost variable			
Auto and transit cost ($) & in-vehicle time (minutes)	X	X	X
Walk and transit- walk time (minutes)		X	
Walk and transit- out-of-vehicle time (minutes)	X		X
Bike- time (minutes)	X	X	
Transit wait time (minutes) & transfers		X	
Land use variables			
Transit- origin mixed use & intersection density	X	X	
Transit- destination mixed use	X		
Transit- destination intersection density	X	X	
Transit- destination retail floor area ratio	X	X	X
Bike- origin intersection density	X	X	
Walk- origin mixed use, intersection density & retail floor area ratio	X	X	X
Walk- destination retail floor area ratio		X	
Other variables			
Drive alone- household cars/driver	X	X	
Drive alone- used car to get to work			X
Drive alone- shopping stop(s)	X	X	
Drive alone- pick up/drop off stop(s)	X	X	X
Shared ride- used car to get to work			X
Shared ride- household cars/driver & single person household, 3+ person household	X	X	
Shared ride- shopping stop(s)	X		
Shared ride- pick up/drop off stop(s)	X	X	
Transit- no cars in household	X	X	
Transit- age over 50	X		
Transit- household income over $75,000	X	X	
Bike - age over 50	X		
Bike - social/recreation (stops)	X		
Bike - age 25 to 50 & male		X	
Walk- social/recreation stop(s)	X	X	X
Walk - age over 50	X		
Walk - age 25 to 50 & male		X	
Walk - walked to work			X

Note: An "X" indicates that the variable was significant, or nearly significant, in at least one or more of the sub-models (all, simple and complex tours). Variables where the t-statistic is less than 1.96 (corresponding to a 95% confidence interval) were included in the models based on judgment. If a variable was signed consistently with other like-variables and contributed to the model it was typically left in.

Home Based Non-Work Tours

For home based non-work tours, a modest increase of 10 percent in auto-fuel and parking costs was found to be associated with a small reduction in drive alone demand by 0.6 percent, and increases in carpooling by 0.4 percent, transit by 1.5 percent, bicycling by 1.4 percent and walking by 0.6 percent. Ten percent is a relatively small increase; current fluctuations in fuel prices suggest that costs can increase by 50 percent or even greater within a given year or two.

As mentioned, increases in auto travel time had a larger association with demand for non-auto modes than increases in fuel/parking costs. Increasing auto travel time by 10 percent was associated with a 2.3 percent increase in transit ridership, a 2.8 percent increase in bicycling, and a 0.7 percent increase in walking for non-work travel. Transit use was found to be nearly three times as sensitive to in-vehicle travel time as to fare cost increases for non-work travel. Increasing transit in-vehicle travel times for non-work travel by 10 percent was associated with a 2.3 percent decrease in transit demand, compared to a 0.8 percent reduction for a 10 percent fare increase.

Of the land use variables tested, transit demand for non-work travel increased by 3.4 percent in association with a 10 percent increase retail floor area ratio at the destination, and by 3.0 percent with a 10 percent increase in mix of uses at the destination. Increasing home and destination intersection density by 10 percent was associated with a 2.4 percent and 2.3 percent increase in transit demand for non-work travel respectively. A 10 percent increase in street network connectivity (with more intersections and shorter block faces) at the home and destination was associated with a 2.8 percent and 2.7 percent respective increase in the proportion of walk trips for non-work travel.

Home Based Work Tours

Of all the modes modeled in the analysis, driving alone and carpooling to work were, logically, the most sensitive to increases in auto-fuel and parking costs. Demand for driving alone to work decreased by 0.7 percent and carpooling demand increases by 0.8 percent in association with auto-fuel and parking costs increases of 10 percent. Increasing the fuel and parking costs by 10 percent for the solo commuter was associated with increasing transit demand by 3.71 percent, bike demand by 2.7 percent and walk demand by 0.9 percent for work related travel.

However, time was still found to be more important than cost for home-based work tours. Increasing drive alone commute time by 10 percent was associated with increases in demand for transit by 3.1 percent, bike demand by 2.8 percent and walk demand by 0.5 percent.

A number of land use variables were significantly related to mode choice for home-based work trips. Increasing destination retail floor area ratio by 10 percent was associated with a 4.3 percent increase in demand for transit. A 10 percent increase in home location intersection density was associated with a 4.3 percent increase in walking to work. A 10 percent increase in mix of uses at the home location was associated with a 2.2 percent increase in walking to work. A 10 percent increase in home location retail floor area ratio was associated with a 1.2 percent increase in walking to work. Increasing intersection density at the home location by 10 percent was associated with an 8.4 percent increase in the demand for biking to work.

Mid-Day Work Based Sub Tours

In the case of mid-day tours from work, increases to mixed use and intersection density was associated with increased demand for walking, but reduced demand for drive alone, carpool and transit (except in the case of destination-retail floor area ratio). Walking for mid-day work sub-tours was associated with an increase of 0.9 and 1.0 percent with a 10 percent increase in land use mix and intersection density at the work location. Land use varies considerably across work location. Employment centers range from the most to some of the least compact and most peripheral environments in the region. A 10 percent increase in the level of land use mix or intersection density (as tested) where we work could be relatively modest when comparing the types of work environments that actually exist in the Central Puget Sound Region. Levels of mixed use are the highest in areas where work and residential uses are co-located. According to the results presented, environments were we can live, work, and accomplish other activities will yield the lowest levels of auto use and vehicle emissions.

Travel Distance, Time, and Emissions

This section discusses findings relating travel demand (vehicle miles traveled (VMT) and vehicle hours traveled (VHT), air pollution (grams of oxides of nitrogen (NOx) and hydrocarbons (HC) with the aforementioned land use measures when controlling for socio-demographic factors. At the most general level, the study showed increases in the levels of residential density, street connectivity, land use mix, and retail floor area ratio to be associated with lower per capita vehicle miles and hours of travel, and lower per capita vehicle emissions (NOx and HC, which lead to the formation of ground level ozone). Interestingly, the land use measures remained significant predictors of vehicle emissions *after* controlling for distances traveled (VMT), indicating that residents of more auto dependent environments may actually pollute more *per unit of distance traveled*. This finding is especially surprising for NOx, which is more of a function of distance traveled as opposed to HC emissions which are more closely associated with cold starts.

Vehicle ownership and distance to transit were significant predictors of travel demand. Each additional vehicle a household has, the analysis estimated an 11.71 percent increase in VMT. Similarly, the analysis estimated a 5 percent increase in VMT for each additional mile a participant lives from the nearest bus stop. Each additional intersection per square kilometer was estimated to decrease VMT by 0.39 percent.

Changing the mix of land uses at a location from a single use, e.g. only residential, to one which has an even distribution of floor area across residential, entertainment, retail and office uses was estimated to decrease VMT by 19.7 percent. However, this difference in VMT represents the maximium possible difference in land use mix – in a comparison of more typical urban or suburban environments, differences in VMT are likely to be less.

Looking at hydrocarbons (HC) and Oxides of Nitrogren (NOx), each additional household vehicle was found to be associated with a 19.6 percent increase, and each additional person per household a 20.3 percent increase, in grams of hydrocarbons (HC) produced.[3] Each additional intersection was associated with a 0.4 percent reduction in HC. An increase from the least to the most mixed use environments was associated with a 22.5 percent reduction in hydrorcarbon emissions. Similar changes were found for NOx as well (see chapters 3 and 5).

As would be expected, a family living on Queen Anne hill was estimated to produce fewer grams of HC and NOx than a family with similar demographic characteristics living in the area just north of Redmond Town Center. The difference in net residential density translates into 3.5 percent less HC emissions for Queen Anne residents, and higher levels of intersection density (connectivity) are associated with a lower HC and NOx emissions (17.2 percent and 18.9 percent respectively).

These results are not meant to be taken in isolation - each variable represents only its own incremental impact on travel behavior and emissions. When taken collectively, the conditions which facilitate higher rates of walking, bicycling, and riding the bus – such as a higher mix of uses and greater connectivity -- are also correlated separately with emissions. While it is not reasonable to expect dramatic shifts in land use on average across the region, significant changes in land use can occur in specific locations.

Study Limitations

While the results of this research offer important insights into the role of the built environment in shaping travel patterns, there are important limitations to the study. The study's cross-sectional approach compares the travel patterns of different households located in different land use patterns, when controlling for other factors that impact travel choice. A cross-sectional study design cannot isolate the impact of land use from one's attitudinal predisposition for specific modes of travel or types of community environments. Therefore, it is hard to know how much the effect of the built environment is a function of the design of the community or rather the individual's preferences for particular travel options and/or physical settings. This is known as the

[3] Note that increasing household size may actually result in lower overall per capita vehicle emissions through increased carpooling.

self-selection argument, and can only be addressed with a longitudinal research design that tracks travel behavior of those households that move to a new location.

While not addressed here, emerging research is showing that both attitudinal predisposition and built form affect people's travel behavior (Krizek 2003; Handy et al Forthcoming; Frank et al 2005). That is, people that prefer to be in a walkable environment and actually live in such an environment walk more and drive less than others with similar preferences that live in more auto dependent places. It is not uncommon for individuals to trade off walkability for proximity to work, housing cost, real and perceived differences in school quality and crime, and other factors.

Recent research also documents a significant latent demand for more walkable environments (Levine et al 2004). The results presented here suggest a significant opportunity to achieve travel, health, and environmental benefits by providing more urbane environments in line with the preferences of people currently trading off walkability. This is of course a complicated endeavor and requires consideration of critical aspects associated with residential location choice – some of which are well beyond the scope of the current study. However, based on consumer surveys, it appears that regulatory and fiscal policy result in an undersupply of compact, walkable environments - the very type of environment that may enable more efficient transportation systems, cleaner air, decreased reliance on fossil fuels, and more active-friendly environments.

Secondly, additional research is needed to address the intra-regional variation in exposure to small particulates now found to be associated with cardio-pulminary dysfunction (Frank and Engelke 2005; Frumkin et al 2004). At risk is that more walkable environments may be the same places where exposure to particulates is greater. This does not mean that we should forego more walkable environments -- the cumulative benefits of such approaches to community design, when measured across transportation, environment, and health appear to be significant in the near term and even greater in the long term – especially in light of other more global, long-range issues, such as energy supply and consumption or climate change. Therefore, solutions are needed to address fuels used and engine technologies employed by commercial fleets that operate in more central locations and spatially separate the movement goods from core areas. Housing facilities for at-risk populations, such as the elderly and people with respiratory illnesses, should be located in places where particulates are less concentrated.

Concluding Remarks

The results from this study emphasize the importance of implementing the policies and approaches to transportation investment and land use planning documented within PSRC's Vision 2020 and Destination 2030 plans, and underpinned in the Multi-County and Countywide Planning Policies. Resulting changes in mode choice in association with changes in land use, travel time, and travel costs presented here are approximately additive – or subtractive. This is important when considering the potential implications of land use changes, as well as transportation investments that impact travel time and costs. Based on these findings, reducing travel time for cars would stimulate more driving and less transit and walking, undermining the achievement of adopted policies and goals that would otherwise occur from higher levels of density, mixed use, and street connectivity.

A number of jurisdictions within the Central Puget Sound region have policies in their plans that call for the types of land use actions shown in this research to be highly associated with maximizing transportation system efficiency – that is, decreasing demand for driving alone while increasing demand for walking, bicycling, transit and carpooling. Increased levels of walkability have been repeatedly correlated with higher levels of physical activity and reductions in per capita emissions. Several local government initiatives are currently underway, such as the King County Land Use Transportation, Air Quality, and Health Study (LUTAQH), which can be further informed and enhanced through the application of the results of this and other WSDOT funded research.

Although local actions are important for shaping land use – and travel behavior - transportation investments can also stimulate changes in land use markets and the demand for auto dependent or transit supportive walkable communities. The results of this study can be used by WSDOT to inform its own planning and programming processes, potentially leading to increased benefits from investments while helping to offset air pollution and climate change.

CHAPTER 1: INTRODUCTION AND REVIEW OF PREVIOUS WORK

INTRODUCTION

This project is part of a program designed by the Washington State Department of Transportation to increase the overall understanding of how land use patterns relate to travel choice in the Central Puget Sound Region. It builds upon a growing set of findings that document how the physical design of our communities relates to our travel and activity patterns. Over the years, research has demonstrated that our transportation choices can impact the quality of the air we breathe, levels of physical activity and likelihood of being overweight or obese, energy consumption, and the production of greenhouse gases. This study provides new information that can be applied within regional and local land use and transportation planning and investment decision-making processes.

There are two primary goals of the *Travel Behavior and Land Use Correlation Analysis in the Central Puget Sound Region*:

1. Provide a better understanding of land use and transportation interactions, by mode and location, at land use parcel and local street network levels within the four-county area of the Central Puget Sound Region.

2. Measure the relationships between land use and household vehicle emissions when controlling for household demographic factors.

In this analysis, a set of tour-based discrete choice models were used to predict the likelihood of choosing various modes of travel over others, for specific population cohorts under differing land use and transportation network conditions. The mode choice analyses presented in this report used separate modeling efforts to look at work and non-work travel.

Trips reported in the Puget Sound Household Travel Survey of 1999 collected by the Puget Sound Regional Council were linked into chains, referred to in this report as "tours", which constitute the "unit of analysis" for the primary modeling effort. A hypothetical tour is shown in Figure 1 below. This example tour consists of four separate trips—home to day care, day care to work, work back to day care and then finally back home.

Figure 1: Work Trip Tour with Stop at Day Care Facility

Activity and tour based modeling is predicated on the concept that people's mode choice is conditioned on all of the activities that take place within a tour. Thus the knowledge that the traveler has to stop, for example, to pick up a child on the way to and from work will affect the decision on mode for the initial trip to work. This concept has been applied for models in Portland, Oregon, San Francisco, New York and Columbus, Ohio. The following three types of tours are modeled in this study:

- home – work – home;
- mid day work based travel; and
- non-work travel – shopping and entertainment focused.

All of the analyses in this study accounted for exogenous (other) factors impacting mode choice, including level of service (LOS) for both auto and transit travel. The methods and results are sensitive to many of the real world factors impacting each mode choice decision reported by the household travel survey respondents.

The tour-based approach used to model relationships between land use and modal choice takes into account factors known to influence mode choice such as vehicle operating cost, regional accessibility to employment, and other time/cost sensitive factors. This approach enables the isolation of land use relative to these other factors, and facilitates a more systematic and realistic assessment of the relative contribution of different land use patterns in shaping travel choice decisions. Results presented in this report show that land use patterns where Puget Sound residents live and work relate significantly with their travel choices even after adjusting for sociodemographic, level of service of transit, and cost functions.

However, the research design was not able to control for self-selection. The premise of self-selection is that people live in certain places because of their preference for a certain environment or travel behavior, and it is difficult to disentangle the 'pure' impacts of the built environment from a person's attitudes or preferences. The only way to separate the two factors is with a longitudinal analysis, that is, one conducted over a long period of time with the same set of participants. In this analysis, the assessment of travel patterns comes from data collected at only one point in time -- the 1999 Puget Sound Household Travel Survey. This data source made a cross sectional research design necessary, which compares travel choices among those survey respondents living in different urban environments but with similar demographics and mode availability and levels of service. The cross sectional design cannot isolate the effect of lifestyle preferences on location choice and resulting travel patterns.

An important outcome of modal choice decisions is per capita generation of air pollution. Results from this study indicate specific types of land use strategies that will be most effective in reducing auto use, and improving air quality. While air quality has improved in recent years in the Central Puget Sound Region, there remain considerable concerns over the impacts of development and transportation decisions on vehicle emissions. This concern stems from the fact that, although it recently qualified as a "maintenance" area for air quality, the region in the past continued to approach the allowable National Ambient Air Quality Standards (NAAQS) – and in some occasions, there have been near violations. When projected into the future, these trends suggest that the region will continue to have air quality concerns. This concern was great enough for the Puget Sound Clean Air Agency (PSCAA) to conduct a multi-sectoral stakeholder based assessment in 2000 and 2001 of what can be done to improve air quality in the near and longer term.

As the region's designated authority for the US Environmental Protection Agency's required State Implementation Plan (SIP), PSCAA's process identified land use and transportation investment strategies as central to achieving healthy air.

This assessment has produced strategies that are policy relevant and have the ability to demonstrate how transportation investments and land use can *collectively* and *uniquely* impact modal choice for specific work and non-work related purposes. Therefore, the results are presented in ways that directly inform transportation planning and programming processes. For example, which land use strategies demonstrate the greatest odds of increasing transit and non-motorized travel and conversely lowering auto use for specific tours – for specific household size and income cohorts? While land use factors are clearly a focus of this assessment, so is the level of service and resulting accessibility afforded across modes through changes to the transportation system. Therefore, we also report on the efficacy of increases in performance across modes and their resulting influence on costs and travel choice.

The *Travel Behavior and Land Use Correlation Analysis in the Central Puget Sound Region* project combines portions of work from two research projects:

1. A State Research Office project titled *Applying Development Pattern Metrics to Improve the Understanding of Land Use/Transportation Interactions.*
2. A Federal Highways Administration (FHWA) Transportation, Community and System Preservation (TCSP) grant titled *Convening with Communities: Implementing Land Use and Other TDM Strategies in Two Intersecting Major Transportation Corridors*.

This project also builds upon an on-going King County project that was also led by Lawrence Frank and Company, Inc. titled *Land Use, Transportation, Air Quality and Health Study* (LUTAQH).

STRUCTURE OF THE REPORT

Chapter 1 provides an overview of the study, its purpose, approach, and how it is set within the current body of existing research relating land use and transportation investments with travel choice. A detailed set of the methods used and the databases developed for the study are provided in Chapter 2, which also includes descriptions of the original datasets upon which the study is based. Readers that are interested in doing similar types of work would be most interested in Chapter 2. Analyses of land use, travel, and vehicle emissions relationships are presented in Chapter 3. This chapter includes basic descriptive statistics, as well as a detailed presentation of the more complex regression models and results. The tour type and mode choice models, and the mode-specific elasticities derived from these models, are presented in Chapter 4 of the report. The first part of the chapter presents models that predict the likehood of complex or simple (no interim stop) tours for home based work and home based non-work tours. The second part of the chapter presents models that predict the choice of mode that would likely be taken for home based work, home based non-work, and mid day work tours. Chapter 5 presents a summary and results from the analyses conducted in Chapter 4, and Chapter 6 offers some suggestions as to how the results of this work can be applied in practice. A set of appendices are included that supplement and support the methods and analyses that are presented in the body of the report.

REVIEW OF PREVIOUS WORK

The relationship between land use and transportation mode choice has been studied for over half of a century (Mitchell and Rapkin 1954), yet surprisingly little agreement exists to date about *how* the built environment impacts travel behavior (Boarnet and Crane 2001). Though we may not fully understand why, we do know that there are substantial differences in travel behavior depending on where people live (Frank 2000). By the same reasoning, it is assumed by many that the design of the built environment where we work would also have an impact on our travel patterns.

Moreover, that there may be a synergistic relationship between the design of the physical environment in which we live and where we work. Frank and Pivo (1995) measured land use at both trip ends and concluded that this can improve the predictive and explanatory power in transportation mode choice models—a specification rarely used in the formulation of mode choice (Cervero 2002). The following section discusses how these interrelationships have been previously analyzed, and the strengths and weaknesses of the various approaches taken.

METHODS OF ANALYSIS

The current study uses highly detailed land use and travel data and is a multi-variate assessment of travel demand, resulting vehicle emissions, and mode choice. Crane (2000) classifies studies of the relationship between land use and travel behavior into three methods of analysis: descriptive studies, simulation studies, and multivariate statistical studies. Descriptive studies, though instructive because they use actual behavioral data, are limited because they only provide an accounting of travel behavior. Simulation studies, which have the benefit of not being bound to data limitations, are restricted to hypothetical impacts due to changes in policy and behavior. Multivariate statistical studies have the benefit of the descriptive studies using actual travel behavioral data, but aim to explain behavior based on theoretically derived determinants.

Multivariate statistical analyses of transportation mode choice (e.g. car, transit, walk, cycle) have become increasingly popular and better specified, probably due to the availability of high quality data. Socio-demographic data, included in almost all recent empirical studies, are typically measured at the individual or household level through census data or travel survey questionnaires (Ewing and Cervero 2001). Land use variables, most commonly measured at the traffic analysis zone or census tract level, have become more differentiated with respect to the specific attributes of the built environment and are therefore becoming increasingly able to inform policy on the effects of those particular land use characteristics on travel behavior (Ewing and Cervero 2001). Handy (1996b) has noted that many variables used to assess the effect of the built environment on travel behavior are too general, not allowing for actual characteristics of the built environment to be investigated. Regardless of scale of measurement, the built environment variables typically used to measure the effects of land use are population density, employment density, accessibility, connectivity, and land use mix.

DEMOGRAPHICS, LAND USE, AND MODAL CHOICE

Traditional neighborhoods, broadly defined as neighborhoods built pre-World War II, tend to have walking, cycling, and transit chosen as a transportation mode more often than more recently built suburbs (Sallis et al 2004; Saelens et al 2003; Handy 2002). It is often asserted that the choices we make in terms of which mode to take for a specific trip is the result of the relative utility of available modes of travel (Meyer, Kain, and Wohl 1965; McFadden 1978; Frank 2005). However, a myriad of factors corroborate to determine which modes in effect are *perceived* to have the greatest utility and are most likely to be chosen. Travel decisions depend on socio-demographic factors including income, age, and household structure (Crane 2000) the type of trip, the characteristics of each mode choice (Green 2000), as well as the built environment. In order to find the independent effect of the built environment on travel decisions, researchers must control for these other factors. Individual characteristics and socio-demographic variables,[4] directly affect transportation mode choice through preferences and resources. But more importantly, socio-demographic factors vary over space. Therefore, it is possible that land use effects on travel behavior may be due to the socio-demographics of land use rather than the land use itself. Stead (2001) states that the often-excluded dimension of socio-demographics may make the relationship between land use and travel behavior spurious: “land-use characteristics are associated with different socioeconomic factors, which also have an effect on travel patterns” (Stead 2001: 500).

However, studies that have controlled for socio-demographic factors have found significant relationships between land use and modal choice. Therefore, while the link between the built environment and modal choice is explained in part through the spatial variation in socio-demographic factors, it appears not to be spurious as much as somewhat “mitigated.” (Frank and Andresen 2004). Both Cervero and Kockelman (1997) and Kockelman (1997), using the same data set, found a significant relationship

[4] Socio-demographic represents both socio-demographic and socioeconomic variables.

between the built environment and mode choice, but the magnitude of the effects of the built environment were small relative to those of socio-demographics; McNally and Kulkarni (1997) found a weak, though significant, relationship between transportation mode choice and land use; and Badoe and Miller (2000) found that once socio-demographic variables are factored into the analysis, the effect of the built environment variables declines.

One of the most thorough assessments of the links between built form and travel choice was done by Ewing and Cervero and published in 2001. This "meta-analysis" led to the development a set of elasticities that demonstrate how much of a change in travel choice results from an incremental change in specific aspects of land use (Ewing and Cervero 2001). These elasticities were based on many of the original studies reported above and have been used to help calibrate the INDEX model developed by Criterion Planners and Engineers that is now being used by the Puget Sound Regional Council in their current update of the Vision 2020 Plan.

GEOGRAPHIC SCALE

From a theoretical standpoint, measurements of both socio-demographic and land use must be at an appropriate scale. Socio-demographic variables, for example, are best specified and measured at the individual or household level because these are the decision-making units (Boarnet and Crane 2001). Similarly, land use variables must be measured at a scale that is most meaningful to people when they make travel related decisions. With a few noticeable exceptions (Cervero 1991; Cervero 1996; Boarnet and Sarmiento 1998; Frank et al 2004; Frank et al 2005), most empirical studies have been at a larger but manageable scale such as the census tract (Steiner 1995; Handy 1996a; Handy 1996b; Frank and Pivo 1995). In one occasion, the scale of measurement was an entire county (Ewing et al 2003); or even a metropolitan region (Sturm and Cohen 2004).

Transit zones and census tracts, the most common scale of measurement for land use variables, are large, for example, relative to a person's immediate neighborhood. Also, if the boundaries of the spatial units are reorganized, there is potential for radical changes in the variable values and, hence, any inferences based on those variables. This phenomenon is referred to as the modifiable area unit problem or MAUP (Openshaw 1984). Additionally, land use is usually measured only at one trip end, the origin or home of the individual. This may be a considerable problem because the origin of many trips is not the home. This study uses parcel level data to examine land use around trip origin and destination.

MODE SPECIFIC FACTORS

The characteristics of each mode are also important factors in deciding how, when and where to travel—trade-offs that regulate the demand for each mode choice (Handy 2002). The most measurable of these trade-offs or relative attractiveness factors is the travel time for the various modes.

The choice of mode for a particular trip is, among other factors, a function of the convenience of each mode. Alternatively, relative transportation times of competing modes are also good measures of convenience. Formal travel demand models that consider these costs (see Train 1986 and Small 1992 for literature reviews) typically ignore variables that measure the built environment. More recent work in this framework (see Boarnet and Crane 1998; Boarnet and Crane 2001; Boarnet and Sarmiento 1998; Crane and Crepeau 1998) finds measures of the built environment to be significant. However, aside from showing that mode choice and trip generation are sensitive to relative costs, results from these studies are not generalizable enough to translate into policy decisions.

One set of models built on a household survey that was designed and stratified to capture differences in land use has been developed by Metro in the Portland, Oregon region. The most recent version of these models is documented in "Metro Travel Forecasting Trip-Based Demand Model Methodology Report" in a draft dated February 12, 2003. Here accessibility to jobs and retail jobs within ½ mile of the household, as well as access to jobs within 30 minutes by transit was shown to reduce auto ownership. This, in turn affects mode choice for these areas. Pedestrian access to retail jobs within ½ mile, and mix of use variables within ½ mile at the trip destinations were also shown to positively affect transit mode choice. These models include values of the household socio-demographics and are thus controlled for these variables.

LAND USE, TRAVEL BEHAVIOR, AND AIR QUALITY

One of the earliest analyses of relationships between land use, household travel, and air quality was conducted in the 1990s under a grant from the Washington State Department of Ecology (Frank and Stone, 1998). This study in the Central Puget Sound Region was based upon the earlier work of Frank and Pivo noted above (Frank and Pivo 1994). This was one of the first published studies to document relationships between land use, household travel, and household emissions. It concluded that increases in residential density, intersection density, and mixed use are associated with significant reductions in oxides of nitrogen (NOx), hydrocarbons (HC), and carbon monoxide (CO). The study developed land use measures at the census tract scale and controlled for socio-demographic factors and work trip distance and was published in Transportation Research Part D (Frank et al 2000).

A landmark study to investigate the links between land use, travel behavior and air quality was the LUTRAQ (Land Use, Transportation, and Air Quality) study carried out for 1000 Friends of Oregon in the early 1990's. This study included subjective measures of the built environment (Pedestrian Environment Factors – PEFs) that were quantified on a scale, and used in the development of multi-variate statistical models that were used by both this study and Metro. This study led to the design of Metro's 1994-1995 household activity and travel survey that included a choice based sampling of the built environment. This latter survey was then used in the development of the current models that include objective measures of the built environment.

Urban centers that promote increased physical activity and reduced auto dependence can lead to reduced odds of obesity (Frank et al 2004) and less ozone. The creation of walkable environments has further benefits in terms of reduced energy consumption and reduced greenhouse gas formation (LUTAQH 2005). However, research is required to more fully understand the intra-regional variation in small particulates and how exposure to particulates for at risk populations may be mitigated (Frank and Engelke 2005). As most aptly put by southern physician Dr. George A. Bray, "Genes load the gun: environment pulls the trigger." (Bray, 1998)

Investigations on the relationships between land use and exposure to air pollutants suggest that exposure to harmful ground level ozone may be somewhat mitigated through increased walkability (LUTRAQ 2001; Frank et al 2000). However, recent research documents that heart attacks can be triggered through increased exposure to fine grain particulates for at risk populations (Pope et al 2000). A primary impetus for spreading out development and the fleeing of urban environments in the turn of the 19^{th} century was the desire for cleaner air (Frumkin et al 2004). While ozone is a secondary pollutant and is a regional airshed problem, particulates vary in concentration in small areas (Kleeman et al 2000).

LAND USE AND TRAVEL CHOICE IN THE CENTRAL PUGET SOUND

In the central Puget Sound Region, there have been several studies linking the built environment with travel patterns:

- As noted above, Frank and Pivo controlled for socio-demographic factors and found significant relationships between residential density and land use mix and the proportion of household trips that were in single occupant vehicles, on transit, and on foot. That 1994 study employed the 1989 wave of the Puget Sound Transportation Panel (PSTP) collected by the Puget Sound Regional Council. (Frank and Pivo 1995)
- Dr. Kevin Krizek later analyzed multiple years of the PSTP to gain an understanding of how the same household located in two different types of land use patterns altered their travel choices (Krizek 2003).
- Dr. Anne Vernez Moudon and her colleagues have recently collected travel data from a sample of households in the Seattle area and have found significant increases in the likelihood that someone will walk or bike based on the presence of specific types of destinations within a walkable distance from where they live (Moudon et al 2005).
- This current study builds on an effort funded by King County (LUTAQH) to assess the links between land use, travel patterns, air quality, and public health whose findings also document significant increases in the odds of walking in association with increased presence of destinations where people live.

LUTAQH further documents that significant reductions in vehicle emissions are associated with higher levels of street connectivity where people live and more retail use where they work (Frank et al 2005).

SUMMARY

An overview of this study, its purpose, approach, and how it is set within the current body of evidence and existing research relating land use and transportation investments with travel choice was reviewed in this chapter. The next chapters describe:

- methods and databases (Chapter 2),
- analyses of land use, travel, and vehicle emissions (Chapter 3),
- tour type and mode choice models and mode-demand elasticities (Chapter 4),
- summary of analyses results (Chapter 5), and
- some suggestions as to how the results of this work can be applied in practice (Chapter 6).

CHAPTER 2: RESEARCH APPROACH / PROCEDURES

RESEARCH APPROACH

Analytical methods used for database development and analysis are outlined in detail for the two primary analyses conducted in this study. Methods are presented in association with:

1. Tour Based Mode Choice Modeling
2. Travel Distance, Time, and Vehicle Emissions Estimation

TOUR-BASED MODE CHOICE MODELING

Recent travel behavior research suggests that modeling spatial relationships between travel behavior and land use is vastly improved through the use of a tour-based rather than a trip-based approach (Shiftan et al 2003). Tour-based modeling more closely matches the ways in which travel decisions are actually made, so is more likely to capture true behavioral causality (as opposed to spurious correlations). For mode choice, people typically decide which mode to use for the entire tour before leaving home, taking into account not just the trip to the first destination, but both the outbound and return trips and any intermediate stops that need to be visited. For example, a person typically will not use transit to leave home if they know that they will be returning home in the evening after the transit service stops running. Also, a person will not decide to take transit back home from work if they have driven their car to work in the morning. It is true, however, that the walk mode may substitute for car or transit for some trips during a tour—e.g. parking the car or getting off the bus, walking to a few activity locations, and then returning to the parking lot or bus stop.

This analysis assesses the relationships between land use and mode choice using three different tour types:

- Home based work (HBW) tours
- Home based non-work/other (HBO) tours (such as those made for shopping and entertainment purposes)
- Mid day work place (Work-other-work, or WOW) tours

Home based work and Home based other tours were further broken down into simple and complex tours. Simple and complex tours are defined as follows.

1. **Simple tours**: About half of all trips are made as part of simple tours—from home to the destination and back home again. Separate analyses are conducted for such tours because it avoids the complicating factor of trip chains and intermediate stops—i.e. it is identical to a home-based trip mode choice model, except that it considers both directions at once.
2. **Complex tours**: Tours with more than one destination before returning home are complex. In most tour-based travel models, mode choice for trip chains is modeled as if it were a simple tour to a primary destination and back. This is because the model structure would be too complex otherwise. This project does not face that constraint, allowing the mode choice to be modeled for the entire trip chain across three or more trips (two or more non-home destinations). Comparing the results using this approach to results based on more conventional approaches reveal interesting evidence about trip chaining behavior and the role of land use.

LINKING WITH LAND USE

The analyses conducted in this project evaluate the correlations between land use, network design, and choice of travel mode, including walking and bicycling. Choice of mode was modeled considering both land use at the tour origin and destination and the detailed mode specific levels of service along tour legs (individual trips).   The household travel survey data was matched with the geographic information system (GIS) based land use database through the selection of proximate land use data, including parcels and street network data contained within a one kilometer distance of all points visited (including both habitual trips to home and work and places visited for shopping and other activities). Rather than measuring land use within a simple (crow fly) one kilometer radius, it was measured within one kilometer on the actual *road network,* thereby more accurately representing real travel distances. Using network distances is especially important in measuring street connectivity and for walk trips, for which extra distance traveled is more of a barrier. Mode specific time/distance impedances were estimated between homes and activity locations to estimate mode choice models.

The final models presented include the relative importance of household structure and pedestrian accessibility to activity locations expressed quantitatively and the level of service (LOS) variables by mode for all trips between activities in a tour away from home, or work, and back again. This research approach fits with current modeling practice, which assumes that the choice of activity location precedes the choice of mode. However, by default, this approach assumes that the choice of household location is independent of a mode preference, which is likely to be incorrect. Further investigation into the relationship between residential location choice may help to clarify to what extent people select their communities based on their travel preferences. For example, frustration with the travel time and congestion associated with suburban commutes rates high amongst reasons provided for moving to more central locations.

TRAVEL SURVEY DATA

The Puget Sound Regional Council's 1999 Household Travel Survey provided the trip, person and household level socio-demographic data for this analysis. This four county (King, Kitsap, Pierce and Snohomish) survey included 14,487 people, living in 6,040 households, who made 130,339 trips. The tables below provide some additional basic descriptives from the survey data. Slightly more survey participants were female than male (Table 2). A very significant percentage of participants were white/non-hispanic (88.8%) followed by Asian/Pacific Islanders (3.7%) and African Americans (2.0%). Nearly 60% of participants are between the ages of 22 and 65 years old. Census data from the year 1990 suggests an underrepresentation of lower income (under $35,000) households and an over representation of upper income (over $75,000) households in the survey.

Table 2: Person Level Attributes (N_person_total=14,487)

Category	Value	Percent
Gender	Male	48.3
	Female	51.5
	Refused	0.2
	Total	100.0
Ethnicity	White/Non-Hispanic	88.8
	Hispanic/Latino	1.7
	African American	2.0
	Asian/Pacific Islander	3.7
	Native American	1.0
	Other	0.7
	DK/RF	2.2
	Total	100.0
Education	Less than high school	26.0
	High school graduate	16.0
	Some college	18.5
	Vocational/Technical	3.0
	Undergraduate/Bachelors degree	19.9
	Graduate/Post-graduate degree	15.1
	DK/RF	1.4
	Missing	0.1
	Total	100.0
Age	<5	7.7
	5 to 15	14.4
	16 to 22	6.2
	22 to 65	59.2
	65+	12.5
	Total	100.0

Over 65% of households have two or more vehicles, as compared to the 4.8% with none. Nearly 30% own a single vehicle (Table 3). The household size of participants is roughly split into thirds between people living alone (26.5%), households with two people (35.1%) and those with three or more people (38.4%). As annual household income increases, so does the percentage of the households surveyed – those in the highest income bracket (with incomes over $75,000) make up the largest percentage of survey respondents. Households earning less than $35,000 are one-quarter of the survey population[5]. Over half of the households are located in King County (54.9%) with the remaining 45.1% located in Kitsap, Pierce, and Snohomish Counties.

Table 3: Household Level Attributes (N_household_total=6,040)

Category	Value	Percent
Vehicles per Household	0	4.8
	1	29.5
	2	42.2
	3	15.3
	4	5.1
	5	1.9
	6	0.8
	7	0.2
	8	0.2
	Total	100.0
People per Household	1	26.5
	2	35.1
	3	16.8
	4	14.7
	5	5.0
	6	1.2
	7	0.4
	8	0.2
	9	0.1
	10	0.0
	Total	100.0
Total 1998 annual household income	Below $35,000	1.2
	Above $35,000	3.5
	Less than $10,000	2.7
	$10,000 to $14,999	2.9
	$15,000 to $24,999	7.5
	$25,000 to $34,999	10.6
	$35,000 to $44,999	13.7
	$45,000 to $54,999	12.8
	$55,000 to $74,999	17.2
	$75,000 or more	20.4
	Don't Know/Refused	7.5
	Total	100.0
County	King	54.9
	Kitsap	8.5
	Pierce	20.0
	Snohomish	16.6
	Total	100.0

[5] Some survey participants would only indicate whether their household income was below or above $35,000 per year. Most participants provided more detailed income data.

The predominate trip purposes survey participants indicated were going to work (9.4%), incidental shopping (8.2%), and social/recreational (7.8%). Table 4 lists all the purposes reported.

Table 4: Trip Level Attributes (N_trip_total=130,399)

Primary Trip Purpose	Percent
Home	46.8
Work at home	0.2
Work	9.4
Work related (to location not regular workplace or home)	2.7
School - Junior college, university, vocational/trade	0.4
School - Daycare, K-12	3.2
Incidental shopping	8.2
Major shopping	1.5
Personal business	5.9
Medical	1.2
Other services (specified)	0.0
Eat out	3.0
Social/Recreational	7.8
Civic activities	0.7
Church activities	0.6
Pick-up/Drop-off person at work	0.5
Pick-up/Drop-off person at school/daycare	2.4
Pick-up/Drop-off person at other	3.4
Change mode of travel	2.1
Other activities (specified)	0.0
Not Given	0.0
Total	100.0

Additional information on the survey is provided in Appendix 1. This appendix contains the executive summary provided by the survey firm, NuStats Research and Consulting, to PSRC in December 1999.

TRAFFIC ANALYSIS ZONE DATA (TAZ)

Traffic analysis zone (TAZ) data from the PSRC's regional model were needed as inputs to the mode choice models. Zone to zone data were used to develop transit level of service measures and to extrapolate travel times for drive alone and carpool modes, which were subsequently used as inputs into the emissions modeling process described below and in Appendix 3. Therefore, the TAZ for each trip destination was identified in order to link the TAZ level data with each trip. PSRC supplied TAZ to TAZ values from its most recent travel demand model for the attributes located in Table 5.

Table 5: TAZ Model Attributes

- Auto - tolls (if there are any)
- Walk to transit – fare
- Walk to transit – first wait time
- Walk to transit – other wait time
- Walk to transit - # transfers
- Walk to transit – in-vehicle time

The following modeling decisions, specifications, and assumptions were central to this project:

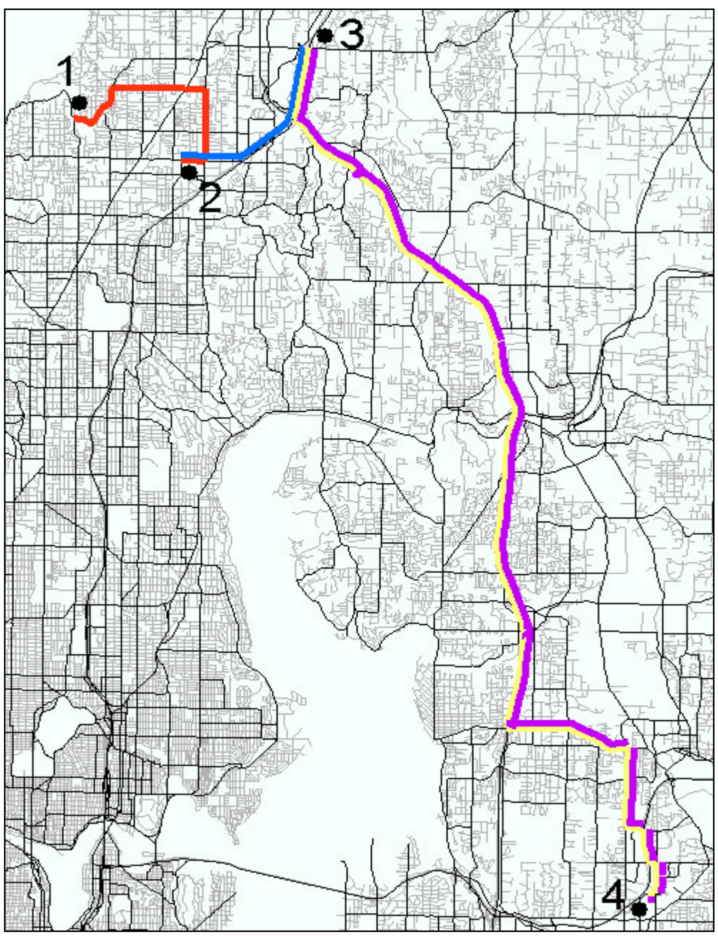
- Drive to transit was not included in the models, because there were not enough observed cases in the HH survey data to include it in the models;
- The walk to transit times were based on parcel-based distance measures to the nearest bus stop;
- Auto time and distance were based on point-to-point estimates of time and distance on local streets, arterials, and freeways; and
- Time-of-day dependent values were used as appropriate for each trip's departure time. The time of day periods from PSRC are AM peak (6:15 to 9:14 AM), Midday (9:15 AM to 3:14 PM), PM peak (3:15 PM to 6:14 PM), Evening (6:15 PM to 11:14 PM) and Night (11:15 PM to 6:14 AM). PSRC's most current TAZ structure (938 zones) was used in this work.

TOUR CREATION

Trips in the Household Travel Survey were aggregated into three tour types for purposes of this analysis—home based work (HBW), home based other (HBO) and work other work (WOW). A home-based tour (HBW or HBO) includes all stops (and the trips between them) made between leaving home and arriving back home again, excluding only those stops made as part of work-based subtours. A work-based subtour (WOW) includes all stops made between leaving a regular workplace and arriving back at that same workplace location.

Figure **2** is an example of a home-based work tour and a work subtour. Location #1 is the participant's household. While traveling to work (destination #3) they make an intermediate stop to drop off their child at daycare (destination #2). During the day the person visits a doctor at location #4 and then returns to work (the work-based subtour). At the end of the day the survey participant retrieves their child and returns home. The home based work tour for this person includes one intermediate stop (the daycare).

Figure 2: Trips to Tours



Tours with intermediate stops can have more than one purpose and mode at individual locations and for individual trips (tour segments). However, it is assumed that not all purposes and modes are the main ones for the tour. A hierarchy of purposes and modes was created and used to categorize tours. A trip's main purpose is based on the following prioritized order of participant reported activity purposes:

Table 6: Trip – Tour Purpose Coding

1 – Work
2 – Work-related
3 – University
4 – School K-12
5 – Medical
6 – Church
7 – Civic
8 – Major shopping
9 – Personal business
10 – Social/recreation
11- Pick-up/drop-off at work
12- Pick-up/drop-off at school
13- Pick-up/drop-off at other
14- Eat out
15- Incidental shopping
16- Other

A tour's main travel mode was assigned using the following priority order based on the various modes used for each trip constituting the tour. For example, if a tour consists of three trips (home to shopping, shopping to lunch, lunch to home) made by the following three modes -- auto shared ride, walk, and walk to transit. – the tour's primary mode according to Table 7 would be walk to transit. Walk to transit has the second highest priority ranking, versus fifth for auto shared ride and eighth for walking. Rankings were set by consideration of the mode which would be a controlling consideration for the person planning their travels. At the trip level, mode choices affected by schedules (transit, ferry, school bus) and availability (auto, bike) have a greater influence in tour planning than the mode which has neither of these constraints – walking.

Table 7: Tour Mode Priority

1 – Drive to transit
2 - Walk to transit
3 – Ferry
4 – School bus
5 – Auto shared ride
6 – Auto drive alone
7- Bike
8 – Walk

Tours were further categorized into levels of complexity and type. Tours with a single stop are simple tours. Tours with multiple stops are complex. Based on the main purpose and origin type, tours were assigned to one of three tour types -- home-based work (HBW), work-other-work (WOW), or home-based other (HBO).

LAND USE VARIABLE CREATION

UrbanSim building and parcel centroid tab files, supplied by the Puget Sound Regional Council (PSRC) were used as the parcel data for this project. These databases were imported into ArcView geographic information system (GIS) software and registered spatially through latitude and longitude coordinates present in the database table. These files were joined using a common parcel identification number (PIN) to form a merged building and parcel file for each county. A final building/parcel base database for the four county region was complete once the files' records were reviewed (frequencies, distributions, and spatial distribution) and categorized, and values imputed, added and/or flagged as indicated in Table 8 below.

Significant work was done to add to the enhancements already made by the PSRC. These enhancements included much needed imputation of values into empty fields critical to this analysis such as building square footage for specific types of uses. To aid us in this process, original parcel data was obtained directly from the County's Assessor's offices. In the case of Snohomish County, data obtained directly off the website enabled the creation of a more complete dataset which could support the operationalization of land use measures around participant households located in that County. A summary of the parcel database development process, including issues confronted and solutions for solving these obstacles is provided in table 7.

Table 8: Building and Parcel Data Development by County

Base Building & Parcel Data Development for Four Counties

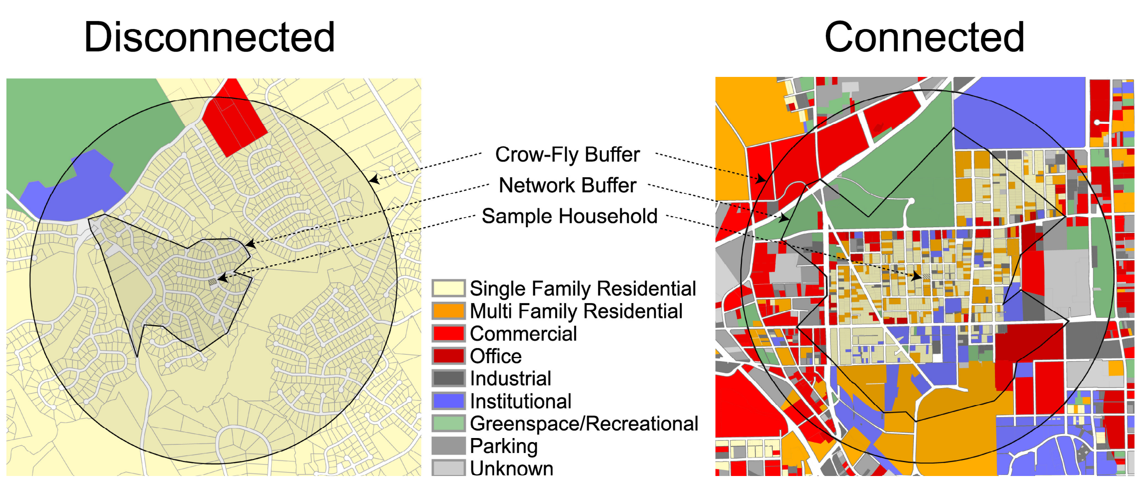
Issue Area	Review	Solution	Records affected
Land use coding	Inconsistent codings across counties	Single coding system with 23 categories	All
# of residential units	Missing and suspect data across all counties	Do not use parcel based #s. Instead use 2000 Census data at block group level.	All
Missing location data	Flag records with missing x/y coordinates	Use other county provided parcel data files to import x/y coordinates	Kitsap-x/ys found for of 1,964 records orignally missing them.
			Pierce-2,511 x/ys found for 10,379 records orignally missing them.
			Snohomish- 23,941 x/ys found for 24,717 records orignally missing them.
Building floor area (small, large, missing)	1.) Visually inspect locations of affected records to determine if geographically concentrated or disbursed.	Flag records (only floor area affected) indicating missing, deleted (N=65 single family, <200 sq ft) or imputed value (done for single family and commercial).	Kitsap and Pierce Counties deleted (N=65 single family, <200 sq ft).
	2.) Review statistical distribution, by use category, for reasonableness.	Imputed values based on county-level regression equation using the assessed improvement (built structure) value (only floor area affected).	Pierce imputed values for 2,997 commercial (Rsquared=32.8%) and 3,205 residential (rsquared=43.7%) under 200 sq ft. Total commercial records = 15,027. Total residential records = 179,047.
			Snohomish County imputed values for approximately 9,000 single family records with 0 sq ft (Rsquared = 56.7%). Total SF records = 156854
Parcel land area (small, large, missing)	1.) Visually inspect locations of affected records to determine if geographically concentrated or disbursed.	All parcels land area accepted as provided in the database.	None
	2.) Review statistical distribution, by use category, for reasonableness.		
Missing land use data	Flag records with missing land use data.	Use other county provided parcel data files to import use	See missing location data results above.
Parcels with multiple buildings	Flag records with common PIN.	Flag for single or mixed use. Assign land area to each building using a floor-area prorated basis.	King: 8,159 parcels with 2 or more buildings on them, Snohomish: 3,362, Kitsap: 4,239, Pierce: 37,715
Buildings in water	Visually inspect building/water body overlay.	Correct location if information available, otherwise detete record.	Minimal number of affected parcels

BUFFERS AROUND TRIP ENDS

Land use variables were calculated for a specified area (buffer) around each activity location within PSRC's 1999 two-day travel survey. The buffer includes the area that can be traveled to up to one kilometer from the activity location in all directions, along the street network. These network buffers establish the area people can actually access around their homes and therefore constitute a more accurate approach to measuring the physical environment unique to each participant's place of residence. The network buffers were constructed using the Network Analyst Extension in ArcView 3.2a using the WSDOT road file and survey trip end locations. The network buffer was calculated based on cumulative road distance from the household. The street network used is a modified one consisting of only those streets on which pedestrians are allowed to travel. Limited access highways and their on-ramps are not included.

In Figure 3 below, a one-kilometer network buffer is shown around a hypothetical activity location in two contrasting land uses. It also shows the difference between radial (crow-fly) and network buffer areas around these two locations. The size of the network buffer for each location varies based on the connectivity of the road network - more intersections allow a greater area to be covered on the ground. A plane of complete accessibility in all directions would result in the network buffer area equaling the straight-line area.

Figure 3: Measuring Land Use at Activity Locations

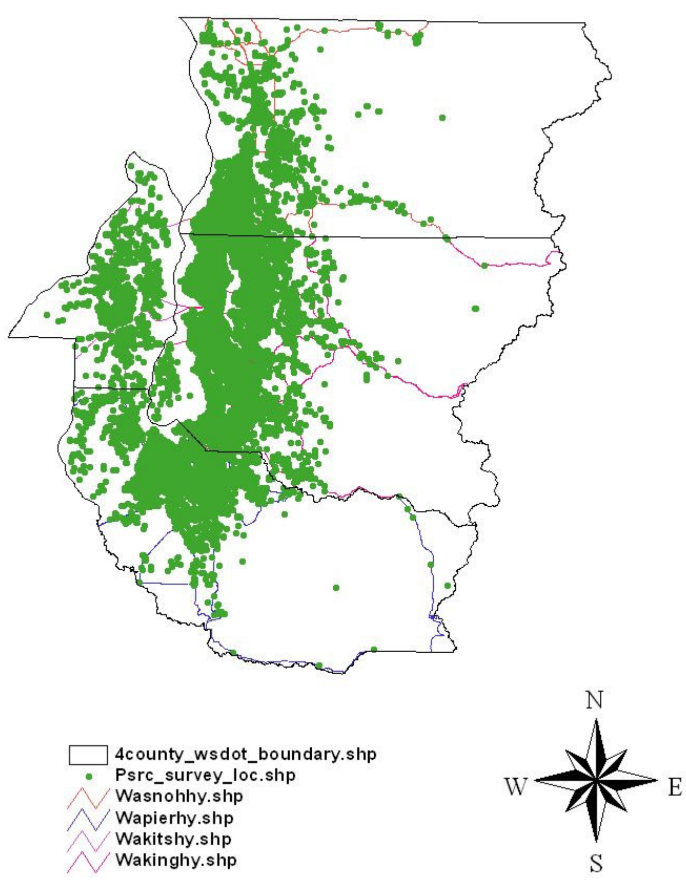


One kilometer road-network-based buffers were drawn around the 23,479 unique 1999 PSRC travel survey locations in the four counties. The distribution of these locations by county is shown in Table 9 and their geographical distribution is shown in Figure 4.

Table 9: 1999 PSRC Travel Survey Locations by County

County		Frequency (unique locations)	Percent
Valid	King	13,692	58.3
	Kitsap	1,702	7.2
	Pierce	4,308	18.3
	Snohomish	3,777	16.1
	Total	23,479	100.0

Figure 4: 1999 PSRC Travel Survey Destinations



CREATING LAND USE VARIABLES

The building/parcel data from the final county-level base files were spatially aggregated into these buffers using GIS software (ArcView 3.2a). The following section describes the methodologies used to construct the buffer level land use measures for survey locations. The types of measures created are shown in Table 10.

Table 10: Types of Land Use and Urban Form Measures

1. Frequency, by land use type, of parcels, total land area and total building floor area
2. Number of jobs per sector, per household buffer
3. Determine which Traffic Analysis Zone (TAZ), Block Group (BG), Block (B), and Census Tract (CT) the locations are in
4. Residential units per household buffer
5. Density Measures
- Net residential density
- Intersection density
- Frequency of bus stops
- Bus stop density
- Frequency of Park and Ride locations
- Park and Ride density (where applicable)
6. Mixed use

Two data layers were used to construct these measures-- the buffer layer for each county and the building/parcel point layer. Land use measures were developed based on the selected attributes of the building and parcel points that lie within the extent of each buffer (Table 11).

Table 11: Land use Attributes

Identification of land uses within each buffer
Total number of each land use within the buffer
Total parcel area for each land use within the buffer
Total building area for each land use within the buffer
Total number of building/parcel records that had missing land use data within each buffer
Total number of building/parcel records that had missing latitude and longitude coordinates within each buffer
Total number of parcel records within the buffer where there was no value for floor area
Total number of building records where the build area was imputed

The associated attributes were then aggregated into one record that corresponded with the buffer in which these building and parcel points were located. Within the final building/parcels layer there were a total of 22 different land use types as listed in Table 12.

Table 12: Land Use Categories

Number	Land use	Number	Land use
1	Agricultural	12	Neighborhood Retail
2	Civic	13	Office Building
3	Doctor-Dentist	14	Open Space
4	Educational	15	Other
5	Entertainment	16	Park
6	Fast Food	17	Parking
7	Grocery	18	Recreational
8	Industrial	19	Restaurant
9	Large Retail	20	Single Family
10	Multi Family	21	Unknown
11	Museum	22	Vacant

There are three main steps to calculating the land use measures based on the land use categories and attributes shown in Table 11 and Table 12. These steps are data summarization, land use base table construction, and aggregation. For additional details on this process please see Appendix 4.

Number of Jobs Per Sector

The second group of measures calculated was the number of jobs per sector using the buffer and building/parcel point layer for each county. Similar to the land use measures discussed above, the purpose of this calculation was to determine the number of jobs, per sector, within each buffer. Given this, the same three-step process used to calculate the land use measures was employed for the construction of the job measures. In this context, Table 13 outlines the job sectors and their associated attribute definitions found within the study area.

Table 13: Field Definitions for the Job Measures

#	Job Sector	Code	Num of Bld	Num of Jobs
1	Agriculture	AG	AG_bld	AG_Job#
2	Construction	CO	CO_bld	CO_Job#
3	Education Higher	EDH	EDH_bld	EDH_Job#
4	Educational k-12	EDK	EDK_bld	EDK_Job#
5	Federal, Civilian	FC	FC_bld	FC_Job#
6	Federal, Military	FM	FM_bld	FM_Job#
7	Fire	F	F_bld	F_Job#
8	Manufacturing	MAN	MAN_bld	MAN_Job#
9	Mining	M	M_bld	M_Job#
10	Public Admin	PAD	PAD_bld	PAD_Job#
11	Retail Trade	RTD	RTD_bld	RTD_Job#
12	State and Local	SL	SL_bld	SL_Job#
13	Services	S	S_bld	S_Job#
14	Transport, Communication	TC	TC_bld	TC_Job#
15	Wholesale Trade	WTD	WTD_bld	WTD_Job#
16	Unknown	UK	UK_bld	UK_Job#

ID Identification per Location (TAZ, BG, B, CT)

The third group of measures involved identifying which other spatial analysis units (traffic analysis zone (TAZ), census block group, block, and tract) each location fell within. The following spatial polygon files were used:

- TAZ layer for the each county
- block group layer for each county
- block layer for each county
- census tract layer for each county
- Survey household data layers

Four new fields were then added to each of the survey database tables, one for each unit of analysis (TAZ, census block group, block, and tract). Each of these fields was then populated based on the corresponding unique identifying number for each unit of analysis.

Residential Units per Household Buffer

The fourth measure calculated was the number of residential units in each location's buffer. Census residential unit data at the block group level was used. Using ArcView GIS (the Area Percentage Tool in the Compile Theme Tools) the percent of each block group that lay in each buffer zone was calculated. This percentage was then used to proportion the total number of residential units that lay within each buffer.

Calculating Residential, Bus Stop, and Intersection Density

Density measures were also calculated for this study. These measures were calculated based on the number of residential units, intersections, bus stops, and Park and Ride locations found within each buffer. All three density measures were calculated using the following formula:

$$x = \frac{y}{Buffer\_Area}$$

Where, depending on the density measure being calculated:

x =	Net residential density, intersection density, bus stops density, or park and ride density
y =	Number of residential units per buffer intersections per buffer, number of bus stops per buffer, or number of park and ride locations per buffer
Buffer_area =	Number of residential acres, total buffer acres for other density measures

Intersection density was calculated using the road network. Facility classification data was critical to this project because it enabled us to detect which facilities were local and arterial streets and which were limited access facilities. Limited access facilities such as highways and crossovers from ramps and feeder roads were removed from the analysis to isolate only those types of intersections that are open to pedestrians and bicyclists. The specific steps followed were:

1. Using the Road network and buffer layer, the roads that were surrounding the buffer areas were selected and converted into their own data layer.
2. The ‘clean and node analyzer’ function was run on the road network to identify all intersections within the road network.
3. These were then exported to a separate data layer (Points.shp)
4. The 'count points in poly' function was used to count the number of points from the points layer that lay within each of the study area boundaries in the household buffers.

Bus stops and Park and Ride locations were mapped based on step four above. The number of bus stops and Park and Ride locations within each buffer were catalogued. Table 14 shows the field definitions used for calculating the density measures.

Table 14: Attribute definitions for the density calculations

Attribute	Definition
Buffer_id	Sequential Buffer identification numbers. i.e. 1,2,3,…n.
Area_feet	Buffer Area in square feet
Area_km2	Buffer Area in square kilometers
Area_m2	Buffer Area in square meters
Acres	Buffer Area in Acres
Pnr_Count	Number of Park and Ride locations within each buffer
Bus_Den	Bus Stop Density = (Bus_Count/Buffer Area in Acres)
Bus_Count	Number of Bus stops within each buffer
Pnride_den	Park and Ride Density = (Pnf_Count/Buffer Area in Acres)
Intr_count	Number of Intersections within each buffer
Interden_a	Intersection Density = (Inter_Count/Buffer Area in Acres)
Interden_k	Intersection Density = (Inter_Count/Buffer Area in km2)

Mixed Use

Mix of uses was calculated based on a measure of entropy between entertaiment and restaurant, residential (single and multi-family), retail and office land uses. Frequency of occurrence and total building floor area for specific land uses were used as inputs. The equation below results in values between 0 and 1. The closer to 1 the value is the more evenly distributed the building floor areas are between uses. A value of 0 indicates a single use buffer.

Mixed use (mx_fl_4) = (-1)*A/LN(4) where:

A = b(1)/a*ln(b(1)/a) + b(2)/a*ln(b(2)/a) + b(3)/a*ln(b(3)/a) + b(4)/a)*ln(b(4)/a))

and where:

- a = total square feet of building floor areas for all of the land uses (of the four) present in a buffer
- b(1) = total square feet of building floor area of entertainment (entertainment and restaurant)
- b(2) = total square feet of building floor area of residential (single family and multi-family residential)

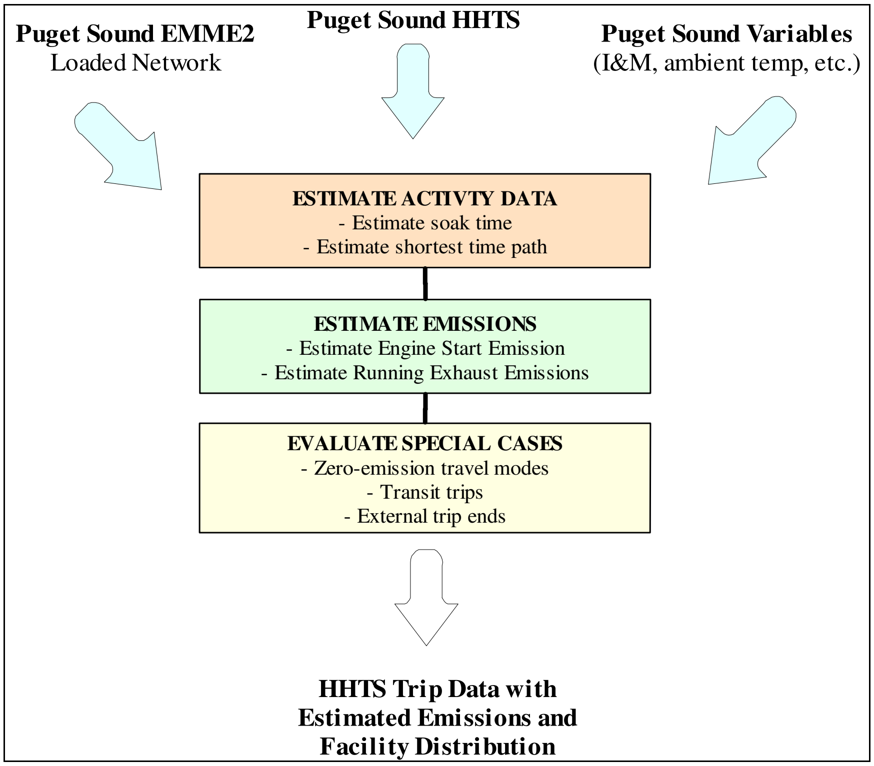
- b(3) = total square feet of building floor area of retail (large and neighborhood),
- b(4) = total square feet of building floor area of office

TRAVEL DISTANCE, TIME & EMISSIONS ESTIMATION

Methods developed for this procedure were led by Dr. William Bachman with GeoStats, LLP and funded by King County, WA as part of the LUTAQH study and the Georgia DOT as part of the SMARTRAQ study. More detail on the methodology is available in Appendix 3. Travel time, distance and vehicle emissions were estimated for each link of each trip made in the 1999 Puget Sound Regional Council's Household Travel Survey (HHTS). These estimates were based on congested flows based on time of day and direction of travel using zone to zone travel time matrices for AM, PM, and off peak travel. A shortest time-path assignment routine was developed and applied based on the known coordinates of each trips origin and destination. Each link of each trip was isolated based on its known facility classification. Modeled travel speeds (based on time of day of travel) were then used as inputs to the vehicle emissions modeling process for the duration of travel on each link of each trip. Origins and destinations are not always on the model network that was used for this assessment. A shortest path routine was developed to connect the point of origin or destination with the nearest point on the model network and an assumption of an average travel speed of 15 miles per hour was made based on the fact that this portion of each trip was likely to be on a local street (since it is not part of the model network).

Puget Sound programmatic and atmospheric variables, and the PSRC's loaded travel demand forecasted model (EMME2) were used as inputs into the process. Average speed and distance by facility type was estimated. The origin and destination coordinates, the trip start time, and loaded Puget Sound Travel Demand Forecasting model networks (AM peak, PM peak, and off peak) were used in this process. This process resulted in a road-link-based emissions factor, as well as travel time and distance for each trip. The US Environmental Protection Agency's emission modeling tools, including MOBILE 6.2, were used. Start emissions (based on engine soak time) and running exhaust emissions were modeled separately based on cool down times recorded between trips for each survey participant. A diagram of the general process is shown in Figure 5.

Figure 5: General process for estimating trip level emissions



Subsequent aggregation of these sub-trip-level emissions per link to the trip, person, and household level enables the assessment of systematic variation between levels of emissions, demographics, and land use.

TDM AND LAND USE ANALYSIS

Mode Choice modeling and vehicle emissions modeling were both based on the reported travel from the Puget Sound Regional Council's 1999 Regional Household Travel Survey. Additional exploratory analysis was conducted using the WSDOT Commute Trip Reduction (CTR) Database that records employer offerings of Travel

Demand Management Programs and employee travel patterns in the Central Puget Sound Region. The primary purpose of this analysis was to assess the linkage between the types of programs that are offered, employee travel patterns, and land use. This was to be done by investigating whether employee mode split and TDM program participation correlated with work-site land use. However, after working with the CTR data it was found that additional data development would be needed to support an analysis of this type.

SUMMARY

Methods presented in this chapter document the approaches used to develop project databases and resulting variables for measuring land use relationships with modal choice and vehicle emissions. A unique set of methods to model vehicle emissions from reported travel data is presented enabling links to be made between household travel, emissions, and land use. Experience with the Commute Trip Reduction (CTR) data to assess the linkage between the types of programs that are offered, employee travel patterns, and land use indicates additional data development is needed before it is applicable for this use.

CHAPTER 3: VEHICLE TRAVEL, LAND USE AND AIR POLLUTION

INTRODUCTION

This part of the analysis used multivariate linear regression models for hydocarbons (HC) and oxides of nitrogen (NOx) to investigate the relationship between independent land use and land use variables at the one kilometer household buffer level, and dependent household-level vehicle miles/hours traveled and emissions produced. Harmful ground level (troposphoric) ozone results from HC and NOx reacting in sunlight. Vehicle emissions are a function of speed and distance of travel, engine operation (hot stabilized or cold start), and vehicle characteristics,[6] travel distances and speeds.

VEHICLE MILES & HOURS OF TRAVEL & LAND USE REGRESSIONS

Multivariate linear regression models for mean daily household level vehicle miles (VMT) and hours traveled (VHT) were developed to investigate their relationship with land use and street network variables at the one kilometer household buffer level. The analysis controlled for household level demographics (number of vehicles and people per household and household annual income). The dependent travel behavior variables were transformed by taking the log10 of the values to make them more linear with regard to the dependent variables, thereby allowing a linear regression model to be used.

Table 15 provides descriptives for the data set used in the VMT and VHT regression models. After eliminating values greater than three standard deviations from the mean for dependent and non-demographic variables, 4,546 households remained in the data set. The average household, consisting of 2.5 people, traveled nearly 67 miles per day, spending 2.1 hours doing so. This hypothetical household lived slightly more than half a mile from the nearest bus stop, and in a community where the average house was on about a quarter acre lot.

[6] Assumptions about vehicle characteristics were based on fleet mix data for the central Puget Sound Region.

Table 15: Descriptives for VMT, VHT & Land Use Data Used in Regression Models

Variable	N	Minimum	Maximum	Mean	Std. Deviation
Lg10(VMT*)	4,552	-0.745	2.408	1.661	0.438
VMT--mean, daily HH level*	4,573	0.000	255.565	66.781	52.580
Lg10(VHT*)	4,546	-2.062	0.881	0.178	0.406
VHT--mean, daily HH level*	4,567	0.000	7.609	2.100	1.563
Vehicles per household	4,567	0.000	8.000	2.024	1.088
People per household	4,567	1.000	10.000	2.494	1.286
Annual household income**	4,567	11.000	18.000	15.855	1.839
Miles to nearest bus stop*	4,567	0.000	5.240	0.561	0.827
Net Residential Density (dwelling units per acre)*	4,567	0.946	71.182	4.365	4.975
Intersection Density (per sq km)*	4,567	0.000	127.417	47.556	25.006
Mixed Use (index)*	4,567	0.000	0.838	0.186	0.206
Valid N (listwise)	4,546				
Notes:	* Values greater than three standard deviations from the mean removed as outliers. ** Ordinal variable with unequal ranges				

Annual household income is an ordinal variable ranging from 11 to 18. .

Table **16** provides the income ranges associated with each code. It is important to note that these ranges are not equal. This is an artifact of how the original travel survey data was collected and tabulated.

Table 16: Income Variable Coding

Coding	Range
11	Less than $10,000
12	$10,000 to $14,999
13	$15,000 to $24,999
14	$25,000 to $34,999
15	$35,000 to $44,999
16	$45,000 to $54,999
17	$55,000 to $74,999
18	$75,000 or more

In both the VMT (Log10) and VHT (Log10) regression models (Table 17), an increase in demographic variables (household vehicles, people and/or income) resulted in the expected increase in both vehicle miles and hours traveled. The models also show, as might be expected, that the lower a households' transit level of service, as represented by the distance to the nearest bus stop, the greater that household's VMT and VHT.

Increases in intersection densities and mixed use at the one kilometer household buffer level were found to be significantly associated with decreases in VMT. These same two independent land use variables, in addition to net residential density, were significantly associated with decreases in VHT. This combination of variables explained 28.4% of the variance in VMT, and 32.9% of the variance in VHT. This is a good R-square for any type of social science research.

Table 17: Vehicle Miles and Hours of Travel & Land Use Regression Models

Variable		**Lg10(VMT*)**			**Lg10(VHT*)**		
		B	t-statistic	Signif.	B	t-statistic	Signif.
	(Constant)	0.681	12.919	0.000	-0.801	-16.842	0.000
Demographics	Vehicles per households	0.048	8.120	0.000	0.041	7.669	0.000
	People per household	0.109	23.087	0.000	0.118	27.750	0.000
	Annual household income**	0.044	13.151	0.000	0.043	14.308	0.000
Transit LOS	Miles to nearest bus stop*	0.021	2.738	0.006	0.017	2.423	0.015
Land Use	Net Residential Density (dwelling units per acre)*			N.S.	-0.003	-2.412	0.016
	Intersection Density (per sq km)*	-0.002	-6.671	0.000	-0.001	-5.216	0.000
	Mixed Use (index ranging 0 to 1)*	-0.095	-3.280	0.001	-0.116	-4.395	0.000
	R square	**0.284**			**0.329**		
Notes:	* Values greater than three standard deviations from the mean removed as outliers. ** Ordinal variable with unequal ranges						

EMISSIONS & LAND USE

Multivariate linear regression models for mean, daily household level vehicle emissions of hydrocarbons (HC) and oxides of nitrogren (NOx) were developed to investigate their relationship with land use variables at the one kilometer household buffer level. The relationship of mean daily household level vehicle emissions with land use variables was investigated using two separate models. Both models contain household level demographics (number of vehicles and people per household and household annual income); but only the second model contains travel behavior (vehicle miles of travel). By not including travel behavior in both models, it is possible see the additional variance explained by vehicle miles of travel (VMT). The dependent emission variables were converted to log values to facilitate their analysis.

HYRDOCARBON EMISSION, TRAVEL BEHAVIOR & LAND USE

The next set of descriptive and regression results focus on daily, household level hydrocarbon emissions as dependent variables. Table 18 provides descriptives for the data set used for the hydrocarbon models. After eliminating values greater than three standard deviations from the mean for dependent and non-demographic variables, data for 4,630 households were used in the HC model. The average household, consisting of nearly 2.5 people, produced 29 grams of hydrocarbons while traveling 67 miles per day. The mean vehicle miles traveled per person per day is 26.9 miles for the data set.

Table 18: Descriptives for HC Emissions, Travel Behavior & Land Use Data Used in Regression Models

Variable	N	Minimum	Maximum	Mean	Std. Deviation
Lg10(HC*)	4,630	-1.398	1.929	1.351	0.389
HC (grams) -- mean, daily HH level)*	4,653	0.000	84.955	29.022	17.290
VMT -- mean, daily HH level*	4,653	0.000	255.565	67.051	52.705
Vehicles per household	4,653	0.000	8.000	2.026	1.087
People per household	4,653	1.000	10.000	2.490	1.282
Annual household income	4,653	11.000	18.000	15.844	1.847
Net Residential Density (dwelling units per acre)*	4,653	0.946	71.182	4.496	5.193
Intersection Density (per sq km)*	4,653	0.000	126.248	46.769	25.251
Mixed Use (range from 0 to 1)*	4,653	0.000	0.838	0.183	0.206
Valid N (listwise)	4,630				
Notes:	* Values greater than three standard deviations from the mean removed as outliers. ** Ordinal variable with unequal ranges				

Increases in demographic variables (vehicle and people per household and income) were found to be significantly associated with increased mean daily household vehicle HC emissions (Table 19). Increases in net residential and intersection densities and mixed use at the one kilometer household buffer level were significantly associated with decreases in emissions. This combination of variables explains 31.6% of the overall levels of variance, and increases to 50.1% in the second model when VMT is added to it. This second model shows VMT as strongly and positively related to emissions – indicating that the farther people in a household cummulatively travel by motor vehicle, the more emissions they create.

The addition of VMT to the model weakens the effect of two of the three land use variables. When the two models are compared (without VMT--#1 and with VMT--#2) the coefficients for net residential and intersection densities remain basically unchanged while the mixed use value decreases for model #2.

A transit LOS variable was ultimately not included in the HC or NOx emission models. Like the VMT and VHT models described previously, the transit level of service (LOS) variable (distance to bus stop) was tried in these models, and in the NOx models described below. Even though it was significantly and positively correlated with emissions it was found to be significant but illogically signed. Its negative coefficient means as the distance to the nearest bus stop increased, a household's emission production would decrease. It appears this variable was interacting with the land use variables. More investigation is required to better understand exactly why this interaction may be occurring.

Several versions of the transit LOS variable were tried in the model. The variable was made into a dichotomous one where various distance cutpoints were tried including 0.25, 0.5, 0.6 and 1 mile from the household to the nearest bus stop. These variables were either still inversely signed and/or insignificant. Another transit LOS variable (bus stop density -- # per acres of land in buffer) was also tried. It was negatively signed (logical) and significant, but intersection density and mixed use became insignificant.

Table **19: HC Emissions Regression Models without & with VMT– mean, daily grams, household level**

Variable		**Lg10(HC*)**					
		Model #1 (no VMT included)			**Model #2 (VMT included)**		
		B	**t-statistic**	**Signif.**	**B**	**t-statistic**	**Signif.**
	(Constant)	0.426	9.634	0.000	0.537	14.129	0.000
Demographics	Vehicles per household	0.078	15.395	0.000	0.058	13.342	0.000
	People per household	0.080	19.999	0.000	0.023	6.191	0.000
	Annual household income**	0.042	14.832	0.000	0.028	11.161	0.000
Travel Behavior	VMT -- mean, daily HH level*	--	--	--	0.004	42.002	0.000
Land Use	Net Residential Density (dwelling units per acre)*	-0.002	-2.089	0.037	-0.003	-3.710	0.000
	Intersection Density (per sq km)*	-0.002	-7.523	0.000	-0.001	-3.369	0.001
	Mixed Use (index, 0 to 1)*	-0.111	-4.482	0.000	-0.069	-3.272	0.001
	R square	**0.316**			**0.501**		
Notes:	* Values greater than three standard deviations from the mean removed as outliers. ** Ordinal variable with unequal ranges						

OXIDES OF NITROGREN, TRAVEL BEHAVIOR & LAND USE

The next set of descriptive and regression results focus on daily, household level oxides of nitrogen and hydrocarbon emissions as dependent variables. Table 20 provides descriptives for the data set used for the oxides of nitrogren models. After eliminating values greater than three standard deviations from the mean for dependent and non-demographic variables, data for 4,626 households were used in the NOx model. The average household in this dataset consisted of nearly 2.5 people and produced 57.7 grams of NOx while traveling nearly 67 miles per day. The mean vehicle miles traveled per person (rather than per household) per day was 26.8 miles for the data set.

Table 20: Descriptives for NOx Emissions, Travel Behavior & Land Use Data Used in Regression Models

Variable	N	Minimum	Maximum	Mean	Std. Deviation
Lg10(NOx*)	4,626	-0.824	2.263	1.636	0.395
NOx (grams) -- mean, daily household (HH) level	4,649	0.000	183.265	57.708	37.702
VMT -- mean, daily household level*	4,649	0.000	255.565	66.767	52.318
Vehicles per household	4,649	0.000	8.000	2.025	1.084
People per household	4,649	1.000	10.000	2.492	1.284
Annual household income**	4,649	11.000	18.000	15.844	1.847
Net Residential Density (dwelling units per acre)*	4,649	0.946	71.182	4.499	5.196
Intersection Density (per sq km)*	4,649	0.000	126.248	46.799	25.254
Mixed Use (index)*	4,649	0.000	0.838	0.183	0.206
Valid N (listwise)	4,626				
Notes:	* Values greater than three standard deviations from the mean removed as outliers. ** Ordinal variable with unequal ranges				

Similar to the HC model, increases in demographic variables (vehicle and people per household and income) were significantly associated with increased mean daily household vehicle NOx emissions (Table 21). Increases in intersection densities and mixed use were significantly associated with decreases in emissions. Net residential density (NRD) was only significant in Model #2, which contains the VMT variable. In that model NRD was negatively signed, indicating increased density is associated with lower NOx emissions. Model #1 explained 29.4% of the variance. This increases to

57.6% in the second model when VMT was added. VMT was strongly and positively related to NOx emissions.

The impact of adding VMT to the model is not the same as was the case for HC emissions. Net residential density is made significant by VMT, whereas for HC emissions adding VMT weakened the NRD contribution. However, similar to the HC models intersection density has a higher coefficient without VMT in the NOx model, but the difference is much less. It doubles (from -0.001 to -0.002) rather than increases one-hundred fold (from -0.001 to -0.1, Table 19).

The unsuccessful attempts to include a transit LOS variable in the final models have already been previously described in the HC regression model discussion.

Table 21: NOx Emissions Regression Models without & with VMT – mean, daily grams, household level

Variable		**Lg10(NOx*)**					
		Model #1 (no VMT included)			**Model #2 (VMT included)**		
		B	**t-statistic**	**Signif.**	**B**	**t-statistic**	**Signif.**
	(Constant)	0.714	15.756	0.000	0.856	24.049	0.000
Demographics	Vehicles per household	0.069	13.228	0.000	0.046	11.115	0.000
	People per household	0.082	19.713	0.000	0.010	2.774	0.006
	Annual household income**	0.043	14.554	0.000	0.025	10.696	0.000
Travel Behavior	VMT -- mean, daily HH level*	--	--	--	0.005	55.983	0.000
Land Use	Net Residential Density (dwelling units per acre)*			N.S.	-0.002	-3.297	0.001
	Intersection Density (per sq km)*	-0.002	-8.367	0.000	-0.001	-3.629	0.000
	Mixed Use (index, 0 to 1)*	-0.099	-3.896	0.000	-0.047	-2.383	0.017
	R square	**0.294**			**0.576**		
Notes:	* Values greater than three standard deviations from the mean removed as outliers. ** Ordinal variable with unequal ranges						

SUMMARY

The results presented here document how demographics and measures of land use influence spatial and temporal aspects of travel demand, including vehicle miles (VMT) and hours (VHT) of travel. Subsequent analyses document how land use and these intervening measures of travel demand (VMT) influence the household generation of oxides of nitrogen and hydrocarbons. Regression model results clearly indicate that land use measures play an important role in both how much we travel and how much we pollute. Interestingly, land use seems to not only influence emissions through its relationship with travel demand (VMT); but also through speed and start functions. This is based on the fact that the land use variables remained significant predictors of emissions even after vehicle miles of travel was included in the models presented in this chapter.

Results presented confirm the conclusions found in much of the previous research on the relationships between land use, travel demand, and vehicle emissions. The results presented in this chapter are far clearer and more specific than was possible in the past. This work provides guidance to municipalities on how policies to reduce vehicle miles of travel and air pollution can be achieved through changes in land use policy, and more importantly, land use regulation.

Currently, local approaches to analyses of transportation concurrency and trip generation during development review are based on an impact assessment measured on a per trip basis. While trip generation rates were not modeled in association with land use in this study, the results do offer some implications for possible enhancements to measuring the impacts of development decisions on the transportation system. In particular, the results presented here document how specific aspects of development decisions, including levels of density, mix, and street connectivity, impact travel demand in terms of miles and hours of travel.

The end result of shifting to a VMT or VHT based impact fee/concurrency system would be increased impact fees for areas that require longer distances of travel between daily activities. The idea of a VMT or VHT based impact fee system, rather than one based on total trips, is not a new idea and is one that is more consistent with the premise of the state's Growth Management Act, which is to steer growth into existing centers. Travel demand and its resulting impacts on transportation facility performance will vary not only based on the land use of the development and its surrounding neighborhood, but also on its regional location. The cumulative amount of demand and impact that is generated from a less centrally located development could likely be far greater due to increased vehicle miles or hours of travel.

The results of the analyses presented in this chapter, placed within the context of adopted Multi-County and County-Wide Planning policies, suggests that the intent of growth management could be well served through investigating approaches that better capture the transportation related impacts of development actions. This research provides one starting point to do so, based on the best regional data available.

CHAPTER 4: TOUR BASED MODELING FOR NON-WORK AND WORK RELATED TRAVEL

INTRODUCTION

Tour type and modal choice models are presented and discussed in this chapter. Descriptives are first presented for different tour types followed by discrete choice models and interpretation of results.

TOUR DESCRIPTIVES

Frequencies for the three tour types and two levels of complexity are shown in Table 22. Simple tours consist of a single destination, while complex tours have multiple destinations before returning to the tour's origin. A slight majority of home-based work (HBW) tours are complex. In comparison, nearly 60% of home-based other (HBO) tours and over three-quarters of work-based subtours (WOW) are simple tours.

Table 22: Tour Type by Simple or Complex

Tour Type	Simple Tours		Multi-Stop Tours		All Tours
Home-based work	4,968	48.2%	5,329	51.8%	10,297
Home-based other	8,896	59.9%	5,957	40.1%	14,853
Work-based subtour	1,065	77.1%	317	22.9%	1,382
TOTAL	14,929	56.3%	11,603	43.7%	26,532

The main purpose for making tours is work related, for both simple and complex tours combined (Table 23).[7] Social/recreation, personal business and then incidental shopping are the next most common purposes for simple tours. For complex tours, trip purposes are similar but reversed in order—personal business and social/recreation are the second and third most common tour purpose. But rather than incidental shopping, work at a non-regular location is the fourth main purpose for complex tours.

[7] This is quite different from trip level statistics, which show that nearly 83 percent of all trips are for non-work purposes.

Table 23: Main Tour Purpose

Main Tour Purpose	All Tours		Simple Tours		Multiple Stop Tours	
	N (tours)	%	N (tours)	%	N (tours)	%
Work-based subtour	1,382	5.2	1,065	7.1	317	2.7
Work	9,299	35.0	4,617	30.9	4,682	40.4
Work - non-regular location	998	3.8	351	2.4	647	5.6
School - college, university	367	1.4	239	1.6	128	1.1
School - Daycare, K-12	541	2.0	365	2.4	176	1.5
Incidental shopping	1,909	7.2	1,559	10.4	350	3.0
Major shopping	928	3.5	292	2.0	636	5.5
Personal business	2,834	10.7	1,064	7.1	1,770	15.3
Medical	894	3.4	372	2.5	522	4.5
Eat out	742	2.8	573	3.8	169	1.5
Social/Recreational	3,415	12.9	2,199	14.7	1,216	10.5
Civic activities	623	2.3	334	2.2	289	2.5
Church activities	513	1.9	293	2.0	220	1.9
Pick-up/Drop-off person at work	202	0.8	152	1.0	50	0.4
Pick-up/Drop-off person at school	1,036	3.9	821	5.5	215	1.9
Pick-up/Drop-off person at other	830	3.1	614	4.1	216	1.9
Other/missing	19	0.1	19	0.1		
Total	26,532	100.0	14,929	100.0	11,603	100.0

Drive alone and shared ride are the two most common main tour modes for both simple and complex tours (Table 24). Shared ride is the most common mode for complex tours, and second most common for simple tours. Walking is the third most common mode for simple tours, but is sixth for complex tours. This is not unexpected given the typical shorter distance of walk trips compared to other modes.

Table 24: Main Tour Mode

Mode	All Tours		Simple Tours		Multiple Stop Tours	
	N (tours)	%	N (tours)	%	N (tours)	%
Car to transit	245	0.9	61	0.4	184	1.6
Walk to transit	957	3.6	500	3.3	457	3.9
Ferry	214	0.8	7	0.0	207	1.8
School bus	154	0.6	105	0.7	49	0.4
Shared ride	10,714	40.4	5,207	34.9	5,507	47.5
Drive alone	12,687	47.8	7,733	51.8	4,954	42.7
Bike	222	0.8	165	1.1	57	0.5
Walk	1,278	4.8	1,100	7.4	178	1.5
Other	61	0.2	51	0.3	10	0.1
Total	26,532	100.0	14,929	100.0	11,603	100.0

As described earlier, simple tours are the most common, making up over half of all tours. Table 25 provides the frequency of tours by the total number of stops made. Stops do not include the tour's origin/final destination—which are the same location (either work or home depending on the tour type). Nearly 40% of tours made between two and five stops.

Table 25: Distribution of Tours by Total Number of Stops

Total Stops on Tour	Frequency (N=Tours)	Percent
1	14,929	56.27
2	4,937	18.61
3	3,146	11.86
4	1,514	5.71
5	936	3.53
6	463	1.75
7	292	1.10
8	155	0.58
9	81	0.31
10	40	0.15
11	16	0.06
12	8	0.03
13	6	0.02
14	6	0.02
15	1	0.00
16	1	0.00
32	1	0.00
Total	26,532	100.00

Table 26 shows how the mean number of stops varies by main tour purpose. Five of seventeen purposes have between two and three mean trips per tour—work at a non-regular location, major shopping, personal business, medical and civic activities. The three purposes (not including "other/missing) with the lowest means (<1.35) are work-based subtour, incidental shopping and eat out.

Table 26: Mean Number of Stops on Tour by Main Tour Purpose

Main Tour Purpose	Mean # of Stops
Work-based subtour	1.34
Work	1.89
Work - non-regular location	2.74
School - college, university	1.8
School - Daycare, K-12	1.71
Incidental shopping	1.23
Major shopping	2.73
Personal business	2.35
Medical	2.38
Eat out	1.35
Social/Recreational	1.61
Civic activities	2.05
Church activities	1.85
Pick-up/Drop-off person at work	1.4
Pick-up/Drop-off person at school	1.29
Pick-up/Drop-off person at other	1.42
Other/missing	1

Walk tours, on average, have the fewest number of stops (1.19), followed by bike and drive alone. In contrast, as shown in Table 27, people using the ferry as their main tour mode have the highest number of average stops (6.23). This amount is twice the next highest average (car to transit), and it is based on the fourth smallest sample (N=214 tours). Car to transit, shared ride and walk to transit have the second to fourth highest mean number of stops. This would be in part due to the nature of these modes to include a mode related stop – either a mode transfer or picking-up/dropping off someone.

Table 27: Mean Number of Stops on Tour by Main Tour Mode

Mode	Mean # of Stops	N (tours)
Car to transit	3.21	245
Walk to transit	1.98	957
Ferry	6.23	214
School bus	1.62	154
Shared ride	2.09	10,714
Drive alone	1.61	12,687
Bike	1.44	222
Walk	1.19	1,278
Other	1.15	61

Table 28 is a cross-tabulation of main tour purpose and mode. The most common reported use of walking is for the work-based subtour, followed by social/recreational. Home-based work tours are drive-alone tours nearly half the time. No other tour purpose captures such a high percentage of the drive alone mode. The next highest is only 10.5%--personal business. The shared ride is comparably used for work (18.5%), social/recreational (17.8%) and personal business (12%). The predominate use of car and walk to transit is to travel to work (80.0% and 69.1% respectively).

Table 28: Main Tour Mode by Main Tour Purpose

Main Tour Purpose	Car to transit	Walk to transit	Ferry	School bus	Shared ride	Drive alone	Bike	Walk	Other	Total
Work-based subtour	0.0%	1.4%	0.0%	0.6%	2.9%	5.7%	2.3%	25.3%	11.5%	5.2%
Work	80.0%	69.1%	60.3%	2.6%	18.5%	47.5%	52.3%	12.7%	47.5%	35.0%
Work - non-regular location	0.8%	1.3%	9.3%	0.0%	2.6%	5.2%	1.8%	1.4%	1.6%	3.8%
School - college, university	3.7%	7.0%	1.4%	1.3%	0.7%	1.3%	8.1%	1.6%	0.0%	1.4%
School - Daycare, K-12	0.4%	2.3%	0.9%	94.2%	2.3%	0.8%	1.8%	1.3%	0.0%	2.0%
Incidental shopping	0.4%	2.3%	0.9%	0.0%	6.2%	8.5%	3.2%	10.1%	1.6%	7.2%
Major shopping	2.0%	1.8%	2.3%	0.0%	4.8%	2.9%	1.4%	0.8%	3.3%	3.5%
Personal business	4.5%	4.6%	5.6%	0.0%	12.0%	10.5%	9.9%	9.5%	6.6%	10.7%
Medical	1.2%	3.1%	2.3%	0.0%	4.4%	2.9%	0.9%	0.8%	9.8%	3.4%
Eat out	0.0%	0.9%	3.7%	0.0%	4.6%	1.4%	2.3%	4.3%	0.0%	2.8%
Social/Recreational	4.5%	5.1%	9.3%	1.3%	17.8%	9.1%	14.9%	18.0%	14.8%	12.9%
Civic activities	2.0%	0.9%	1.9%	0.0%	2.4%	2.4%	0.9%	2.7%	1.6%	2.3%
Church activities	0.4%	0.2%	1.4%	0.0%	2.7%	1.6%	0.0%	0.6%	1.6%	1.9%
Pick-up/Drop-off person at work	0.0%	0.0%	0.0%	0.0%	1.9%	0.0%	0.0%	0.0%	0.0%	0.8%
Pick-up/Drop-off person at school	0.0%	0.0%	0.0%	0.0%	8.5%	0.1%	0.0%	8.8%	0.0%	3.9%
Pick-up/Drop-off person at other	0.0%	0.0%	0.5%	0.0%	7.3%	0.1%	0.5%	2.1%	0.0%	3.1%
Other/missing	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.1%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 29 is the same as Table 28 except simple and complex tours have been split apart, and the percentages are by tour purpose (row percentages), rather than by mode (column percentage). Providing the data this way shows, among other things, how common trip chaining is by non-auto modes. Work subtours made by walking are less than half as common for complex tours (11%) as for simple (27%). The percentage of tours made by car or walk to transit by purpose is similarly small (< 2%) for both simple and complex tours. The exceptions are that 17.6% of simple tours made to a college or university are mainly done using the walk to transit mode, and increases to 19.5% for complex tours. However, for travel to college or a university the drive to transit mode is used for many more (on a percentage basis) complex tours than simple, 5.5% vs. 0.8%. This is reasonable based on the assumption that auto travel to transit covers longer distances than walking and therefore offers additional opportunities for intermediate stops. Also, by looking across tour complexity, it is seen that 77.5% of simple tours for the purpose of going work are made by driving alone compared to 52.2% of complex tours. Shared ride increases with increased work tour complexity from 8.6% to 33.8%.

Table 29: Main Tour Purpose by Main Tour Mode for Simple & Complex Tours

Tour Type	Main Tour Purpose	Car to transit	Walk to transit	Ferry	School bus	Shared ride	Drive alone	Bike	Walk	Other	Total
Simple Tour (one stop)	Work-based subtour	0.0%	0.5%	0.0%	0.0%	23.2%	48.2%	0.5%	27.0%	0.7%	100.0%
	Work	1.2%	7.5%	0.2%	0.0%	8.6%	77.5%	1.9%	2.8%	0.5%	100.0%
	Work - non-regular location	0.0%	1.1%	0.0%	0.0%	13.1%	81.8%	0.3%	3.4%	0.3%	100.0%
	School - college, university	0.8%	17.6%	0.0%	0.8%	13.0%	54.8%	5.4%	7.5%	0.0%	100.0%
	School - Daycare, K-12	0.0%	4.4%	0.0%	28.2%	39.7%	21.9%	1.1%	4.7%	0.0%	100.0%
	Incidental shopping	0.0%	1.0%	0.0%	0.0%	33.5%	57.3%	0.4%	7.7%	0.1%	100.0%
	Major shopping	0.0%	1.4%	0.0%	0.0%	49.0%	47.3%	0.0%	2.1%	0.3%	100.0%
	Personal business	0.0%	1.7%	0.0%	0.0%	33.5%	56.0%	1.2%	7.2%	0.4%	100.0%
	Medical	0.5%	3.8%	0.0%	0.0%	46.2%	46.2%	0.3%	1.6%	1.3%	100.0%
	Eat out	0.0%	0.9%	0.0%	0.0%	66.1%	23.2%	0.9%	8.9%	0.0%	100.0%
	Social/Recreational	0.0%	1.2%	0.0%	0.0%	48.3%	39.6%	1.3%	9.2%	0.4%	100.0%
	Civic activities	0.6%	1.5%	0.0%	0.0%	33.2%	55.1%	0.6%	8.7%	0.3%	100.0%
	Church activities	0.0%	0.7%	0.0%	0.0%	49.5%	46.8%	0.0%	2.7%	0.3%	100.0%
	Pick-up/Drop-off person at work	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	Pick-up/Drop-off person at school	0.0%	0.0%	0.0%	0.0%	86.1%	0.6%	0.0%	13.3%	0.0%	100.0%
	Pick-up/Drop-off person at other	0.0%	0.0%	0.0%	0.0%	93.6%	2.0%	0.2%	4.2%	0.0%	100.0%
	Other/missing	0.0%	0.0%	0.0%	0.0%	89.5%	10.5%	0.0%	0.0%	0.0%	100.0%
	Total	0.4%	3.3%	0.0%	0.7%	34.9%	51.8%	1.1%	7.4%	0.3%	100.0%
Complex Tours (multiple stop)	Work-based subtour	0.0%	2.5%	0.0%	0.3%	21.1%	65.0%	0.0%	11.0%	0.0%	100.0%
	Work	3.0%	6.8%	2.6%	0.1%	33.8%	52.2%	0.6%	0.7%	0.1%	100.0%
	Work - non-regular location	0.3%	1.2%	3.1%	0.0%	35.7%	58.3%	0.5%	0.9%	0.0%	100.0%
	School - college, university	5.5%	19.5%	2.3%	0.0%	38.3%	28.9%	3.9%	1.6%	0.0%	100.0%
	School - Daycare, K-12	0.6%	3.4%	1.1%	23.9%	60.2%	10.8%	0.0%	0.0%	0.0%	100.0%
	Incidental shopping	0.3%	2.0%	0.6%	0.0%	41.4%	52.9%	0.3%	2.6%	0.0%	100.0%
	Major shopping	0.8%	2.0%	0.8%	0.0%	58.6%	36.5%	0.5%	0.6%	0.2%	100.0%
	Personal business	0.6%	1.5%	0.7%	0.0%	52.3%	41.9%	0.5%	2.5%	0.0%	100.0%
	Medical	0.2%	3.1%	1.0%	0.0%	58.0%	36.6%	0.2%	0.8%	0.2%	100.0%
	Eat out	0.0%	2.4%	4.7%	0.0%	66.9%	23.7%	0.0%	2.4%	0.0%	100.0%
	Social/Recreational	0.9%	1.9%	1.6%	0.2%	69.7%	23.0%	0.4%	2.2%	0.1%	100.0%
	Civic activities	1.0%	1.4%	1.4%	0.0%	51.2%	42.9%	0.0%	2.1%	0.0%	100.0%
	Church activities	0.5%	0.0%	1.4%	0.0%	66.4%	31.8%	0.0%	0.0%	0.0%	100.0%
	Pick-up/Drop-off person at work	0.0%	0.0%	0.0%	0.0%	98.0%	2.0%	0.0%	0.0%	0.0%	100.0%
	Pick-up/Drop-off person at school	0.0%	0.0%	0.0%	0.0%	97.2%	0.9%	0.0%	1.9%	0.0%	100.0%
	Pick-up/Drop-off person at other	0.0%	0.0%	0.5%	0.0%	97.7%	1.4%	0.0%	0.5%	0.0%	100.0%
	Total	1.6%	3.9%	1.8%	0.4%	47.5%	42.7%	0.5%	1.5%	0.1%	100.0%

Table 30 shows the frequency of non-work trip purposes chained to work trips. For the 5,329 complex (multi-stop) HBW tours, 8,381 stops were made (excluding the work and home stops at the tour ends). The most common non-work activities done on these tours are incidental shopping (21.9%), change mode of travel (15.9%), personal business (13.4%) and pick-up/drop-off someone at school (12.6%). See Table 30 for all activities.

Table 30: Non-work Activities at Stops on Complex Home-Based-Work Tours

Main Purpose at Intermediate Stops	# of Stops	% All Stops
School - college, university	71	0.8%
School - Daycare, K-12	25	0.3%
Incidental shopping	1,836	21.9%
Major shopping	222	2.6%
Personal business	1,122	13.4%
Medical	196	2.3%
Eat out	573	6.8%
Social/Recreational	793	9.5%
Civic activities	84	1.0%
Church activities	51	0.6%
Pick-up/Drop-off person at work	151	1.8%
Pick-up/Drop-off person at school	1,052	12.6%
Pick-up/Drop-off person at other	872	10.4%
Change mode of travel	1,332	15.9%
Other/missing	1	0.0%
Total	8,381	100.0%

MODE CHOICE MODELING

The multinomial logit (MNL) model, and formulaic extensions like the nested logit model (where interactions between certain alternatives in an overall model is expressed) is used to analyze the discrete nature of transportation mode choice.[8] These models include choice specific attributes, decision-makers' characteristics, and built environment variables. These are called "random utility models" and are an application of microeconomic decision choice theory, which stipulates that people make choices among alternatives to maximize their perceived utility based on the individual's socio-demographic characteristics (income, automobile ownership, age, etc.) and on the characteristics of the competing choices (travel times, distances, etc.). Land use characteristics of trip origins and destinations such as population density, employment density, land use mix, and connectivity impact the costs of travel in terms of time and out

[8] This section was adapted from previous work developed by the authors for the Georgia Department of Transportation. Although significantly altered, a document making some related arguments exists in the final report for the SMARTRAQ project from the Georgia Institute of Technology and the Universtity of British Columbia.

of pocket costs for specific modes of travel. For example, low levels of density, mix, or connectivity increase the time requirements for all modes, but does so disproportionately for walking, which typically takes much longer. The probability of each alternative being chosen depends on its utility, relative to the utility of other alternatives. The mode with the greatest utility has the highest probability of being chosen. The result of estimation is the probability of each transportation mode choice being chosen through a simultaneous set of equations – each representing a specific mode of travel. Thus, the probability that a transportation mode is chosen (i) is given by:

$$\Pr ob_n(i) = \frac{e^{V_{in}}}{\sum_{i=1}^{i=j} e^{V_{in}}}$$

where $j \equiv$ the number of alternatives; e is the natural exponential function; V is the vector of estimated parameters and n represents person n. In our case we do not assume within-person taste variation, so the n is moot. For a full explanation see Ben-Akiva and Lerman, (1985) and Horowitz, Koppelman, and Lerman (1986). It should be noted that given the nonlinear nature of the probability function, V cannot have its ordinary least squares (OLS) interpretation of the marginal effect of X on Y. If a marginal effect is desired, the difference in probabilities when changing a variable x_i should be calculated, but interpreted with caution as the probability difference will not remain constant with different starting values for x_i (Greene 2000).

The method of estimation is not the same as OLS and, therefore, there is no R^2 to measure goodness of fit: rather than minimizing the squared errors (least squares) through the choice of V, the logistic regression maximizes a likelihood function in choosing V. There is, however, a Pseudo R^2 for logistic regression provided by McFadden (1974), the likelihood ratio index: $LRI = 1 - \frac{\ln L}{\ln L_0}$, (2)

where ln L is the log-likelihood function with all the model parameters from the model and ln L_0 is the log-likelihood function only including a constant term. As with the measure of R^2, this index is bounded between 0 and 1. This is referred to as Rho-squared in the model specifications in this document.

TOUR COMPLEXITY MODELS

The probability of taking a simple or complex tour, based on a set of socio-demographic, land use, and relative location of intermediate stops to home and work, is assessed for home based other and home based work tours below.

HOME BASED OTHER TOUR TYPE MODEL

This model was used to predict the type of home based other tour based on origin and destination land use, the presence and number of mid-tour destinations that are near (within one kilometer) or further from of home, and household demographics. A two-kilometer limit was also tried but the results were very much the same, therefore the more proximate travel area of one kilometer was retained. It was hypothesized that people living in areas with high accessibility will tend to make more tours with fewer stops in each tour and stops closer to home, while people living in areas with land use not conducive to local stops will tend to make longer tours that chain together more stops farther from home.

This model had 27 alternatives, consisting of each combination of the number of stops within one kilometer of home and the number of stops farther than one kilometer from home up to a total of six stops. The 27 alternatives were further nested into five groups:

- a single-stop tour, with the stop near home
- a multi-stop tour, with all stops near home
- a single-stop tour, with the stop NOT near home
- a multi-stop tour, with all stops NOT near home
- a multi-stop tour, with some stops near home and others not

Table 31 shows the frequency of tours by type. Nearly half of HBO tours were simple tours where the single destination is more than one kilometer from the survey participant's home. An additional 35.5% of tours make two or more stops more than one kilometer from home. Slightly less than 10% of tours consist of destinations only near home. The remaining 6.2% of tours include a combination of destinations near and far from home.

Table 31: Home Based Other Tour Frequencies

HOME BASED OTHER TOUR TRIP CHAIN TYPE	All HBO Tours	
Observations	10,721	
	Chosen	**% All HBO Tours**
NEST 1-One single stop, not near home		
1 stop, not within 1 km of home	5,216	48.7%
NEST 2- Multiple stops, none near home		
2 stops not within 1 km of home	1,944	18.1%
3 stops not within 1 km of home	1,057	9.9%
4 stops not within 1 km of home	464	4.3%
5 stops not within 1 km of home	212	2.0%
6 stops not within 1 km of home	126	1.2%
NEST 3-One single stop, near home		
1 stop, within 1 km of home	907	8.5%
NEST 4- Multiple stops, all near home		
2 stops within 1 km of home	91	0.8%
3 stops within 1 km of home	30	0.3%
4 stops within 1 km of home	4	0.0%
5 stops within 1 km of home	1	0.0%
6 stops within 1 km of home	1	0.0%
NEST 5- Multiple stops, some near home, some not		
1 near home, 1 other	296	2.8%
1 near home, 2 others	130	1.2%
1 near home, 3 others	77	0.7%
1 near home, 4 others	29	0.3%
1 near home, 5 others	15	0.1%
2 near home, 1 other	53	0.5%
2 near home, 2 others	37	0.3%
2 near home, 3 others	12	0.1%
2 near home, 4 others	7	0.1%
3 near home, 1 other	2	0.0%
3 near home, 2 others	4	0.0%
3 near home, 3 others	2	0.0%
4 near home, 1 other	3	0.0%
4 near home, 2 others	0	0.0%
5 near home, 1 other	1	0.0%

Table 32 presents the mode choice model for HBO tours. The log of the number of stops on HBO tours decreases in association with increasing mixed use and intersection density at the home location. The fraction of stops near home relative to all tour stops increases along with increasing mixed use and intersection density at the home location. In simple terms, the tours become less complex as there are more activity opportunities close to home, and at the same time the percentage of stops on complex tours that are close to home increase. A job density variable was also tried and found to be insignificant.

This model supports the hypothesis that people living in areas with higher intersection density and mixed land uses tend to make tours with fewer stops and stops closer to home. Although not shown in this analysis, those people will also tend to make more home-based tours (i.e. the data suggests that they tend to split their activities into more short tours instead of fewer long, complex tours). This type of behavior can also be related to mode choice, as such short tours are easier to make by walk or bike modes. Therefore, it is important to note that these results do not imply that the number of destinations visited near home declines with connectivity or mix. Rather the results suggest that the number and fraction of stops on a per tour basis decines due to simpler tour patterns.

In addition to land use effects, some significant socio-economic effects were also found in the model. People in households with higher car availability (more vehicles per driver) were found to be associated with more complex non-work tour trip chains with more stops, with fewer of those stops near to home. People with higher incomes and people over age 50 were associated with fewer stops close to home (these people also tend to be more likely to drive and less likely to walk). People in single-person households were associated with more stops close to home, perhaps indicating less complex travel patterns because they do not have to also accommodate the activity patterns of others in the household.

The various constants reflect the overall distribution of the choices – tours with many stops are less common than tours with fewer stops, and tours with a high percentage of stops close to home are less common than tours with more stops farther from home. The nesting logsum parameter of 0.58 indicates higher substitution within nests than between nests. For example, a tour with two stops far from home is more likely to switch to a tour with three stops far from home (an alternative in the same nest), than it is to switch to a tour with two stops near home (an alternative in a different nest).

The results also suggest that an increased number of vehicles per driver is associated with an increased number of stops per tour. This is probably a function of people being more pressed for time (kids and two worker households) and have a more diverse set of travel demand and more destinations. Conversely, the model also suggested that the fraction of stops near home declines as the number of household vehicles per driver increases, and the fraction of stops near home was found to be significantly lower for those with an annual income over $75,000. The fraction of stops near home was highly correlated with the number of vehicles per driver. The fraction of stops near home for single person households was larger than households with more than one person, which is likely due to the fact that single person households have more simple trip making patterns and are more often located in smaller dwellings in more walkable environments. The results also suggest that people over the age of 50 tend to have fewer stops near where they live, which could also be related with income, more cars, and fewer children in the home.

The overall Rho-squared of .475 is relatively high, indicating a very good fit for a disaggregate model estimation. It is also interesting to note that the land use variables are more statistically significant than the socioeconomic variables, as this is not typical in travel choice models. This result indicates the advantages of measuring land use variables at an observation specific scale – which more accurately describes land use unique to each participant. It also suggests very strong linkages between land use and trip-chaining characteristics. This is intuitively correct – the mixed use variable captures the spatial interaction of complementary destinations, which relates directly to tour making characteristics, whereas intersection density measures the degree to which these destinations can be directly linked in an efficient manner.

Table 32: Home Based Other Tour Type Model

NON-WORK TOUR TRIP CHAIN TYPE		
Land use variables	**Coefficient**	**T-stat**
LN(number of stops)- home location mixed use	-0.1703	-4.0
LN(number of stops)- home location intersection density	-0.2285	-6.4
Fraction of stops near home- home location mixed use	1.143	13.1
Fraction of stops near home- home location intersection density	0.788	10.9
Other variables	**Coefficient**	**T-stat**
2 stops- constant	-1.91	-17.4
3 stops- constant	-2.858	-18.0
4 stops- constant	-3.924	-19.9
5 stops- constant	-4.977	-21.5
6 stops- constant	-5.734	-22.1
Fraction of stops near home	-2.544	-10.1
LN(number of stops)*HH vehicles/driver	0.3053	2.1
Fraction of stops near home*HH vehicles/driver	-0.8777	-3.7
Fraction of stops near home*HH income over $75K	-0.5297	-3.3
Fraction of stops near home*Single person HH	0.4575	2.9
Fraction of stops near home*Age over 50	-0.5906	-4.8
Nesting logsum parameter	0.5763	23.3
Model Fit		
Final log-likelihood	-18566.5	
Rho-squared (0 coefficients)	0.475	
Rho-squared (constants only)	-0.015	

HOME BASED WORK TOUR TYPE MODEL

This model predicted the type of home based work tour (simple or complex) based on origin and destination land use, the presence of mid-tour destinations that are near (within 1 km) or further from of home and work, household demographics and travel time. Land use at the tour origin (home) and primary destination (work) was hypothesized to play a significant role in determining whether mid-tour stops are made on the way to or from work, and/or also from during work, as well as determining where those stops are made.

There are 16 alternatives in the model, each combination of:

- 0 vs. 1+ stops made to/from work within 1 km of home
- 0 vs. 1+ stops made to/from work within 1 km of work
- 0 vs. 1+ other stops made on way to/from work
- 0 vs. 1+ stops made during work (work-based subtours)

It is a nested model, with the 16 alternatives nested into 4 groups:

- No stops to, from or during work
- Stop(s) to or from work only
- One or more subtours during work (WOW), without any stops between home and work/ work and home
- Stops both to/from and during work

Table 33 shows the frequency of tours by type. Over half of home based work tours are simple tours, no stops are made either on the way to or from work.

Table 33: Home Based Work Tour Frequencies

HOME BASED WORK TOUR TRIP CHAIN TYPE	**All HBW Tours**	
Observations	**9,299**	
	Chosen	
	N	% All Work Tours
NEST 1-No stops to, from or during work		
No stops	4,765	50.3%
NEST 2-Stop(s) to or from work only		
Within 1km of home only	52	0.6%
Within 1 km of work only	151	1.6%
Other stop(s) only	2,635	28.3%
Near home & near work	6	0.1%
Near home & other	30	0.3%
Near home & other	252	2.7%
Near home, near work & other	1	0.0%
NEST 3-One or more tours during work		
Stops during work only	705	7.6%
NEST 4-Stops both to/from & during work		
Near home & during work	12	0.1%
Near work & during work	71	0.8%
Other stop(s) & during work	539	5.8%
Near home & near work& during work	0	0.0%
Near home & other & during work	8	0.1%
Near work & other & during work	72	0.8%
All 4 types	0	0.0%

Increases in mixed use, intersection density and retail floor area ratio at the home and/work location were estimated to increase the likelihood of a home based work tour containing a nearby (within one kilometer) secondary tour destination (Table 34). The likelihood of stops occurring near home on a home based work tour was found to increase with higher retail floor area ratios at the home location. Increases in work location mixed use and intersection density was also found to increase the likelihood of a work-based subtour (WOW). However, WOWs were less likely with increases to the home location's mixed use level. This suggests that people trade off the need for a mid day trip of they can accomplish their errands near to where they live. The opposite signs on these variables indicate a strong substitution effect between making stops near home on the way to or from work versus making stops near work during work.

Other, non-land use variables also were significant in the model. "No Stop" tours (NEST 1) were estimated to be less likely when annual household income exceeds $75,000 and the number of household vehicles per driver increases. This is a typical result, with higher income people with greater car availability tending to participate in more activities and have more complex tour patterns.

Travelers from households with three or more people were associated with a higher likelihood of making stops near home, but were less likely to make them near work while traveling to or from work, and also less likely to make WOWs. Some of these extra stops for larger households may include dropping off children at school or daycare near home.

People with longer home to work drive times were associated with a greater likelihood to make stops that are not near (greater than one kilometer) from home or work. This is logical, as people with longer commutes pass a greater number of places to make stops that are not near home or work.

Increases in work-based subtours were associated with people from households earning over $75,000 per year; when the household income was under $35,000 a decrease was found. This is again a typical finding, since people in higher income jobs tend to have more flexibility to leave work during work hours. Little difference was detected when the distance used for defining "nearby" bus stops was increased to two kilometers from home and work. An employment density variable was also tried and found to be insignificant. The constants reflect the overall relative frequency that the alternatives are chosen, or the net of all land use and socio-demographic variables. As in the non-work tour type model, the nesting parameter is significantly different from 1.0 (a multinomial logit model), indicating greater substitution between alternatives within the same nest than across nests. The overall Rho-squared of 0.521 again is relatively high, indicating a very good fit, for a disaggregate model estimation.

Table 34: Home Based Work Tour Type Model

HOME BASED WORK TOUR		
Land use variables	**Coefficient**	**T-stat**
Stops near home- home location mixed use	0.3764	2.9
Stops near home- home location intersection density	0.4997	4.5
Stops near home- home location retail floor area ratio	0.0791	1.1
Stops near work- work location mixed use	0.2838	4.8
Stops near work- work location intersection density	0.0966	2.6
Stops near work- work location retail floor area ratio	0.1535	4.5
Stops during work- home location mixed use	-0.1980	-2.1
Stops during work- work location mixed use	0.2652	3.3
Stops during work- work location intersection density	0.1488	3.3
Other variables	**Coefficient**	**T-stat**
No stops- HH income over $75K	-0.4323	-3.4
No stops- HH vehicles per driver	-1.049	-3.8
Stops near home- constant	-6.367	-15.2
Stops near home- HH has 3+ persons	0.4705	2.3
Stops near work- constant	-5.248	-13.7
Stops near work- HH has 3+ persons	-0.257	-2.7
Other stops- constant	-3.252	-7.3
Other stops- Driving time home to work (min)	0.04186	8.3
Stops during work- constant	-5.136	-6.9
Stops during work- HH has 3+ persons	-0.7359	-4.5
Stops during work- HH income under $35K	-0.778	-3.3
Stops during work- HH income over $75K	0.5364	3.2
Near home & near work- constant	2.181	4.0
Near home & other stop- constant	1.821	4.3
Near home & during work- constant	2.13	4.8
Near work & other stop- constant	2.685	7.1
Near work & during work- constant	2.586	6.6
During work & other stop- constant	1.869	5.1
Stops for 3 of the 4 types	-2.342	-5.7
Stops for all 4 types	-10	const
Nesting logsum parameter	0.4741	7.6
Model Fit		
Final log-likelihood	-12361.6	
Rho-squared (0 coefficients)	0.521	
Rho-squared (constants only)	0.028	

TOUR-BASED MODE CHOICE MODELING STRUCTURE

Mode choice was modeled for three types of tours:

1. Home based work (HBW)
2. Home based other (HBO)
3. Work based other back to work (WOW)

Three separate models, based on tour complexity, were developed for both the home-based-work and home-based other tours:

1. All tours, using Complex LOS[9] (combining the data from models 2 and 3 below);
2. Simple tours (visit one destination and return home); and
3. Complex tours (visit more than one destination), using Complex LOS (time and cost variables for the entire trip chain).

The work sub-tour model, WOW, was only developed for all tours. There are too few WOW tours in total and very few complex ones; therefore separate simple and complex tour models were not created. The models included the following mode choices and related availability assumptions:

1. Drive alone: available to only licensed drivers in households owning 1 or more vehicles
2. Shared ride: available for all observations
3. Transit (walk to bus): available if there is a transit connection for every trip in the chain, but allowing intervening walk trips for trips in the chain that are 1.5 miles or less. Availability is determined at the traffic analysis zone level.
4. Bike:
    - Available only for tours up to 40 miles round trip distance
    - Speed is 12 mph (5 minutes per mile)
5. Walk:
    - Available only for tours up to 10 miles round trip distance;

[9] Complex level of service (LOS) captures the distance to transit, and travel distance/time for auto, walk, bike for all of the destinations visited in the tour.

    - The access and egress distances for walk to transit are the distances to the nearest bus stop from the origin and destination parcels;
    - Speed is 3 mph (20 minutes per mile)

6. Ferry, park and ride, school bus and taxi were not included in the mode choice set due to a lack of observations.

The following cost assumptions were also made:

- Parking cost is the daily destination parking cost for work tours and twice the hourly destination parking cost for non-work tours.
- Car operating cost is 12 cents per mile.
- Shared ride costs are divided by 2.0 for work tours and by 2.5 for non-work tours
- Distances for the auto mode, walk mode and the bike mode are based on shortest-path, road-network-based estimates
- Transit times are based on the path-finding procedures implemented by PSRC within EMME/2, to find the least generalized-cost transit path between any two points. (Note that many origin-destination pairs have no transit service available between them, so the transit alternative is not available in the model for those cases.)

HOME BASED OTHER (NON-WORK) TOUR

Table 35 describes the basic characteristics of the home based other (HBO) tours. These tours made up 50.9% of all tours (N= 20,543). All five modes (drive alone, shared ride, transit (walk to bus), bike and walk) were represented in the HBO tour set. Somewhat more than half (57.2%) of HBO tours were simple tours, consisting of a single non-work destination and a home origin. Compared to simple tours, a smaller precentage of multi-stop tours had drive alone, bike and walk as a main mode, and a larger percentage were by shared ride and transit. In simple tours when drive alone was an available option it was chosen 49.5% (2786/5623) of time, whereas for multi-stop tours it was chosen for 38.9% (1661/4274) of trips.

Table 35: Home Based Other (non-work) Tour Models Descriptives

TOURS FROM HOME TO OTHER	All Tours			Simple Tours			Multi-Stop Tours		
Observations	10,475			5,992	57.2%		4,483	42.8%	
Mode	**Chosen**		**Available**	**Chosen**		**Available**	**Chosen**		**Available**
Drive alone	4,447	42.5%	9,897	2,786	46.5%	5,623	1,661	37.1%	4,274
Shared ride	5,281	50.4%	10,475	2,631	43.9%	5,992	2,650	59.1%	4,483
Transit (walk to bus)	130	1.2%	4,894	65	1.1%	2,875	65	1.4%	2,019
Bike	72	0.7%	9,453	53	0.9%	5,683	19	0.4%	3,770
Walk	545	5.2%	4,924	457	7.6%	3,639	88	2.0%	1,285

Results from the mode choice model of HBO tours are presented in Table 35. All models include variables which are significant, or nearly significant, in at least one or more of the models (all, simple and complex tours). Variables where the t-statistic is less than 1.96 (corresponding to a 95% confidence interval) were included in the models based on judgment. If a variable was signed consistently with other like-variables and contributed to the model it was typically left in.

Higher travel time and mode costs associated with nearly all other travel modes decreased their usage relative to the drive alone option. Relative to the drive alone option, land use variables increases are associated with increased relative utility of transit, bike and walk in the model (Table 36). Shared ride is not present in the land use variable set because land use variables were not signficant. The choice of whether to drive alone or share a ride appears to be more a function of trip purpose and household size than of land use. This is consistent with results from earlier research on land use and travel choice in the Central Puget Sound Region (Frank and Pivo in 1994).

Relative to driving alone, simple transit tours were associated with increases in origin intersection density and destination retail floor area. For complex tours transit usage increased relative to driving alone with destination mixed use, and, for simple tours, destination retail floor area as well. Relative utility of bicycling to work increased with intersection density for simple tours. Origin mixed use and the combined origin/destination intersection density (constrained to have the same coefficient) increased in relation to increased walking for complex tours. Origin/destination intersection density was also significant for simple walk tours. Origin/destination retail floor area ratio[10] was significant for all walk tours (simple and complex tours combined). Also, transit usage increased in relation with increases in origin and destination mixed use and intersection density.

Driving alone and shared ride increased in association with the ratio of available automobiles to drivers in a household, and if the tour included a shopping stop (simple tours) or picking up/dropping off someone (multi-stop tour). Shared ride also increased along with simple/complex multi-stop tour alternative-specific constants (ASC) and with households of three or more people. Alternative-specific constants are the constants reflecting the relative choices net of all other variables in the model, capturing all other differences between the modes – convenience, safety, reliability, etc. Transit and bike use decreased, and walking increased, in association with the addition of simple/complex tour ASC. As would be expected, no household automobiles was found to be associated with increased transit use. For people over 50 years old, the transit usage variable was negatively signed, and this was consistent with walk and bike variables, but these were not significant. Generally, the more physical exertion a mode required, the less likely older people were to use it. One interesting result is that both biking and walking increased when the tour included a social or recreational purpose.

[10] Retail floor area ratio (FAR) is the ratio of total retail building floor area divided by the total parcel land area on which it sits.

Table 36: Home Based Other (Non-Work) Tour Models

TOURS FROM HOME TO OTHER	All Tours		Simple Tours		Multi-Stop Tours	
Time and cost variable	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**
Auto and transit cost ($)	-0.06479	-6.5	-0.08361	-6.4	-0.03452	-2.2
Auto and transit- in-vehicle time (min)	-0.013	*	-0.013	*	-0.013	*
Walk and transit- out-of-vehicle time (min)	-0.03112	-19.9	-0.03316	-18	-0.02535	-8.1
Bike- time (min)	-0.02539	-5.8	-0.0247	-4.6	-0.0272	-3.6
Land use variables	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**
Transit- origin mixed use	0.1625	1.1	0.1701	0.7	0.1552	0.7
Transit- destin. mixed use	0.262	1.6	0.04804	0.2	0.6872	2.5
Transit- origin intersection density	0.2198	1.6	0.3936	2.1	0.2701	1.2
Transit- destin. intersection density	0.1801	1.7	0.1849	1.6	0.1262	0.7
Transit- destin. retail floor area ratio	0.2835	4.2	0.1831	2.8	0.4252	5.3
Bike- origin intersection density	0.2872	1.9	0.308	1.8	0.2524	0.9
Walk- origin mixed use	0.1647	2.2	0.1466	1.7	0.3397	1.9
Walk- origin/destin intersection density**	0.2254	6.5	0.1791	4.4	0.4427	5.6
Walk- origin/destin retail floor area ratio**	0.08092	2.4	0.07175	1.5	0.0809	1.5
Other variables	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**
Drive alone- HH cars/driver	2.207	9.7	1.83	6.7	3.229	7.3
Drive alone- shopping stop(s)	0.8357	6.8	0.9795	6.6	0.3564	1.5
Drive alone- pick up/drop off stop(s)	-1.456	-2.5	N.A.		-2.436	-3.5
Shared ride- simple tour ASC	0.9812	4.4	1.403	5.4	N.A.	
Shared ride- complex tour ASC	1.161	7.3	N.A.		1.123	4.4
Shared ride- HH cars/driver	1.185	6.1	0.8365	3.6	2.16	5.6
Shared ride- single person HH	-1.52	-18.1	-1.501	-13.4	-1.589	-12.2
Shared ride- 3+ person HH	0.6119	13	0.5886	9.8	0.6576	8.6
Shared ride- shopping stop(s)	0.3139	2.6	0.3642	2.4	0.01679	0.1
Shared ride- pick up/drop off stop(s)	2.391	4.4	N.A.		2.388	4.0
Transit- simple tour ASC	-0.9491	-2.8	-1.085	-2.6	N.A.	
Transit- complex tour ASC	-0.3979	-1.1	N.A.		-0.3206	-0.5
Transit- no cars in HH	2.266	7.3	2.62	5.9	1.916	4.2
Transit- age over 50	-0.2878	-1.2	-0.5091	-1.5	-0.2633	-0.7
Transit- HH income over $75K	-0.8674	-2.2	-0.7948	-1.5	-1.172	-1.9
Bike- simple tour ASC	-1.01	-3.1	-1.354	-3.6	N.A.	
Bike- complex tour ASC	-0.7731	-1.8	N.A.		-0.1088	-0.2
Bike - age over 50	-0.7857	-3.1	-0.7298	-2.5	-0.963	-2.0
Bike - social/recreation (stops)	0.7333	3.0	0.6768	2.4	0.936	1.9
Walk- simple tour ASC	2.488	10	2.289	7.8	N.A.	
Walk- complex tour ASC	2.991	9.9	N.A.		2.961	5.4
Walk- social/recreation stop(s)	0.8046	6.3	0.759	5.3	0.8219	2.8
Walk - age over 50	-0.4852	-4.2	-0.4114	-3.3	-0.722	-2.6
Model Fit						
Final log-likelihood	-7211.2		-4619.4		-2537.5	
Rho-squared (0 coefficents)	0.475		0.437		0.541	
Rho-squared (constants only)	0.216		0.170		0.280	
Values of time* **						
Auto and transit- in-vehicle time ($/hr))	$ 12.04		$ 9.33		$ 22.60	
Walk and transit- out-of-vehicle time ($/hr))	$ 28.82		$ 23.80		$ 44.06	
Bike- time ($/hr)	$ 23.51		$ 17.73		$ 47.28	

Notes
* Constrained for reasonableness. It is typical to obtain reasonable transit coefficients for only home based work tours.
** Constrained coefficient for origin/destination to the be same.
*** Ratio of mode specific time coefficients to auto and transit cost coefficient
N.A. = not applicable

ELASTICITIES INTRODUCTION

Demand elasticities are provided below to convey the likely associations between changes in land use, travel time, and travel costs and mode choice. Elasticities are derived from the mode choice model described in the previous section. The model was run for each variable presented below. Each run held all variables constant except one which was increased by 10%. The resulting change in mode share was compared to the base case (as supplied by the survey data). Demand elasticities were then computed. Elasticities are equal to the percent change in demand (for a particular mode) resulting from a change in the input variable (e.g. vectors of land use, time or cost)[11]. Results across variables are approximately additive, meaning the collective effect of changes in land use, time, or cost can be summed. This is important when considering the policy implications of transportation investments that impact travel time and costs and land use changes that are also related with mode choice.

Direct elasticities are shown in bold in tables below for the mode(s) that contain a given input variable in their utility functions (as shown in the models presented above). For example, the "home-mixed use index" variable is contained in the transit and walk utility functions. They are specific variables in the mode choice model—"transit origin-mixed use index" and "walk origin-mixed use index". *Cross-elasticities* also result when the choice of a particular mode has an additional effect on another mode. In the case of the "home-mixed use index" example, drive alone, carpool and bicycle have cross-elasticities which is when the choice of any one of these modes of travel resulting from the changes in the direct elasticity have a subsequent impact on share of trips predicted on other modes. You would expect specific patterns of cross elasticities to emerge – such as trade offs between driving alone and carpooling for longer trips made by households in auto dependent land use patterns. There are only cross-elasticities for the land use variables for the car modes, since none of these variables are in the car mode utilities.

The size of cross-elasticities is very sensitive to initial mode shares. For example, the cross-elasticities for changes in the auto time and cost are large because auto has a large initial mode share. The reasons for the small cross-elasticities for the car modes are

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[11] More specifically, elasticities are equal to the percent change in demand due to change in input variable divided by the percent change in input variable.

that a big change in transit or walk mode share won't make much of a difference in car mode share. For example, if the car mode share is 0.90 then the non-car mode share is only 0.10. If the non-car mode share increased by 10% to 0.11, it would only mean about a 1% drop in car mode share (from 0.90 to 0.89). The same reasons are true in reverse for the large cross elasticities for transit, bike and walk for a change in auto time or cost.

If the variable applies to more than one mode (e.g. intersection density is for multiple modes in some models) then the elasticities are actually a combination of direct elasticities (people switching to that mode because the mode's utility has changed) and cross-elasticities (people switching to another mode because that other mode's utility has changed). For example, if destination retail floor area ratio increases, more people may choose to walk; but even more will switch to transit for non-work travel.

HBO ELASTICITIES RESULTS

Elasticities are shown in Table 37 for ten input variables and five modes. Six land use variables at either the home or destination and four time or cost variables are shown.

Car Use

Increasing the input variables has the smallest associated change in demand for driving alone and carpooling, as compared (on a percentage basis) to other modes. This is reflective of the dominant share of travel in cars and the low likelihood of substitution with other modes. Driving alone and carpooling demand changes have the highest associated changes with increases in auto-fuel and parking costs. As those costs increase, demand for driving alone decreases (-0.06) and carpooling increases (0.04).

- A 10% increase in auto-fuel and parking costs is associated with a reduction in drive alone by 0.6%, an increase in carpooling of 0.4%, an increase in transit use by 1.5%, an increase in bicycling by 1.4%, and an increase in walking 0.6%.
- Increases or decreases in auto travel time can have relatively large associations with changes in demand for non-auto modes.
- Increasing auto travel time by 10% was associated with an increase in transit ridership by 2.3%, an increase in bicycling by 2.8%, and an increase in walking

by 0.7%. Conversely, reductions in auto travel time would be expected to be associated with lower levels of transit, bicycling, and walking for non-work travel.

Transit

Changes in levels of destination retail floor area ratio and mixed use are associated with the highest changes in demand for transit, as compared to other modes, for non-work travel. Transit demand was also positively associated with the level of intersection density at the home and destination locations.

- Increasing a tour's destination retail floor area ratio and level of land use mix by 10% was associated with increased levels of transit demand by 3.4% and 3% respectively.
- Increasing home and destination intersection densities by 10% were associated with a 2.4% and 2.3% respective increase in transit demand.

Transit use was nearly three times as sensitive to in-vehicle travel time increases than to fare cost increases (-0.23 and -0.08 respectively), likely indicating a consumer premium placed on travel time over cost.

- Increasing transit in-vehicle travel times by 10% was associated with decreased transit demand by 2.3%, compared to a 0.8% reduction for a 10% fare increase.

Walking

The likelihood of walking was most positively related with increases in intersection density over other land use variables. Home (tour-end) mixed use was also positively associated with the likelihood of walking. The following elasticities were found between land use variables and walking:

- Increasing street network connectivity at the home location by 10% was associated with a 2.8% increase in walking, and increasing street network connectivity by 10% at the destination was associated with an additional 2.7% increase in walking for non-work tours.

- Increasing land use mix at the home location by 10% was associated with a 0.6% increase in walking for home based non-work tours.

Bicycling

Elasticities reported for bicycle travel are based on a limited dataset (very few bike trips were reported) resulting in limited variation in the land use patterns from which observations live. This limited sample size also leaves open the possibility for anomalies in the data to overwhelm what otherwise would be a more representative sample. Increasing the level of land use mix and increasing auto-fuel and parking costs have nearly equivalent demand elasticities for bicycle use (0.15 and 0.14 respectively). Otherwise stated:

- Increasing the level of land use mix where people live by 10% was associated with a 1.5% increase in bicycling demand for non-work travel;

Increasing auto travel time was associated with less bicycling for non-work travel.

- Increasing auto travel time by 10% was associated with a 2.8% reduction in bicycling for non-work travel.

While increases in land use mix were associated with increases in bicycling, increases in other land use variables were associated with *less* bicycle use (with demand shifting to transit and/or walk). An increased range of land uses offers the bicyclists more destinations. The small but negative association in bicycle use with other changes in land use, such as increase retail floor area ratio or increase intersection density is most likely associated with increasing demand for walking over cycling in these types of environments.

Table 37: Home based Other Tour – Mode Elasticities (HBO, non-work tours)

Mode	Drive Alone	Carpool	Transit	Bike	Walk
Home-Mixed use index	-0.01	-0.01	**0.08**	0.15	**0.06**
Destination-Mixed use index	0.00	0.00	**0.30**	-0.02	-0.01
Home-Intersection density	-0.02	-0.02	**0.24**	**-0.08**	**0.28**
Destination-Intersection density	-0.02	-0.02	**0.23**	-0.08	**0.27**
Home-Retail floor area ratio	0.00	0.00	-0.01	-0.02	**0.04**
Destination-Retail floor area ratio	-0.01	-0.01	**0.34**	-0.02	**0.03**
Auto-Travel time	**-0.01**	**-0.01**	0.23	0.28	0.07
Transit-In-vehicle time	0.00	0.00	**-0.23**	0.00	0.00
Transit-Fare	0.00	0.00	**-0.08**	0.00	0.00
Auto-Fuel and parking cost	**-0.06**	0.04	0.15	0.14	0.06

HOME BASED WORK TOUR

Table 38 summarizes the characteristics of the home based work (HBW) tours. Home based work (HBW) tours are 42.4% of all tours (N= 20,543). All five modes (drive alone, shared ride, transit (walk to bus), bike and walk) are represented in the HBW tour set. More than half (58.7%) of HBW tours in the dataset were simple tours consisting of a single work destination and a home origin. Compared to simple tours a smaller percentage of multi-stop tours had drive alone, transit, bike and walk as a main mode, and larger percentage were by shared ride, at least in part due to the need to pick-up passengers.

Table 38: Home Based Work Tour Models Descriptives

TOURS FROM HOME TO WORK	All Tours			Simple Tours			Multi-Stop Tours		
Observations	8,707			5,112	58.7%		3,595	41.3%	
Mode	**Chosen**		**Available**	**Chosen**		**Available**	**Chosen**		**Available**
Drive alone	5,924	68.0%	8,392	4,067	79.6%	4,882	1,857	51.7%	3,510
Shared ride	1,956	22.5%	8,707	436	8.5%	5,112	1,520	42.3%	3,595
Transit (walk to bus)	551	6.3%	6,266	369	7.2%	4,133	182	5.1%	2,133
Bike	115	1.3%	6,573	96	1.9%	4,188	19	0.5%	2,385
Walk	161	1.8%	1,710	144	2.8%	1,343	17	0.5%	367

Results from the mode choice model of HBW tours are presented in Table 39. Higher travel time and mode costs associated with each mode were found to be associated with decreased usage relative to the drive alone option. This was particularly the case in association with walk and transit – walk time. Compared to driving alone to work, land use variables increased the relative utility of transit, bike and walk. Relative to driving alone to work, the utility of walking to work for simple tours increased with mixed use, retail floor area ratio (FAR) and intersection density at the origin and retail FAR at the destination. Only intersection density at the origin was associated with a significant increase in the relative utility of walking to work for complex tours as opposed to driving alone. Overall, land use was associated with increased relative utility of non-SOV options for simple tours. Relative to driving, transit use was significantly associated with origin mix and intersection density and destination retail FAR – which had the stongest value of any land use variable in the model. Increased retail FAR at the destination was associated with increased relative utility of taking transit to work for multi-stop tours. The relative utility of biking to work as opposed to driving increased significantly in association with intersection density at the origin.

Overall, the land use variables presented in the model were associated with utility increases for walking, transit, and biking to work relative to the car; but only for simple tours. Multi-stops tours were less a function of land use for work related travel. As was the case with non-work tours, shared ride was not present in the land use variable set. The choice of whether to drive alone or share a ride to work is likely to be associated more with the presence of specific TDM incentives and parking costs.

The likehood of driving alone increased dramatically in association with the ratio of available automobiles to drivers in a household and if the tour included a shopping stop. And by definition, the opposite is true if the tour included picking up/dropping off someone for multi-stop tours. Commuters from single person households were less likely to carpool and those that live in houseolds with three or more persons were more likely to pick up and drop off passengers to and from work – which by definition is a multi-stop tour. Shared ride also increased in association with multi-stop tour alternative-specific constants (ASC)– but not for households with three or more people as was the case with non-work tours. As noted previously, ASCs reflect the relative choices that net from all other variables in the model, capturing all other differences between the modes – convenience, safety, reliability, etc. Transit use and walking increased in association with simple/complex tour ASC. As would be expected, no household automobiles resulted in increased transit use relative to driving. However, the odds of taking transit were significantly less than driving alone for those that earn over $75,000 per year. People between 25 and 50 years old were more likely to bike and walk to work than those that are older and men are more likely to walk or bike to work than women.

Table 39: Home Based Work Tour Models

TOURS FROM HOME TO WORK	All Tours		Simple Tours		Multi-Stop Tours	
Time and cost variable	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**
Auto and transit cost ($)	-0.0792	-8.3	-0.07379	-6	-0.08962	-5.7
Auto and transit- in-vehicle time (min)	-0.01245	-5.0	-0.00879	-1.7	-0.01332	-4.4
Walk and transit- walk time (min)	-0.03837	-12.4	-0.03617	-11.1	-0.05136	-4.6
Transit wait time (min)	-0.02066	-1.7	-0.04661	-2.9	0.01137	0.5
Transit- transfers	-0.1259	-3.0	-0.2035	-2.5	-0.1167	-2.1
Bike- time (min)	-0.01926	-7.3	-0.01572	-5	-0.0336	-4.6
Land use variables	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**
Transit- origin mixed use	0.1916	2.4	0.1871	1.9	0.1673	1.2
Transit- origin intersection density	0.2848	3.9	0.3013	3.4	0.1927	1.5
Transit- destin. intersection density	0.08429	1.8	0.06908	1.3	0.1198	1.4
Transit- destin. retail floor area ratio	0.309	7.7	0.37	7.3	0.1671	2.4
Bike- origin intersection density	0.5342	5.0	0.5978	5.2	0.2548	1.0
Walk- origin mixed use	0.3326	2.6	0.354	2.6	-0.4153	-0.7
Walk- origin intersection density	0.4763	3.7	0.376	2.7	1.437	2.3
Walk- origin retail floor area ratio	0.1964	2.5	0.1604	1.7	0.3833	0.8
Walk- destin. retail floor area ratio	0.1245	1.5	0.2187	2.4	-0.3277	-1.1
Other variables	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**
Drive alone- HH cars/driver	4.819	19.0	4.809	16.5	4.919	9.6
Drive alone- shopping stop(s)	0.4456	4.2	N.A.		0.4073	3.7
Drive alone- pick up/drop off stop(s)	-1.705	-5.2	N.A.		-2.559	-6.7
Shared ride- simple tour ASC	0.9812	4.4	1.403	5.4	N.A.	
Shared ride- complex tour ASC	2.169	9.1	N.A.		1.121	2.7
Shared ride- HH cars/driver	0.8411	3.4	0.3762	1.3	1.972	4.2
Shared ride- single person HH	-0.8084	-5.2	-0.8425	-3.2	-0.9127	-4.5
Shared ride- 3+ person HH	0.02512	0.3	0.1186	1.0	-0.07232	-0.6
Shared ride- pick up/drop off stop(s)	3.16	10.7	N.A.		3.174	10.6
Transit- simple tour ASC	2.476	8.2	2.977	7.1	N.A.	
Transit- complex tour ASC	3.009	8.6	N.A.		2.676	4.5
Transit- no cars in HH	1.106	3.9	0.9554	2.9	1.779	2.6
Transit- HH income over $75K	-0.9744	-6.4	-1.181	-5.8	-0.6034	-2.5
Bike- simple tour ASC	-0.3058	-0.8	-0.2038	-0.5	N.A.	
Bike- complex tour ASC	-0.4454	-1.0	N.A.		-0.9122	-0.7
Bike - age 25 to 50	0.7343	3.0	0.5294	2.1	2.347	2.3
Bike - male	1.169	5.1	1.146	4.5	1.247	2.3
Walk- simple tour ASC	3.241	8.8	3.319	8.3	N.A.	
Walk- complex tour ASC	3.627	6.8	N.A.		2.868	2.3
Walk- social/recreation stop(s)	1.265	1.8	N.A.		1.967	2.2
Walk - age 25 to 50	0.6191	2.6	0.5405	2.1	1.331	1.7
Walk - male	1.112	4.8	1.055	4.4	1.382	1.8
Model Fit						
Final log-likelihood	-3990.1		-2426.3		-1477.1	
Rho-squared (0 coefficents)	0.639		0.644		0.651	
Rho-squared (constants only)	0.443		0.285		0.521	
Values of time *						
Auto and transit- in-vehicle time ($/hr)	$ 9.43		$ 7.15		$ 8.92	
Walk and transit- walk time ($/hr)	$ 29.07		$ 29.41		$ 34.39	
Transit wait time ($/hr)	$ 15.65		$ 37.90		$ (7.61)	
Transit- transfers ($)	$ 1.59		$ 2.76		$ 1.30	
Bike- time ($/hr)	$ 14.59		$ 12.78		$ 22.49	

Notes
* Ratio of mode specific time coefficients to auto and transit cost coefficient
N.A. = not applicable

HOME BASED WORK ELASTICITY RESULTS

Elasticities are shown in Table 40 between land use, travel cost, and travel time variables and five modes of travel for work related purposes. Five land use variables at either the home or destination and four time or cost variables are shown.

Car Use

As was the case for home based other (HBO) tours, driving alone and carpooling demand changes were associated with increases in auto-fuel and parking costs. Increased costs were associated with a decreased demand for driving alone (-0.07) and increased demand for carpooling (0.08).

- Decreases of 0.7% in demand for driving alone and increases of 0.8% in carpooling demand were associated with auto-fuel and parking costs increases of 10%.

When comparing home based work and home based other tours, a 10% auto travel time increase was associated with a greater change in drive alone home based work travel (-0.3% vs., -0.1% respectively), as was the case with home intersection density (-0.4% vs. -0.2% respectively) and work/destination retail floor area ratio (-.3% vs. -0.1%).

Increases in any of the land use or cost related input variables had the smallest associated change on the demand for driving alone and carpooling, as compared (on a percentage basis) to the other modes. This is reflective of the dominance of these modes and the real and perceived inability to substitute driving for other modes of travel.

Increased drive alone travel time to work and auto-fuel and parking costs were associated with increased demand for transit, bike and walk.

- Extending drive alone commute time by 10% was associated with an increased transit demand of 3.1%, bike demand by 2.8% and walk demand by 0.5%.

- Increasing the cost of fuel and parking costs by 10% for the solo commuter was associated with an increased transit demand of 3.71%, bike demand by 2.7% and walk demand by 0.9%.

Transit

Like with HBO tours, transit demand increases were associated with increased destination retail floor area ratio. However, the level of associated change for work related transit use was higher than for non-work related travel (0.43 vs. 0.34 respectively).

- Increasing destination retail floor area ratio by 10% was associated with a 4.3% increase in demand for transit.

Walking

Land use measures at the home location were found to be associated with demand for walking to work. Increases to each of the following land use variables had elasticities associated with increased walking to work: intersection density (0.43), mixed use (0.22), and retail floor area ratio (0.12):

- A 10% increase in home-intersection density was associated with a 4.3% increase in walking to work.
- A 10% increase in home mixed use was associated with a 2.2.% increase in walking to work.
- A 10% increase in home retail floor area ratio was associated with a 1.2% increase in walking to work.

Bicycling

As was the case with non-work travel, bicycling was found to have inconsistent relationships with measures of land use. While increased street connectivity at the home based work tour end was found to be associated with the largest demand elasticity for biking to work, increases in the other land use variables were associated with decreased demand for biking to work:

- Increasing intersection density at the home location by 10% was associated with an 8.4% increase in the demand for biking to work.

Table 40: Home based Work (HBW)

Mode	Drive Alone	Carpool	Transit	Bike	Walk
Home-Mixed use index	-0.01	-0.01	**0.09**	-0.07	**0.22**
Home-Intersection density	-0.04	-0.04	**0.26**	**0.84**	**0.43**
Work-Intersection density	-0.01	-0.01	**0.14**	-0.04	-0.02
Home-Retail floor area ratio	0.00	0.00	-0.01	-0.02	**0.12**
Work-Retail floor area ratio	-0.03	-0.03	**0.43**	-0.15	**0.01**
Auto-Travel time	**-0.03**	**-0.02**	0.31	0.28	0.05
Transit-In-vehicle time	0.02	0.03	**-0.39**	0.08	0.01
Transit-Fare	0.01	0.01	**-0.11**	0.03	0.01
Auto-Fuel and parking cost	**-0.07**	0.08	0.37	0.27	0.09

WORK OTHER WORK TOURS

Work other work (WOW) tours made up 6.6% of all tours in the dataset (N= 20,543) and are summarized in Table 41. Four of five modes (drive alone, shared ride, transit (walk to bus) and walk) are represented in the WOW tour set. The bike mode was not included due to an insufficient number of observations. More than three quarters (77%) of WOW tours were simple tours consisting of a single destination traveled to and from work. The predominant mode was drive alone. Transit was the least commonly used, and the mode for which there was the least data. There are only 11 transit WOW tours. Compared to simple tours a larger percentage of multi-stop tours have drive alone and transit as a main mode, and smaller percentage were by shared ride and walk.

Table 41: Work Other Work Tour Models Descriptives

TOURS FROM WORK	**All Tours**		**Simple Tours**		**Multi-Stop Tours**	
Observations	1,361		1,048 77.0%		313 23.0%	
Mode	**Chosen**	**Available**	**Chosen**	**Available**	**Chosen**	**Available**
Drive alone	715 52.5%	1,327	510 48.7%	1,021	205 65.5%	306
Shared ride	312 22.9%	1,361	247 23.6%	1,048	65 20.8%	313
Transit (walk to bus)	11 0.8%	576	3 0.3%	373	8 2.6%	203
Walk	323 23.7%	977	288 27.5%	825	35 11.2%	152

Results from the mode choice model of WOW tours are presented in Table 42. Higher travel time and mode costs for transit (walk and auto accessed) were associated with decreased usage relative to the drive alone option. Land use variables remained in the model only for transit and walk modes. Increasing retail floor area ratios was associated with increased transit (significant for all and multiple stop tours) and walk (significant for all and simple tours) usage relative to driving alone. Walking, with reduced significance for complex tours, also increased in association with increasing mixed use at the work site and intersection density at the work site and at the destination.

People who drove alone, shared a ride or walked to work were associated with a greater likelihood to use the same mode for trips made while at work. Using one of those modes for trips made during work hours is more challenging for someone who didn't arrive by them. For example, either a person would need to borrow a vehicle to drive alone, or find a ride from someone. If the tour contains a destination where the main purpose is to pick-up/drip off someone, then driving alone is less likely. Walking, with reduced significance for complex tours, was statistically more likely if the tour contains a social/recreational stop.

Table 42: Work Other Work (WOW) Tour Models

TOURS FROM WORK	All Tours		Simple Tours		Multi-Stop Tours	
Time and cost variable	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**
Auto and transit cost ($)	-0.01984	-0.8	-0.02691	-1	0.03019	0.5
Auto and transit- in-vehicle time (min)*	-0.020		-0.020		-0.020	
Walk and transit- out-of-vehicle time (min)	-0.06588	-11.3	-0.06368	-10.4	-0.09829	-4.6
Land use variables	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**
Transit- destin. retail floor area ratio	0.4705	3.5	0.227	0.8	0.626	2.9
Walk- origin mixed use	0.1957	1.2	0.1139	0.7	0.9959	1.3
Walk- origin/destin intersection density**	0.198	2.8	0.1504	1.8	0.3745	2.2
Walk- origin/destin. retail floor area ratio**	0.1765	2.4	0.2379	2.6	0.02687	0.2
Other variables	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**	**Coefficient**	**T-stat**
Drive alone- used car to get to work	3.838	5.8	4.85	4.3	3.001	2.8
Drive alone- pick-up/drop-off stop(s)	-3.238	-5.2	-5.000		-2.785	-4.2
Shared ride- simple tour ASC	0.7276	4.8	0.7152	3.8	N.A.	
Shared ride- complex tour ASC	0.4741	0.8	N.A.		-0.5164	-0.6
Shared ride- used car to get to work	1.866	3.7	1.812	3.1	2.19	2.0
Transit- simple tour ASC	-0.4171	-0.5	1.039	0.8	N.A.	
Transit- complex tour ASC	0.4773	0.6	N.A.		-0.2674	-0.2
Walk- simple tour ASC	4.748	6.7	5.703	4.9	N.A.	
Walk- complex tour ASC	3.882	4.8	N.A.		4.067	2.6
Walk- social/recreation stop(s)	1.758	2.9	1.678	2.7	2.728	0.6
Walk - walked to work	2.216	2.4	2.409	2.1	2.419	1.0
Model Fit						
Final log-likelihood	-851.3		-671.7		-172.3	
Rho-squared (0 coefficents)	0.443		0.431		0.503	
Rho-squared (constants only)	0.347		0.347		0.341	
Notes						
* Constrained for reasonableness. It is typical to obtain reasonable transit coefficients for only home based work tours.						
** Constrained coefficient for origin/destination to the be same.						
N.A. = not applicable						

WORK-OTHER-WORK ELASTICITY RESULTS

Work-other-work tour elasticities are shown in Table 43 for nine input variables (five land use variables at either the work or destination and four time or cost variables) and four modes of travel. Increases to the land use variables were associated with increased demand for walking, but reduced demand for drive alone, carpool and transit (except in the case of destination-retail floor area ratio).

Increased walk demand is shown for to be associated with increases to all land use measures, with the top three being nearly equal—work-mixed use (0.09), and work and destination intersection density (0.10 and 0.09 respectively).

- Walk demand increases of 0.9 to 1.0% were associated with a 10% increase in work location land use mix and work location intersection density.

Table 43: Work other Work (work based subtours)

Mode	Drive Alone	Carpool	Transit	Walk
Work-Mixed use index	-0.03	-0.03	-0.09	**0.09**
Work-Intersection density	-0.03	-0.03	-0.18	**0.10**
Destination-Intersection density	-0.03	-0.03	-0.18	**0.09**
Work-Retail floor area ratio	-0.01	-0.02	-0.18	**0.05**
Destination-Retail floor area ratio	-0.02	-0.03	**1.18**	**0.03**
Auto-Travel time	**-0.01**	**-0.01**	0.36	0.03
Transit-In-vehicle time	0.00	0.01	**-0.36**	0.00
Transit-Fare	0.00	0.00	**-0.02**	0.00
Auto-Fuel and parking cost	**-0.02**	0.02	0.09	0.02

SUMMARY

Overall, the results presented in this chapter provide some very significant relationships between aspects of land use, tour type, and modal choice. The tour type models show stronger coefficients for land use than the socio-demographics factors – which is a unique finding in travel behavior research. However, it makes sense that land use, which represents the arrangements of destinations within the urban environment, would be strongly correlated to our choice to make stops near where we live and work, and whether we choose to make multiple stops before returning home.

The modal choice analyses each resulted in models that had “strong goodness of fit” as described in the Rho-square statistic. Higher travel time and mode costs associated with nearly all modes decreased their usage relative to the drive alone option. Relative to the drive alone option, land use variable increases were associated with increases to the relative utility of transit, walk, and, in a few instances, bicycling. Shared ride was not present in the land use variable set because land use variables were not signficant. The choice of whether to drive alone or share a ride appears to be more associated with trip purpose and household size, than land use. This is consistent with results from earlier research on land use and travel choice in the Central Puget Sound Region (Frank and Pivo in 1994).

A variety of land use mix measures were tested and the normalized mixed-use variable, which is defined as the evenness of distribution of square footage of development between retail, entertainment, office, and residential use within the one kilometer network based buffer, was the most significant measure of land use mix. Net residential density variables were tried in the models but never significant – this is believed to be a function of how much of their effect is captured by the mixed use, intersection density, retail floor area ration, and level of service variables.

Other land use variables such as total employment density and retail employment density in the buffers were tested, but were not significant. The retail floor area variables were more significant than corresponding total retail employment variables. In addition to those retained in the models, additional car availability, income, age, and time of day variables were tested but were not significant.

In initial tests, significant nesting was found for a nest with the walk and bike modes for home based work tours, and a nest with the two car modes for non-work tours. This means that trade offs were likely to occur between specific modes of travel over others such as whether to drive alone or carpool, or to walk or bike. It is less likely for someone to be choosing between driving and walking for most trips, as they have very different requirements in terms of time and distance.

These results show when the model is specified more correctly with parcel-level data, the need for such variables and nests disappears. All models include variables which are significant, or nearly significant, in at least one or more of the models (all, simple and complex tours). Variables where the t-statistic is less than 1.96 (corresponding to a 95% confidence interval) are included based on judgment. If a variable is signed consistently with other like-variables and contributes to the model it is typically left in. Also with more data observations more variables would be significant. This does not indicate anything about behavior, just sample size limitations. The model fit and values of time are in typical accepted ranges for these types of models.

CHAPTER 5: SUMMARY AND CONCLUSIONS

INTRODUCTION

The results from this study fill some important gaps in the understanding of how the land use patterns in which we live and work might impact travel choices and resulting outcomes, such as regional air pollution. To date, research on land use and travel behavior has focused primarily on residential environments, with little attention paid to work environment design. Moreover, research has been focused at the trip level, or aggregations of trips to person and household levels, thus overlooking the influence of trip chaining. This has made it difficult to understand how travel behavior, which often occurs in the form of tours or trip chains, relates with land use. This study represents the first such effort in the Central Puget Sound Region to link disaggregate level land use information with trip chaining patterns.

This study builds upon earlier research linking land use, travel, and vehicle emissions in the Central Puget Sound Region funded by the Washington State Department of Ecology and the Washington State Department of Transportation. The earlier set of studies used zonal measures of land use at the census tract level, whereas the current study employs observation specific measures of land use within a one-kilometer network distance of where people live and work. These improvements to measuring the built environment have been made possible through advancements in the ways in which land use data is collected and the GIS tools now available to use these data. The current study matches these more precise land use measures with “link-specific” emissions estimates generated for the 1999 Puget Sound Household Travel Survey. This process, developed by LFC, Inc. in partnership with GeoStats, LLP for the King County LUTAQH study, is a path-breaking effort in that it enables the matching of disaggregate location specific land use data with network specific speeds and emissions characteristics. Therefore, the current study is really two separate sets of analyses (1) focusing on land use, travel and air quality, and (2) tour based modal choice and land use.

LAND USE, TRAVEL, AND VEHICLE EMISSIONS

Chapter 3 presented results of the regression models for vehicle miles (VMT) and hours (VHT), which included land use and household socio-demographic factors.

Models presented document that increases in intersection density and land use mix are associated with significant reductions in VMT when controlling for demographic factors. Decreases in VHT were found in association with increased residential density, mix, and intersection density when controlling for the same demographic factors. Oxides of Nitrogen (NOx) and Hydrocarbons (HC) were found to be inversely associated with intersection density and land use mix. All of the models specified in this study had fairly high R-squares, indicating that the variation in the dependent variables (VMT, VHT, NOx, and HC) was explained by the variables in the model. In most instances, the variation was more a function of demographic and auto and transit level of service than land use – which is to be expected.

INTERPRETING THE VMT AND VHT REGRESSION RESULTS

The relationship between land use and VMT and VHT is further clarified in Table 44, which presents results in terms of orders of magnitude of effect. The regression models presented in this analysis use a non-linear transformation of the dependent variables due to the skewed distribution of households across the independent variables (land use). By taking the log10 of the dependent variables, many of the land use measures were then found to be significant that would not have been so if a linear distribution has been used. This finding is consistent with other research on land use and activity patterns (Frank et al 2005). Therefore, interpreting the effect of emissions changes associated with the land use variables requires first transforming the regression equation back to its original scale, grams of emissions. For regression equations with logged dependent variables, the effect of changing an independent variable by one unit, while holding all other variables constant, is reported as the resulting percent change in the dependent variable. This transformation is done by raising ten to the power of the value of each coefficient, and subtracting one, and multiplying by 100, to give a percent. Table 40, below, contains these estimated percent changes.

Table 44: VMT & VHT Model Coefficient Interpretation

Independent Variables		A Unit Increase in an Independent Variable Correlates with the following:	
		% Change in VMT	**% Change in VHT**
Demographics	Number of HH vehicles	11.71%	9.85%
	No. of persons in household	28.56%	31.22%
	Total 1998 annual household income	10.64%	10.41%
Transit LOS	Miles to nearest bus stop	5.00%	4.04%
Land Use	Net Residential Density (dwelling units per acre)		-0.57%
	Intersection Density (number per sq km)	-0.39%	-0.28%
	Mixed Use Index (ranges 0 to 1, with a unit increase =1)	-19.70%	-23.51%

For example, for vehicles per household the VMT regression equation coefficient is 0.048 (Table 17). The value of ten raised to the power of 0.048 is 1.1171. After subtracting one and multiplying by 100 the remaining value is 11.71%, as indicated in the table above. Each additional household vehicle is associated with a VMT increase of 11.71%. The percentage increase in VMT associated with each additional mile a participant lives from the nearest bus stop is 5%. Each additional intersection per square kilometer is associated with a VMT decrease of 0.39%. Changing the mixed use of a location from a single use, e.g. only residential (mixed use index =0), to one which has an even distribution of floor area across land uses, e.g. residential, entertainment, retail and office uses (mixed use index =1), is associated with a VMT decrease of 19.7%. This represents a change found only at the margins, from one extreme to the other across the mixed use index range of 0 to 1.

It is also important to place this within the context of community level comparisons. For example, Table 45 shows that Upper Queen Anne has on average slightly more than 53 intersections per square kilometer than found in the suburban area north of the Redmond Town Center. Assuming the same household demographics, this difference correlates with an estimated 19% less VMT and 13.9% less vehicle time spent traveling for Queen Anne residents.[12]

Table 45: VMT & VHT Differences Between North of Redmond Town Center & Upper Queen Anne

Variable	Difference btw. Communities (Queen Anne - Redmond)	% Change in Mean Daily Household VMT	% Change in Mean Daily Household VHT
Net Residential Density (dwelling units per acre)	8.13		-4.6%
Intersection Density (per sq km)	53.42	-19.0%	-13.9%
Mixed Use Index (ranges 0 to 1)	0.12	-2.7%	-3.2%

INTERPRETING THE EMISSIONS REGRESSION RESULTS

The proportional changes in grams of NOx emissions associated with incremental changes in the units for the independent variables are presented in Table 46. These results are based on the regression coefficients provided in the previously discussed Table 19 and Table 21. Results from the models with VMT, as well as without VMT are presented. For the regression model containing VMT as an independent variable the estimated percent changes associated with emissions were systematically less, except for net residential density, This is expected since land use in part is responsible for explaining VMT.

[12] A set of approximately 75 randomly selected households from each of these two areas of the region were used as the basis for this comparison. These households were recently recruited as part of the National Institutes for Health (NIH) Funded Neighborhood Quality of Life Study (PI, Dr. James Sallis). Land use variables were measured at the one kilometer network buffer level for each household and then averaged at the community level for both Upper Queen Anne and North of Redmond.

Table 46: Vehicle Emission Model Coefficient Interpretation

Variable		% Difference in Mean Daily Household Grams of:			
		HC	NOx	HC	NOx
		Model #1 (no VMT)		Model #2 (with VMT)	
Demographics	Vehicles per household	19.6%	17.3%	14.4%	11.1%
	People per household	20.3%	20.7%	5.5%	2.3%
	Annual household income	10.2%	10.4%	6.6%	5.9%
Travel Behavior	VMT -- mean, daily HH level			0.9%	1.1%
Land Use	Net Residential Density (dwelling units per acre)	-0.4%		-0.7%	-0.6%
	Intersection Density (per sq km)	-0.4%	-0.4%	-0.1%	-0.1%
	Mixed Use Index (ranges 0 to 1)	-22.5%	-20.4%	-14.7%	-10.3%

In Model #1 (no VMT), each additional vehicle was associated with a 19.6% increase, and each additional person a 20.3% increase. Each additional intersection was associated with a 0.4% reduction, and an increase from the least (only a single land use) to the most evenly mixed use environments was associated with a 22.5% reduction in hyrdorcarbon emissions. Similar changes were found for NOx as well.

When VMT is added the regression model coefficients change, and therefore so do the expected percent changes associated with the independent variables. Comparing the change in effect between Model #1 and #2 showed a decrease for all variables except net residential density. This is because most of what land use explained was VMT, and once introduced in the NOx model, the remaining emissions' association with land use was attributable to vehicle speeds, and cold start functions, which appear to remain positively associated with land use. That is, people in the more sprawling areas of the region appear to generate more NOx per unit of distance traveled.

The vehicle emission comparison of two households with the same demographics living in different types of communites (the area to the north of Redmond Town Center and Upper Queen Anne) was similar to the results of the previous VMT and VHT comparisons. The family living in Quenn Anne was estimated to produce fewer HC and NOx then the Redmond family. For example, in Model #1 (no VMT) shown in Table 47, the difference in net residential density translates into 3.5% less HC emissions for Queen Anne residents. The difference in intersection density is associated with reducing HC and NOx emission the most (17.2% and 18.9% respectively). As was the case with the VMT and VHT models the effect of the land use variables decreased in Model #2 with the introduction of the additional explanatory independent variable of VMT.

Table 47: Vehicle Emission Differences Between North of Redmond Town Center & Upper Queen Anne

Variables	Difference btw. Communities (Queen Anne - Redmond)	% Difference in Mean Daily Household Grams:			
		HC	NOx	HC	NOx
		Model #1 (no VMT)		Model #2 (with VMT)	
Net Residential Density (dwelling units per acre)	8.13	-3.5%		-5.4%	-4.5%
Intersection Density (per sq km)	53.42	-17.2%	-18.9%	-7.1%	-7.1%
Mixed Use Index (ranges 0 to 1)	0.12	-3.1%	-2.8%	-1.9%	-1.3%

While it is not reasonable to expect dramatic shifts in land use on average across the region, significant changes in land use do occur in specific locations. Furthermore, the results presented are not meant to be taken in isolation. Therefore, each variable represents only its own incremental impact on behavior and emissions. When taken collectively, such as the normal coinciding of higher mix and connectivity and perhaps even one less car, there can be significant differences in air pollution that result on a per household basis.

TOUR TYPE AND MODAL CHOICE RESULTS

Interpretation of the tour type and modal choice model results is provided to make the results more relevant for policy and decision making within the region.

TOUR TYPE MODEL RESULTS

Results show that people living in areas with higher intersection density and mixed land uses tended to make tours with fewer stops and stops closer to home. These same people also tended to make more home-based tours (i.e. they tend to split their activities into more short tours instead of fewer long, complex tours). This type of behavior can also be related to mode choice, as such short tours are easier to make by walk or bike modes. Therefore, it is important to note that this does not imply that the number of destinations visited near home declines with connectivity or mix. Rather the results suggest that the number and fraction of stops on a per tour basis declines due to simpler tour patterns. It has been argued that this type of travel pattern may be associated with increased air pollution due to cold starts activity – however, the results presented here suggest that this is not the case. Instead, the longer vehicle trips associated with lower levels of density, mix, and connectivity overwhelm the impact that higher trip generation rates may have on emissions.

Socio-economic factors also impacted the choice to take simple or complex tours for non-work purposes. More vehicles per driver were associated with more complex non-work tour trip chains with more stops, and fewer stops near to home. Higher incomes and being over 50 are both associated with fewer stops close to home (these people also tend to be more likely to drive and less likely to walk). People in single-person households tend to make more stops close to home.

MODE CHOICE MODEL RESULTS APPLIED

Similar to what was done with the regression results above, Table 48 applies the home-based other tour elasticities to two specific communities—Queen Anne and the area to the north of Redmond Town Center. These communities allow a comparison of demand for different modes based on the difference in land use – specifically mixed use, intersection density and retail floor area ratio at the home origin of tours. Queen Anne has higher values for each of the variables, with percentage difference shown in the table.

NON-WORK TRAVEL (HOME BASED OTHER)

Multiplying these percentage differences in land use by the mode-specific demand elasticities for home-based other tour (Table 37) provides the results shown below for tours originating in the two communities. Queen Anne's better mix of land uses and increased network connectivity were found to be associated with less demand for auto modes (drive alone and carpool) for Queen Anne residents, when compared to Redmond residents—0.7% less due to the increased mixed use index, and 2.6% less due to intersection density.

These variables, combined with Queen Anne's greater retail floor area further results in increased transit use by residents of Queen Anne. Queen Anne's intersection density was estimated to be associated with over a one-third increase in transit (31.1%) and walking (36.2%) demand as compared to Redmond. Mixed use differences were associated with smaller increases in transit and walk demand—5.8% and 4.3% respectively for the two communities.

Queen Anne's more intensely built retail (retail floor area ratio) provides more retail destinations nearer to home, and thereby possibly shifting demand to transit and bike use to increased demand for walking.

Table 48: Home based Other (HBO) – Comparing Queen Anne Mode Demand to Redmond

Variables	Land Use (Home)			Relative Mode Demand: Queen Anne compared to Redmond				
	Redmond	Queen Anne	% Diff.	Drive Alone	Carpool	Transit	Bike	Walk
Mixed use index (range of 0-1)	0.17	0.29	72%	-0.7%	-0.7%	5.8%	10.9%	4.3%
Intersection density (number per acre)	41.27	94.69	129%	-2.6%	-2.6%	31.1%	-10.4%	36.2%
Retail floor area ratio	0.09	0.61	563%	0.0%	0.0%	-5.6%	-11.3%	22.5%

WORK RELATED TRAVEL (HOME BASED WORK)

Due to the differences in land use, the work commute demand for auto modes (drive alone and carpool) is less in Queen Anne than Redmond—a 0.7% decrease in automobile use associated with Queen Anne's better mixture of land uses, and a 5.2% decrease associated with its better-connected street network (intersection density).

Queen Anne's more walkable community characteristics were also associated with increased demand for transit (except for retail floor area ratio) and walking. Queen

Anne's intersection density was estimated to be associated with over a one-third increase in transit (34%) and 56% increase in demand for walking when compared to the area to the north of Redmond Town Center. Differences in land use mix were associated with smaller increases in transit and walk demand—6.5% and 15.9% respectively.

Queen Anne's more intensely built retail (retail floor area ratio--FAR) provides more retail destinations nearer to home. This higher retail FAR was associated with decreased transit and bike use levels, and increased walking (67.5%) as compared to the area north of Redmond town center.

Table 49: Home based Work (HBW) – Comparing Queen Anne Mode Demand to Redmond

Variables	Land Use (Home)			Relative Mode Demand: Queen Anne compared to Redmond				
	Redmond	Queen Anne	% Diff.	Drive Alone	Carpool	Transit	Bike	Walk
Mixed use index	0.17	0.29	72%	-0.7%	-0.7%	6.5%	-5.1%	15.9%
Intersection density	41.27	94.69	129%	-5.2%	-5.2%	33.7%	108.7%	55.7%
Retail floor area ratio	0.09	0.61	563%	0.0%	0.0%	-5.6%	-11.3%	67.5%

SUMMARY

The comparisons presented in this chapter between Upper Queen Anne Hill and the area north of Redmond Town Center provide a mechanism to see how the results apply to different places are across the region. Moreover, the comparison helps to convey the degree of difference in land use between two contrasting types of communities. The application of results in this manner further enables us to see the extent to which specific land use and travel costs can be associated with miles and hours of travel, vehicle emissions, and modal choice decisions.

The primary means of interpreting the mode choice elasticities, as presented in Chapter 4, is to assess mode choice outcomes in association with a percentage increase or decrease in a given land use or travel cost variable. However, through the application of the results to real communities in the region, it becomes clearer how the findings of the study can be put into practice. While the results do not assume that the actual mode split for these two communities should equate exactly with what is shown here, the basic premise is that specific travel choices do track with aspects of the built environment that are determined through land use and transportation investment policy.

CHAPTER 6: RECOMMENDATIONS / APPLICATION / IMPLEMENTATION

INTRODUCTION

A variety of recommendations resulting from the research presented in this report are described below. The recommendations are divided into three sections:

- Application of the results to local land use and regional transportation planning and programming processes;
- Activities WSDOT can support to improving the quality of the research that is possible to increase our understanding of how the built environment shapes travel and other behavior patterns; and
- Recommendations for future research that would build on this and other efforts underway in the region.

APPLICATION OF RESULTS

The findings from this research provide insight into how land use actions, resulting from adopted policies and enforced development regulations, correlate with travel patterns and the demand for specific modes of travel. Specific findings from this research suggest how these policies over time should be augmented to meet regional goals of reduced auto dependence and associated air pollution. The design of the environments where we live and work offer opportunities to improve the quality of life for residents in the Central Puget Sound. Depending on whether an area has a retail, employment, or residential focus, land use strategies have been shown in this work to increase the utility of walking, biking, and transit relative to driving alone for work and non work purposes. The degree of specificity presented in this study enables more prescriptive information to be developed that can be incorporated into plans, policies, and ultimately regulations and into project level review processes. On the land use side, the results offers considerable insight into the possible benefits of considering a VMT or VHT based impact fee system whereby not only trip generation but also trip distance and travel time were taken into account.

While the results from this work offer specific recommendations as to which types of land use practices are most highly associated with non-single occupancy vehicle modes of travel, there are also some important findings that can be applied to transportation investment practices. WSDOT has a well-established priority programming process that is used to rank projects based on a set of criteria that establish the relative merit of competing projects. Results from this project suggest the types of transportation investments that would be most supportive of specific modal outcomes. Modal specific LOS variables presented in the models suggest how much changes in travel are associated with increases or reductions in the time and costs associated with each mode of travel. With some more work, it will be possible to translate the results into cost benefit types of trade-offs based on the relative utility that results from mode specific investments. In addition, land use impacts the relative utility of specific modes of travel as a function of its impact on convenience, cost, and time requirements across available modes of travel. Further investigation into how land use changes impact the relative utility of different types of transportation investment futures could help understand how specific combinations of transportation investments and land use actions might corroborate to shape travel choice.

ACTIVITIES THAT WILL ENHANCE THE RESEARCH

WSDOT, working in partnership with other state and governmental organizations, can help to spearhead improved data collection protocols for a variety of data types required to understand how our built environment shapes our behavior. Standards should be developed for the collection of parcel level land use data – including a consistent coding scheme for land use type. Some form or review should be created to ensure that critical attributes from the parcel data are collected. This is particularly problematic since tax assessors tend to care the least about the characteristics that matter the most to urban planning and research, focusing more on things like the value of the property and improvements.

WSDOT can support the collection of travel behavior and other types of data in the state in a manner that achieves a representative set of observations in different types of urban environments – ranging from the most walkable to the most auto-dependent. To date, the vast majority of analyses linking land use and built form with travel behavior, including the current study, have been based on the use of secondary travel datasets that were stratified based on the socio-demographic factors with little thought about capturing any variation in land use. Therefore, if there is little land use variation, it is arguably somewhat of a self-fulfilling prophecy that the socio-demographic factors would be more significant. This will facilitate research WSDOT is funding such as this project, which relies on the ability to compare activity patterns for households across a range of land uses.

Traditionally, WSDOT has been a very innovative transportation agency. Increasing interest in how transportation investments and associated land use actions impact public health may present new opportunities. By partnering with other agencies focusing on health related and air quality related outcomes, it may be possible to share in the gain and in the blame of transportation investments and land use actions that increase the viability of transit, walking, biking, and carpooling. WSDOT's active role in the Puget Sound Regional Council's Vision 2020 process represents the types of forum where such ideas noted above may be advanced.

FUTURE RESEARCH

In response to the limitations of the current study, some additional research is proposed. Foremost, this study is cross-sectional and does not offer the ability to isolate land use influences on behavior from attitudinal predisposition for specific modes of travel or for different types of community environments. Longitudinal studies that capture travel patterns before and after people move is one way in which this issue could be addressed. In the nearer term, future travel surveys could contain questions about attitudinal factors, such as why participants chose the community they live in, in order to provide some ability to isolate built form from attitudinal predisposition in a more cost effective manner.

Emissions modeling could readily be conducted at the trip tour level offering a greater understanding of how land use influences emissions at a unit of analysis (the tour) that more accurately depicts travel choice. Emissions modeling at the tour level would enable the assessment of how much of each tour type's emissions are a function of cold starts or hot stabilized travel. While ozone is an important secondary pollutant, awareness of the harmful effect of particulate matter attributable to transportation is becoming a greater concern. Research on the linkages between land use and exposure to particulates is critical.

The effects of land use and land use could be further investigated with improved Commute Trip Reduction (CTR) data. With employee mode split data for the commute to CTR work locations, coupled with the land use data at the one kilometer buffer level, a validation of results could occur. CTR locations with different land use patterns and their reported mode splits could be compared with the mode demand elasticities generated through this project.

The research presented here does not account for the *quality* of the pedestrian environment. Therefore, according to our models, someone living in White Center, with nearby commercial and a connected street network, should express a high relative utility for walking. Unfortunately, there are many places without sidewalks in White Center. Sidewalks are one of several attributes that may have significant impacts on travel behavior, in addition to building setbacks, intersection layout and street crossings, and many others. However, analysis of these variables is limited, since most places in the region do not have complete sidewalk availability data (although this is changing), or data on some of the other, more qualitative environmental characteristics listed above.

Recently, data was collected data on the pedestrian environment in 12 communities in King County through the National Institutes of Health funded Neighborhood Quality of Life Study. This new data presents an opportunity to integrate the micro scale pedestrian environmental data with the travel data analyzed in this study to assess the relative impacts of micro scale design features on travel choice. The integration of the City of Seattle's sidewalk GIS layer would also further the ability to understand how sidewalk presence impacts travel choice. A travel survey has been conducted for King County in three of these twelve communities: White Center, Kent East Hill, and Redmond, enabling a direct linkage to be made between microscale environmental data, travel behavior data, and more traditional land use measures of density, mix, and connectivity.

REFERENCES

Badoe, D.A. and E.J. Miller (2000) “Transportation—land-use interaction: empirical findings in North America and their implications” *Transportation Research Part D: Transport and Environment* 5: 235 – 263.

Ben-Akiva, M. and S.R. Lerman. *Discrete Choice Analysis: Theory and Application to Travel Demand*. Cambridge, MA: The MIT Press, 1985.

Boarnet, M.G. and R. Crane (1998) “Public finance and transit-oriented planning: evidence from Southern California” *Journal of Planning Education and Research* 17: 206 – 219.

Boarnet, M.G. and R. Crane (2001) *Travel by Design: The Influence of Urban Form on Travel.* Oxford: Oxford University Press.

Boarnet, M.G. and S. Sarmiento (1998) “Can land use policy really affect travel behavior?” *Urban Studies* 35: 1155 – 1169.

Bray, GA 1998. “Contemporary Diagnosis and Management of Obesity.” Newton, PA: *Handbooks in Health Care*.

Cervero, R. (1991) “Land use and travel at suburban activity centers” *Transportation Quarterly* 45: 479 – 491.

Cervero, R. (1996) “Mixed land uses and commuting: evidence from the American Housing Survey” *Transportation Research Part A: Policy and Practice* 30: 361 – 377.

Cervero, R. (2002) “Built environments and mode choice: toward a normative framework” *Transportation Research Part D: Transport and Environment* 7: 265 – 284.

Cervero, R. and K. Kockelman (1997) “Travel demand and the 3Ds: density, diversity, and design” *Transportation Research Part D: Transport and Environment* 2: 1999 – 219.

Crane, R. (2000) “The influence of urban form on travel: an interpretive review” *Journal of Planning Literature* 15: 3 – 23.

Crane, R. and R. Crepeau (1998) “Does neighborhood design influence travel? A behavioral analysis of travel diary and GIS data” *Transportation Research Part D: Transport and Environment* 3: 225 – 238.

DKS Associates with Mirai Associates. *Final Report: Modeling TDM Effectiveness: Developing A TDM Effectiveness Estimation Methodology (TEEM) and Case Studies for the SR520 Corridor, Part of the Implementing Corridor TDM Programs in the Puget*

Sound Region Project; Washington State Department Of Transportation, April 2003. (*http://www.wsdot.wa.gov/mobility/tdm/520casev1/finalreport.pdf*)

Ewing, R. and R. Cervero (2001) "Travel and the built environment: a synthesis" *Transportation Research Record* 1780: 87 – 114.

Ewing, R., T. Schmid, R. Killingsworth, A. Zlot, S. Raudenbush (2003) "Relationship between urban sprawl and physical activity, obesity, and morbidity" *American Journal of Health Promotion* 18(1): 47 – 57.

Frank, L.D. and G. Pivo (1995) "Impacts of mixed use and density on utilization of three modes of travel: single-occupant vehicle, transit, and walking" *Transportation Research Record* 1466: 44 – 52.

Frank, Lawrence D., and Brian Stone, Jr. (1998). "Land Use Effects on Travel Demand and Air Quality," Washington State Department of Ecology and the Environmental Protection Agency,

Frank, L.D. (2000). "Land use and transportation interaction: Implications on public health and quality of life." *Journal of Planning Education and Research*, 20, 6-22.

Frank, L.D., Andresen, M.A., & Schmid, T.L. (2004). "Obesity relationships with community design, physical activity, and time spent in cars." *American Journal of Preventive Medicine,* 27, 87-96.

Frank, Lawrence and Engelke, Peter. (2005) "Multiple Impacts Of The Built Environment On Public Health: Walkable Places And the Exposure To Air Pollution." International Regional Science Review.

Frank, L.D., Sallis, J.F., Chapman, J., & Saelens, B.E. (2005). "Linking objectively measured physical activity with objectively measured urban form: Findings from SMARTRAQ." *American Journal of Preventive Medicine*, 28 (No. 2, Suppl. 2), 117 125.

Frank. Lawrence, Saelens, Brian, Powell, Kenneth. (2005). "Travel Patterns by Attitudinal Predisposition." Refereed Paper Presented at the Active Living Research Conference in San Diego California.

Frumkin, Howard, Frank, Lawrence, Jackson, Richard. (2004) *The Public Health Impacts of Sprawl*. Island Press.

Greene, W.H. (2000) *Econometric Analysis 4th ed.* Upper Saddle River, N.J.: Prentice Hall.

Handy, S. (1996a) "Understanding the link between urban form and nonwork travel behavior" *Journal of Planning Education and Research* 15: 183 – 198.

Handy, S. (1996b) “Methodologies for exploring the link between urban form and travel behavior” *Transportation Research Part D: Transport and Environment* 1: 151 – 165.

Handy, S. (2002) “Travel behavior-land use interactions: an overview and assessment of the research” in H.S. Mahmassini (ed.) *In Perpetual Motion: Travel Behavior Research Opportunities and Application Challenges*. Kidlington, UK: Elsevier Science, 223 – 236.

Handy, S., X. Cao, and P.L. Mokhtarian. "Correlation or Causality Between the Built Environment and Travel Behavior? Evidence from Northern California." Transportation Research D, forthcoming.

Horowitz, Joel L.; Frank S. Koppelman and Steven R. Lerman. *A Self-instructing Course in Disaggregate Mode Choice Modeling*. Prepared for the Urban Mass Transit Administration (now Federal Transit Administration), Washington, DC, December 1986.

Kleeman, Michael, James Schauer and Glen Cass. (2000) “Size and composition distribution of fine particulate matter emitted from motor vehicles.” *Environmental Science and Technology* 34: 1132-1142.

Krizek, Kevin J. (2003). “Operationalizing Neighborhood Accessibility for Land Use Travel Behavior Research and Regional Modeling.” *Journal of Planning Education and Research*. 22(3): p. 270-287.

Kockelman, K.M. (1997) “Travel behavior as a function of accessibility, land use mixing, and land use balance: evidence from San Francisco Bay area” *Transportation Research Record* 1607: 116 – 125.

Levine, Jonathan, Aseem Inam and Gwo-Wei Torng. (2004) A Choice-Based Rationale for Land-Use and Transportation Alternatives: Evidence from Boston and Atlanta. *Journal of Planning Education and Research* 24(1).

McFadden, D. 1974. “Conditional Logit Analysis of Qualitative Choice Behavior.” Pp. 105 – 142 in *Frontiers in Econometrics*, edited by P. Zarembka. New York: Academic Press.

McFadden, D. (1981) “Econometric Models of Probabilistic Choice” in C.F. Manski and D. McFadden (eds.) *Structural Analysis of Discrete Data Using Econometric Applications*. Cambridge, MA: MIT Press, 198 – 272.

McNally, M.G. and A. Kulkarni (1997) “Assessment of influence of land use-transportation system on travel behavior” *Transportation Research Record* 1607: 105 – 115.

Meyer, J.R. Kain, J.F. and Wohl, M. (1965) *The Urban Transportation Problem*. Harvard University Press.

Mitchell, R.B. and C. Rapkin (1954) *Urban Traffic: A Function of Land Use*. New York: Columbia University Press.

Moudon, Anne Vernez Lee, Chanam Cheadle, Allen D. Collier, Cheza W. Johnson, Donna Schmid Thomas L. and Weather, Robert D. (2005). "Cycling and the built environment, a US perspective." *Transportation Research: Part D.* Vol 10. No. 3. Pages 245-261.

Openshaw, S. (1984) *The modifiable areal unit problem*. CATMOG (Concepts and Techniques in Modern Geography) 38. Norwich: Geo Books.

Pope, C., R. Burnett, M. Thun, E. Calle, D. Krewski, K. Ito, and G. Thurston. 2000. "Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution." Journal of the American Medical Association 287: 1132-41.

Saelens, B.E., Sallis, J.F., & Frank, L.D. (2003). "Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures." *Annals of Behavioral Medicine*, 25, 80-91.

Sallis, J.F., Frank, L.D., Saelens, B.E., & Kraft, M.K. (2004). "Active transportation and physical activity: Opportunities for collaboration on transportation and public health research." *Transportation Research Part A: Policy and Practice*, 38, 249-268.

Small, K.A. (1992) *Urban Transportation Economics*. Chur, Switzerland: Harwood Academic.

Stead, D. (2001) "Relationship between land use, socioeconomic factors, and travel patterns in Britain" *Environment and Planning B: Planning and Design* 28: 499 – 528.

Steiner, R.L. (1995) "Residential density and travel patterns: review of the literature" *Transportation Research Record* 1466: 37 – 43.

Sturm R, Cohen DA. (2004) "Suburban Sprawl and Physical and Mental Health." *Public Health*, Vol. 118, No. 7, Oct 2004, pp. 448-496

Train, K.E. (1986) *Qualitative Choice Analysis: Theory, Econometrics, and an Application to Automobile Demand*. Cambridge, MA: MIT Press.

APPENDIX 1: 1999 PUGET SOUND HOUSEHOLD TRAVEL SURVEY, EXECUTIVE SUMMARY, DRAFT FINAL REPORT, DECEMBER 1999

1999 Puget Sound Household Travel Survey
Draft Final Report

December 1999

by NuStats Research and Consulting

[http://www.psrc.org/datapubs/pubs/hhtravel.pdf]

Executive Summary

NuStats Research and Consulting conducted the 1999 Puget Sound Household Travel Survey on behalf of the Puget Sound Regional Council (PSRC). The purpose of the study was to provide data for the continuing development and refinement of the Regional Travel Demand Forecasting Model, as well as to provide a better understanding of travel behavior in the Puget Sound region.

The study area consists of King, Kitsap, Pierce and Snohomish counties. The resultant data set will be used to fulfill the model's functions of estimating trip generation and distribution, mode choice, and assignments. The study consisted of households keeping track of travel for a 48-hour period. And for those household members sixteen years of age or older, an "attitude" survey about transportation issues was also administered.

A pilot test was conducted during early June to test the survey procedures and materials. Respondents and data collection staff provided valuable feedback about the survey process and materials. All changes to the process and materials were changed prior to the full implementation of the study. A four-phase data collection procedure was used: 1) advance calls, 2) recruitment, 3) reminder calls, 4) data retrieval. The entire data collection process was conducted between July and early November 1999.

A total of 9,985 households agreed to receive a letter and a brochure about the survey; 9,028 households were recruited to participate and 6,000 households completed 48-hour place-based diaries. A completion rate of 66.5%, which is the percentage of completes to recruited households, was achieved (each person in the household had to provide trip information in order for the household to be considered a complete).

A few of the key findings include the following:

• The average household size in the entire study area is 2.4 persons.

• The average vehicle ownership is 1.9 for the four-county study area.

• 4.9 percent of all households in the survey do not own a vehicle; another 64.6% own two or more.

• The median household income for 1999 is $49,246, with 56% of all households earning $45,000 or more.

• 60% of survey participants have lived in the four-county study area for longer than five years.

• The average daily person trip rate for the entire region is 7.2, and per household it is 16.1.

• Slightly more than three in four (76%) respondents live in a single family home; another 12% live in an apartment.

• Females tend to make slightly more average daily trips (3.7 each) than males (3.5 each).

• One in four respondents is 55 years of age or older.

• Persons between the ages of 35 and 54 generate a two-day average of 8.3 trips each; this is significantly more than the two-day average of 7.2 trips per person overall.

• Among those 16 years of age or older, 38.3% work full-time only while 17.7% attend school full time only. Another 16.4% of the respondents are retired.

• Among those employed, 43.4% report being in a white-collar professional or managerial position or business owner. Another one in four reports being in a white-collar sales, clerical or technical position.

• Virtually all (99%) of employed respondents work outside of their home at least one day each week. Nearly eight in ten (79%) commute by car only, while 3% reported getting to work via car/bus combination. Six percent reported commuting by bus.
• Other than to go home, work (11.5%), incidental shopping (11.3%), and social/recreational
(9.2%) purposes are most frequently reported trip purposes.
• Major shopping (25.6), medical (21.8), and work (20.3) trips have the longest reported commute time in minutes.

From the personal "attitude" survey:
• About one-third of respondents (29%) have a desktop computer at home.
• One-fourth (25%) of respondents has Internet access.
• Over one-third (36%) of the respondents estimate that it costs between $1,000 and $3,000 per year to maintain their vehicle(s).
• Eight in ten respondents reported they would take an alternate route to where they are going if they knew ahead of time that they would be caught in traffic.
• Respondents are somewhat pessimistic about transportation issues. They disagree that transportation investments adequately address the issues of where people live, work or shop and that the quality of life is getting better. They also disagree that they are able to travel their regular route more quickly compared to 12 months ago. They agree that traffic congestion is as bad as everyone says it is.
• Respondents agree that reducing traffic congestion should be the primary goal of transportation plans.
• In relieving traffic congestion, respondents disagree that building more roads will solve the problem.

APPENDIX 2: MODAL ADJUSTMENTS BASED ON SPECIAL CONDITIONS

NOTE: This appendix is not for distribution. The work described here was funded by King County, Washington, the Federal Transit Administration, and the Bullitt Foundation. This article has been submitted for journal publication.

Modal Adjustments Based On Special Conditions

Auto and Light Truck

Vehicle occupancy is an important consideration in analysis of emissions by all modes. For light duty automobiles, vehicle occupancy was calculated based upon trip attributes reported in the Household Activity Survey, including:

- number of household members on the trip;
- unique identifiers for the particular household members on the trip; and
- total number of persons (household and non-household) on the trip.

For automobile and light duty truck trips, the emissions for each trip were assigned to the survey respondent (driver or passenger) in terms of their vehicle occupancy percentage based on the number of persons on the trip. Thus, the trip emissions were divided by vehicle occupancy to calculate the per person trip emissions. For example, if a carpool trip consists of two household members, person “A” and person “B,” in which person “A” takes person “B” to work and then continues on to his / her employment site, person “A” would be assigned 50% of the trip emissions. Similarly, person “B” would be assigned the other 50% of the trip’s emissions.

If the carpool consists of three persons, “A,” “B,” and “C,” in which “A” and “B” are members of the same household and “C” is neither a household member nor a survey participant, persons “A” and “B” would each be assigned 33% of the trip emissions. The non-survey respondent’s (person “C”) portion of emissions would not be included in the analysis as these emissions skew the trip level vehicle emissions and can not be traced to an origin residence or employment destination.

Subtracting the number of household member person identifiers recorded for the trip from the total reported number of household members on the trip helped identify if children who were household members but not survey participants were along for the ride. (A child under the age of ten would not have a person identifier but would be included in the total number of household members on the trip.) If children under age ten were present, their number was subtracted from the total reported household members in the vehicle for calculating of vehicle occupancy.

Bus

Bus trips include school and transit trips. Accurate calculation of emissions for these trips suffers from assumptions of occupancy and static speed. Occupancy rates for school and transit buses were assumed to be 20 persons in off-peak conditions and 50 during peak periods. Emissions for bus trips were estimated using the portion of the trip that occurred on the bus, divided by the occupancy rate. For the calculation of these emissions, it was assumed that any local road travel occurred outside of the bus. In other words, bus trips were assumed only to take place on arterial and freeway trip links.

Motorcycle/Moped

Motorcycles were modeled exactly like light-duty automobiles. Using Mobile 6.2, the ratio of the average gram / mile emissions rates for motorcycles as compared with the average light duty auto was used to create a 60 percent factor for the calculation of motorcycle emissions. It was also assumed that motorcycle trips had an occupancy rate of one driver.

Non-motorized

Walk and bicycle modes were assigned zero emissions.

Carpool

Carpools were assumed to have an average occupancy rate of 2.2.

Vanpool

Vanpools were assumed to have an occupancy rate of 7 persons per van. Trip emissions were factored by these rates to reflect the per person trip emissions.

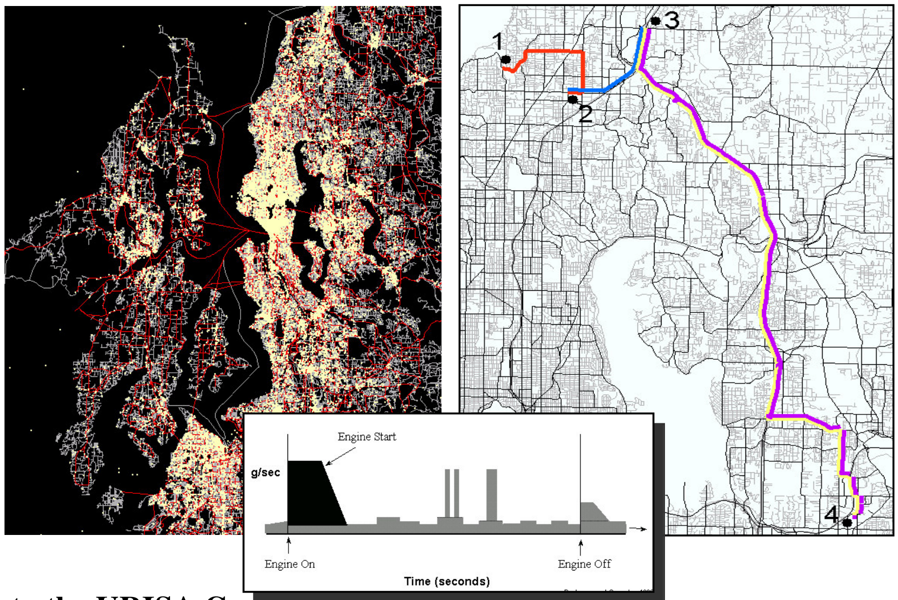
Taxi/Limousine

Emissions created by taxi and limousine trips were increased by 50% to account for the extra distance required for pickup and return. Vehicle occupancy was calculated in the same manner as other light duty automobiles.

APPENDIX 3: ESTIMATING VEHICLE TRIP EMISSIONS FROM TRAVEL SURVEY DATA

NOTE: This appendix is not for distribution. The work described here was funded by King County, Washington, the Federal Transit Administration, and the Bullitt Foundation. This article has been submitted for journal publication.

Estimating Vehicle Trip Emissions from Travel Survey Data



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Abstract:

Understanding the complex relationship between travel behavior, land use, and public health can be vastly improved through the inclusion of disaggregate or household level measures of vehicle emissions. Our study presents a methodology to derive systematic trip-level emissions from regional household activity and travel studies. These emission estimates provide the basis for modeling statistical relationships between household and person level travel choices, land use patterns, and regional air quality. Emissions information can be estimated for these trips by triangulating reported elements from activity surveys, observed facility performances, design characteristics, and estimated activity parameters revealed in a travel-forecasting model. Therefore, the objectives of this research are to; (1) develop a travel activity estimation methodology that provides necessary variables for trip-level emissions modeling, (2) estimate emissions using the most current USEPA modeling tools, (3) separately model engine start emissions and running exhaust emissions. This concept and technical process is being conducted in two urban areas (Seattle and Atlanta). The process for developing emissions for trips involves estimating the amount of travel time spent on a variety of facility classes and the running of MOBILE 6.2 for a variety of possible trip conditions. Preliminary findings document significant inverse relationships between measures of land use and per capita emissions, after controlling for demographics and regional location.

Purpose and Objectives

Lawrence Frank and Company (LFC) and GeoStats are currently under contract with King County, Washington to look at regional and community based land use and transportation investment strategies that can help to offset auto use and air pollution while promoting physical activity. The study's environmental emphasis supports the estimation of trip-level emissions from the 1999 Puget Sound Regional Council's household activity survey. These emissions estimates for the recorded trips in this survey provides the ability to generate a variety of statistical measures that potentially identify how land use policies and practices impacts not only travel choice, but also air quality. Emissions information can be estimated for these trips using reported elements from the activity survey, and from estimated activity parameters. This paper summarizes techniques used to develop a sub trip level approach to calculating vehicle emissions based on household travel data.

The major objectives of this research were:

- To develop a travel activity estimation methodology that provides necessary variables for trip-level emissions modeling
- To estimation emissions using the most current USEPA modeling tools
- To separately model engine start emissions and running exhaust emissions

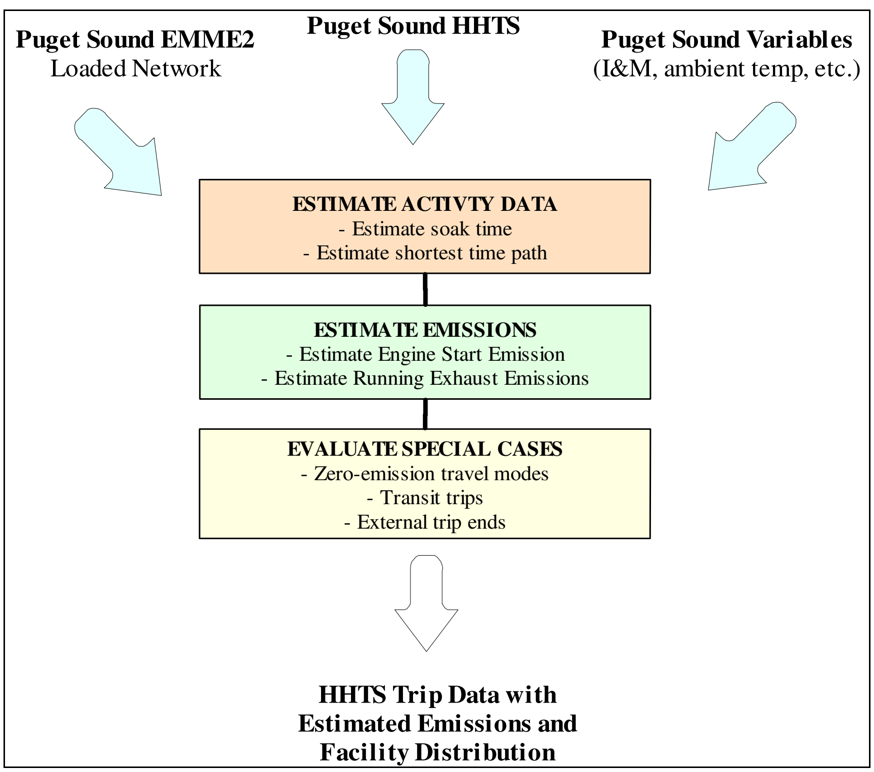


Figure 1 – General process for estimating trip level emissions

The general process for the work conducted in the Puget Sound is shown in Figure 1. Travel survey data, Puget Sound programmatic and atmospheric variables, and the Puget

Sound loaded travel demand forecasted model were used as inputs into the process. These elements were used in estimating a link-based emissions factor for each of the trips in the survey. Subsequent aggregation of the emissions per link to the trip, person, and household level enabled the assessment of systematic variation between levels of emissions and specific land use and transportation investment policies under consideration in that region. Findings from this estimation process, including model coefficients are being applied to assess the efficacy of specific programmatic actions at reducing criteria and greenhouse gas emissions for that region.

Trip Activity

For this study, trip activity refers to the mode, path, speed and travel time for the reported trip. Reported fields were used as much as possible to define the trip activity. Some of the reported information could be used to define the emission-specific characteristics of the trip, while other reported elements were used to derive further unreported parameters.

Engine Start Activity (soak time)

The amount of time that a vehicle is at rest with the engine off is an important factor (soak time) in estimating the extent of elevated emissions that occur during the beginning of a trip. A vehicle that has cooled off significantly will require a longer period of time before an engine temperature reaches a point when on-board emissions control equipment can operate efficiently. Shorter engine-off periods do not require as much time (warm starts). Estimating the amount of 'soak time' is simply a matter of determining the amount of time between trips.

Running Exhaust Activity

Running exhaust activity refers to trip characteristics that are necessary for predicting hot-stabilized emissions. The most current USEPA mobile emissions model (MOBILE 6.2) allows users to separately calculate emissions for different road facility types (local, arterial, ramp, and freeway). This has been recently added to the MOBILE 6.x series of models because the driving characteristics (acceleration rates) vary enough amongst the different facility types to warrant different baseline emission rates. This suggests that a vehicle with an average speed of 45 on an arterial has different emissions than a vehicle with an average speed of 45 on a freeway. This capability can help to evaluate the differences in trip emissions for two different trips that have similar travel times but different travel distances. In addition, this also enables us to assess differences in emissions based on the proportion of trip by facility type while accounting for facility performance or "congested flows."

Since the reported trip paths were not recorded, the average speed and distance by facility type must be estimated. The origin and destination coordinates, the trip start time, and loaded Puget Sound Travel Demand Forecasting model networks (AM peak, PM peak, and Off peak) were used in this process as follows:

1. The distance from the origin to the closest point on the road network was determined and stored.

2. The distance from the destination to the closest point on the road network was determined and stored.
3. These estimated distances approximate the amount of local road travel experienced by the traveler.
4. The shortest time path was estimated from the origin to the destination using link travel times (AM peak, PM peak, or Off peak) as determined by the reported trip start time.
5. The traversed links were stored along with the estimated average speed and facility type.

This process was followed for each trip recorded in the survey database. Figure 2 graphically depicts a sequence of consecutive trips as determined from this process.

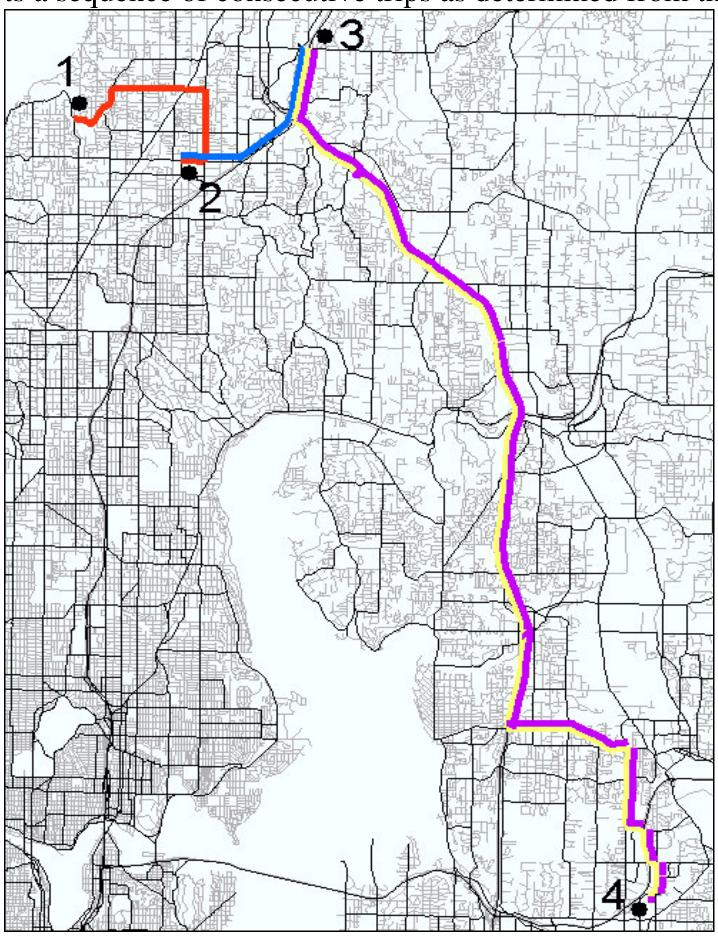


Figure 2 - Sequence of trips for respondent

<u>Methodology Assumptions</u>

Two primary assumptions in this estimation process are defined as follows:

Estimated path vs. actual path: The estimated path represents the shortest travel time path for the estimated congestion conditions represented in the loaded model network. The actual travel path followed by the survey respondent may be quite different. This may not be as important as it seems because we are really only identifying the average speeds and fractions of the trip that occurs on arterials and freeways. The respondent's reported time is better indicator of the actual travel time than the estimated path time. The main assumption is that the estimated path is representative of the average speeds by facility type.

Local road travel: Since local roads are not represented in the model networks, Euclidean distances at an average speed of 15 mph were used. The MOBILE 6.2 model assumes that local road average speeds are 22 mph. Our slower speed is designed to account for the fact that the local road path is not as direct as the Euclidean distance.

Trip-Level Emissions Estimation

Emission factors were estimated using the USEPA's MOBILE 6.2 model. These factors were applied to the vehicle activity estimates described in section 2 in order to generate grams of CO, HC, NOx, and CO_2 for each unique trip. Emissions were separately estimated for engine start and running exhaust pollutants in order to facilitate subsequent analysis.

Engine Start Emissions

MOBILE 6.2 allows for 70 different ranges of engine soak time (period of engine 'cool down' between trips). Soak time is the dominant variable in estimating the amount of elevated emissions due to cold or warm start conditions. First, MOBILE 'header', and 'run' parameters were identified for the Seattle region and placed into a MOBILE6 input file. A separate utility program was created to generate the 70 ASCII lookup tables that cover the allowed time ranges (i.e. 1-2 minutes, 30-35 minutes). 'Scenarios' were added to the input file for each of the 70 possible soak time ranges. MOBILE 6.2 was run with the input file to generate a lookup table that was applied to the individual trips. Another utility program was written and used to cycle through each of the trips and apply the correct engine start value. Figures 3 through 5 show the range of values for each pollutant. CO_2 is not elevated during engine start conditions and does not vary significantly by soak time.

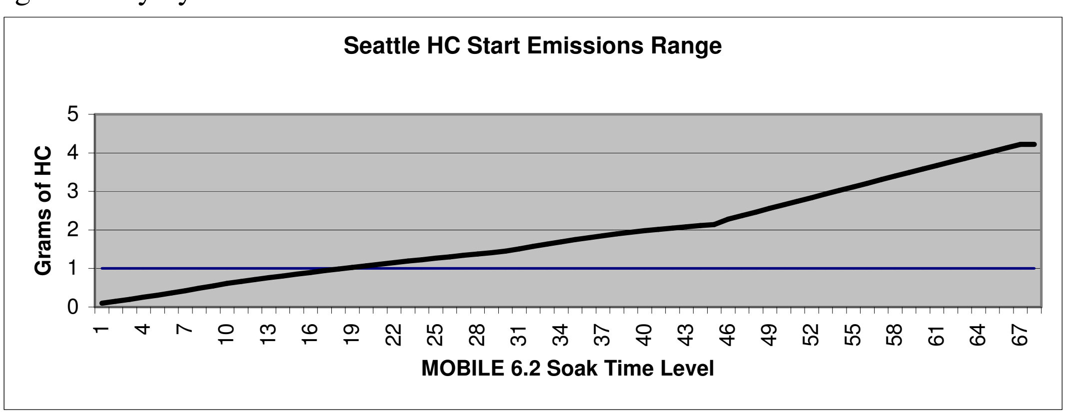


Figure 3

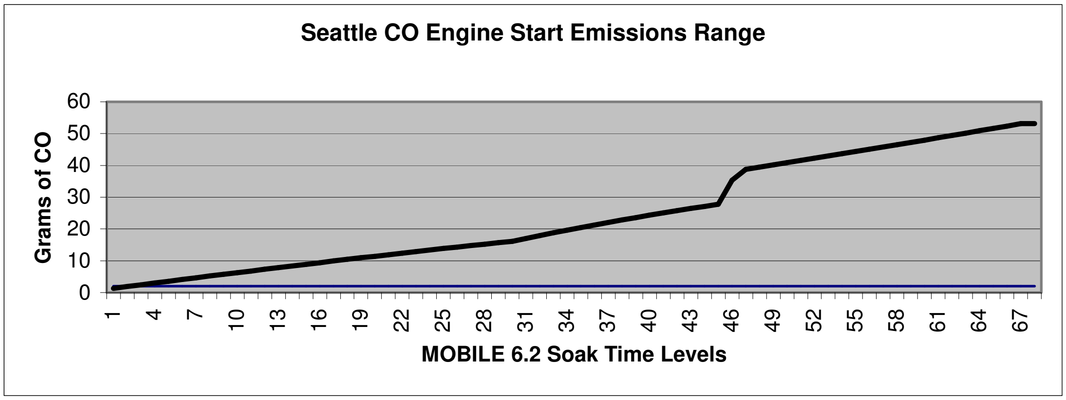


Figure 4

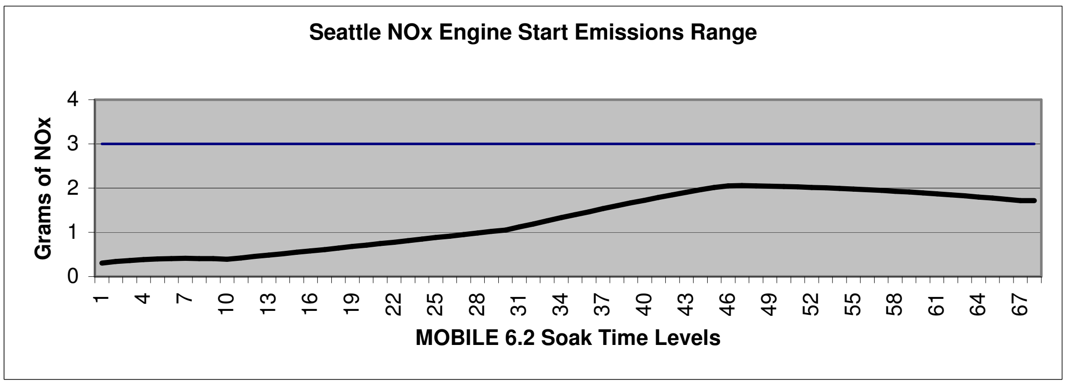


Figure 5

Running Exhaust Emissions

Running exhaust emissions were estimated for each trip in an approach similar to the one used for engine start emissions. MOBILE 6.2 was used to generate a Seattle-specific emissions factor lookup table for each pollutant. MOBILE 6.2 scenarios were generated for each possible speed (5 mph increments) and facility type classification (freeways, arterials, and local roads). Figures 6-8 show the emission rates curves generated in this process. It should be noted that local road emissions do not vary by speed. Therefore, an assumed speed of 22 MPH was applied within MOBILE 6.2 regardless of other input file parameters. It should also be noted that there is very little difference in the emission rates for freeway and arterial for given speed ranges suggesting only limited sensitivity to speed profiles unique to each facility type (e.g. stop and start conditions arterials versus what is more often observed on limited access facilities).

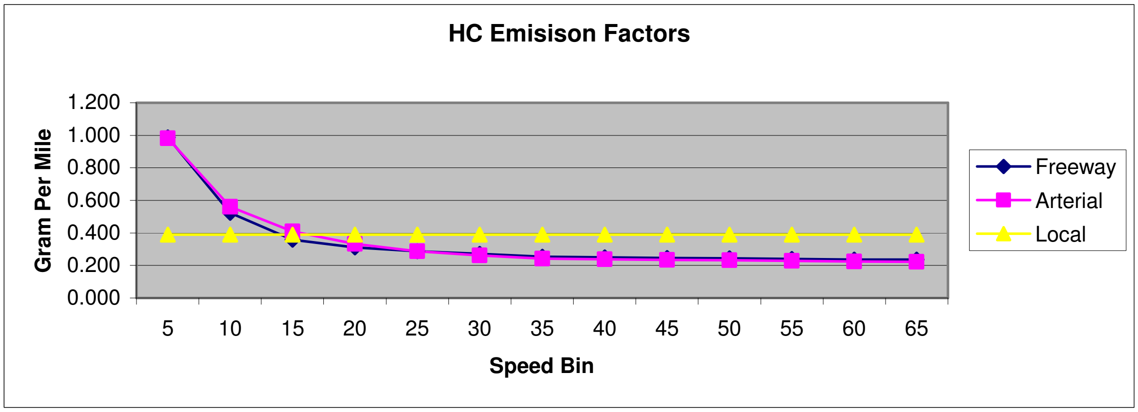


Figure 6

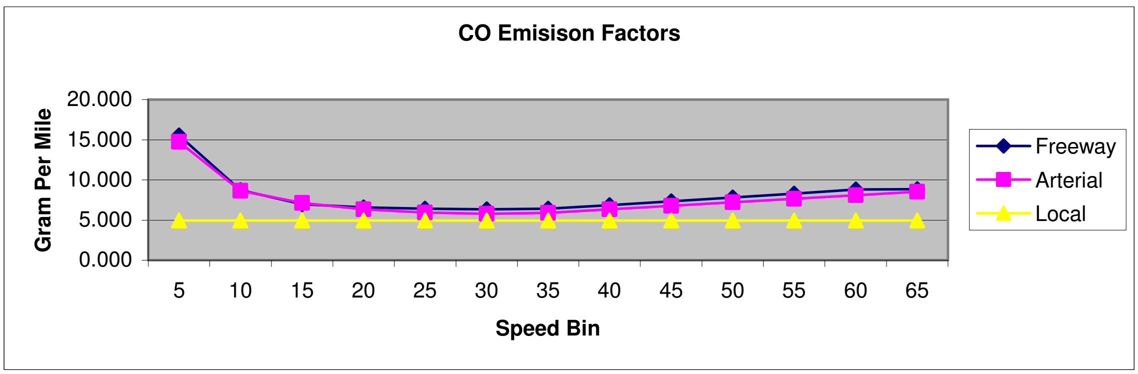


Figure 7

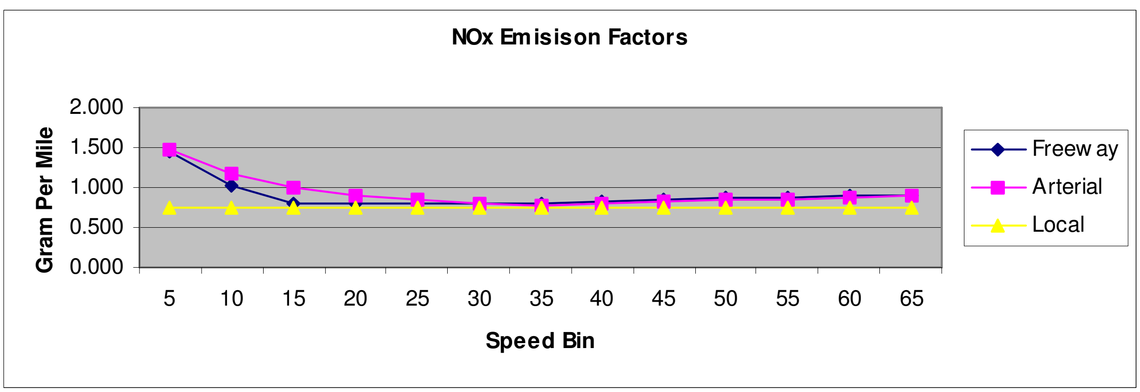


Figure 8

Assumptions

In both engine starts and running exhaust emissions modeling, assumptions were made regarding the operating conditions and the vehicle age. The model was run assuming that the trips were conducted in July, 1999, that an inspection and maintenance program was being conducted using an IM240 test for odd model year vehicles, and that a default national model year distribution represents Seattle distributions.

Mode Specific Adjustments and Trip Ends

Modal Adjustments

Motorcycle and bus emission rates followed a similar procedure as identified in section 3, but the vehicle type was modeled explicitly. Therefore emission factor lookup tables were generated for both vehicle types.

Buses: Bus trips include school and transit trips (modes 18 and 20). Occupancy rates were assumed to be 20 persons during off-peak conditions and 50 during peak periods. Also, no engine start emissions were assigned to the individual trips. Bus trips also assumed that any estimated local road travel occurred outside of the bus during a trip chain. Bus trips, therefore, only included arterial and freeway trips. Emissions for a person's transit trip were estimated using the portion of the trip that occurred on the bus, divided by the occupancy.

Motorcycles: Motorcycles were modeled exactly like light-duty automobiles except that separate emission factor lookup tables were generated and used.

Non-motorized: Non-motorized modes were assigned 0 emissions. (modes: walk, ferry, bicycle, other, and dk/rf).

Carpool / Vanpool: Carpools were assumed to have an average occupancy rate of 2.2 and vanpools were assumed to have an occupancy rate of 7. Trip emissions were factored by these rates to reflect the per person-trip emissions.

Trips with an External Trip End

Trips that one or both ends outside the model network area were handled in a separate manner to estimate the facility percentages. If the trip was 5 minutes or shorter, it was assumed that the person traveled on local roads only. For trips less than 15 minutes, ten minutes of travel were assigned to arterials and five minutes to local. Any portion of a trip outside the study area and greater than 15 minutes in duration was assigned to freeways. These factors were defined from brief analyses of long trips within the study area.

Results

Table 1 summarizes some of the results from the analysis by reviewing mean emissions by travel mode. A few issues are identified in this table that reveal a need for further refinement. Of particular concern are the school bus and bus transit trips. Emissions for these trips suffer from assumptions regarding occupancy and average speed. Off-peak occupancies were assumed to be 20 persons (peak occupancies were assumed to be 50). Also, travel speeds for buses were assumed to be the same as the modeled link average speed. Reality may show that these speeds are below average. The effect of the increased speed could cause elevated estimation of NOx emissions.

Table 1 - Mean trip emissions by mode

Mode	Number of trips	Mean HC (grams)	Mean CO (grams)	Mean NOx (grams)	Mean CO2 (grams)
Auto Driver	63907	2.61	62.6	7.99	3470
Auto Passenger	22790	1.10	25.7	3.32	1447
Walk	6185	0.00	0.0	0.00	0
School Bus	2818	Xx	xx	xx	xx
Bus (Transit)	2641	2.29	48.0	9.10	1474
Carpool Passenger	946	1.26	30.5	3.87	1677
Bicycle	943	0.00	0.0	0.00	0
Ferry / Boat	663	0.00	0.0	0.00	0
Other	222	0.00	0.0	0.00	0
Carpool Driver	217	1.59	39.0	4.89	2118
Vanpool Passenger	212	0.86	22.4	2.75	1184
Motorcycle, moped	95	12.01	69.9	7.31	1587
Vanpool Driver	63	0.51	12.5	1.58	679
Taxi / Limo	42	5.01	115.5	15.02	6451
DK / RF	22	0.00	0.0	0.00	0

Summary and Conclusions

While considerable attention and debate exists over the impacts of urban sprawl on the environment, surprisingly little work has been done to document the effects of specific land use and transportation investment policies on household vehicle emissions. This paper presents a new approach to estimate household vehicle emissions at the sub trip or facility link level. We believe that this approach can become a useful tool for various agencies to employ to assess how specific transportation and land development activities will, in concert, result in better or worse air quality when factored at the regional scale. While in-vehicle GPS will bring additional objective information on travel patterns, the widespread use of GPS within travel data collection will be several years in the making. In the meantime, more rigorous methods to assess actual travel choices and their air quality impacts are desperately needed. This paper is one attempt to move the state of the practice in this direction and to provide decision makers with a cost effective source of information that can readily be applied at the project or site, sub area, and regional scales.

Bibliography

Bachman, William, Towards a GIS-Based Modal Model of Automobile Exhaust Emissions, US Environmental Protection Agency, Air Pollution Prevention and Control Division, 1998.

Frank, Larry, Brian Stone William Bachman, “Linking Land Use with Household Vehicle Emissions in the Central Puget Sound: Methodological Framework and Findings”, Transportation Research Part D, p 173-196, Elsevier Science, New York, NY. 2000.

Frank, Larry, William Bachman, Brian Stone, "Testing Urban Design and Air Quality Relationships in the Atlanta Metropolitan Region", International Journal of Vehicle Design, International Scientific Symposium, Avignon, France.

Frey, Christopher H., Alper Unal, and JianJun Chen, “On-Board Emission Data Analysis and Collection for the New Generation Model,” Research Report, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Ann Arbor, MI, 2002.

U.S. Environmental Protection Agency, “User’s Guide to MOBILE 6.1 and MOBILE 6.2: Mobile Source Emissions Factor Model”, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Ann Arbor, MI, 2002.

U.S. Environmental Protection Agency, “EPA’s Onboard Analysis Shootout: Overview and Results”, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Ann Arbor, MI, 2002.

REFERENCES

Badoe, D.A. and E.J. Miller (2000) “Transportation—land-use interaction: empirical findings in North America and their implications” *Transportation Research Part D: Transport and Environment* 5: 235 – 263.

Boarnet, M.G. and R. Crane (1998) “Public finance and transit-oriented planning: evidence from Southern California” *Journal of Planning Education and Research* 17: 206 – 219.

Boarnet, M.G. and R. Crane (2001) *Travel by Design: The Influence of Urban Form on Travel.* Oxford: Oxford University Press.

Boarnet, M.G. and S. Sarmiento (1998) “Can land use policy really affect travel behavior?” *Urban Studies* 35: 1155 – 1169.

Cervero, R. (1989) *America’s Suburban Centers—The Land Use-Transportation Link*. Boston: Unwin Hyman.

Cervero, R. (1991) “Land use and travel at suburban activity centers” *Transportation Quarterly* 45: 479 – 491.

Cervero, R. (1996) “Mixed land uses and commuting: evidence from the American Housing Survey” *Transportation Research Part A: Policy and Practice* 30: 361 – 377.

Cervero, R. (2002) “Built environments and mode choice: toward a normative framework” *Transportation Research Part D: Transport and Environment* 7: 265 – 284.

Cervero, R. and R, Gorham (1995) “Commuting in transit versus automobile neighborhoods” *Journal of the American Planning Association* 61: 210 – 225.

Cervero, R. and K. Kockelman (1997) “Travel demand and the 3Ds: density, diversity, and design” *Transportation Research Part D: Transport and Environment* 2: 1999 – 219.

Crane, R. (2000) “The influence of urban form on travel: an interpretive review” *Journal of Planning Literature* 15: 3 – 23.

Crane, R. and R. Crepeau (1998) “Does neighborhood design influence travel? A behavioral analysis of travel diary and GIS data” *Transportation Research Part D: Transport and Environment* 3: 225 – 238.

Curtis, F.A., L. Neilsen, and A. Bjornsor (1984) “Impact of residential street design on fuel consumption” *Journal of Urban Planning and Development* 110: 1 – 8.

Ewing, R. and R. Cervero (2001) “Travel and the built environment: a synthesis” *Transportation Research Record* 1780: 87 – 114.

Ewing, R., T. Schmid, R. Killingsworth, A. Zlot, S. Raudenbush (2003) “Relationship between urban sprawl and physical activity, obesity, and morbidity” *American Journal of Health Promotion* 18(1): 47 – 57.

Frank, L.D. and G. Pivo (1995) “Impacts of mixed use and density on utilization of three modes of travel: single-occupant vehicle, transit, and walking” *Transportation Research Record* 1466: 44 – 52.

Greene, W.H. (2000) *Econometric Analysis 4th ed.* Upper Saddle River, N.J.: Prentice Hall.

Handy, S. (1996a) “Understanding the link between urban form and nonwork travel behavior” *Journal of Planning Education and Research* 15: 183 – 198.

Handy, S. (1996b) “Methodologies for exploring the link between urban form and travel behavior” *Transportation Research Part D: Transport and Environment* 1: 151 – 165.

Handy, S. (2002) "Travel behavior-land use interactions: an overview and assessment of the research" in H.S. Mahmassini (ed.) *In Perpetual Motion: Travel Behavior Research Opportunities and Application Challenges*. Kidlington, UK: Elsevier Science, 223 – 236.

Kennedy, P. (2003) *A Guide to Econometrics 5th ed*. Malden, MA: Blackwell Publishing.

Kockelman, K.M. (1997) "Travel behavior as a function of accessibility, land use mixing, and land use balance: evidence from San Francisco Bay area" *Transportation Research Record* 1607: 116 – 125.

McCann, B.A. and R. Ewing (2003) *Measuring the Health Effects of Sprawl: A National Analysis of Physical Activity, Obesity and Chronic Disease*. Washington, DC: Smart Growth America, Surface Transportation Policy Project.

McFadden, D. 1974. "Conditional Logit Analysis of Qualitative Choice Behavior." Pp. 105 – 142 in *Frontiers in Econometrics*, edited by P. Zarembka. New York: Academic Press.

McFadden, D. (1981) "Econometric Models of Probabilistic Choice" in C.F. Manski and D. McFadden (eds.) *Structural Analysis of Discrete Data Using Econometric Applications*. Cambridge, MA: MIT Press, 198 – 272.

McNally, M.G. and A. Kulkarni (1997) "Assessment of influence of land use-transportation system on travel behavior" *Transportation Research Record* 1607: 105 – 115.

McNally, M.G. and S. Ryan (1993) "Comparative assessment of travel characteristics for neotraditional designs" *Transportation Research Record* 1400: 67 – 77.

Messenger, T. and R. Ewing (1996) "Transit-oriented development in the sunbelt" *Transportation Research Record* 1552: 145 – 153.

Mitchell, R.B. and C. Rapkin (1954) *Urban Traffic: A Function of Land Use*. New York: Columbia University Press.

Newman, P.W.G. and J.R. Kenworthy (1989) *Cities and Automobile Dependence: A Sourcebook*. Brookfield, VT: Gower Technical.

Openshaw, S. (1984) *The modifiable areal unit problem*. CATMOG (Concepts and Techniques in Modern Geography) 38. Norwich: Geo Books.

Peiser, R.B. (1984) "Land use versus road network design in community transport costs evaluation" *Land Economics* 60: 95 – 109.

Ross, C.L. and A.E. Dunning (1997) *Land Use Transportation Interaction: An Examination of the 1995 NPTS Data*. Washington, DC: U.S. Department of Transportation.

Small, K.A. (1992) *Urban Transportation Economics*. Chur, Switzerland: Harwood Academic.

Stead, D. (2001) "Relationship between land use, socioeconomic factors, and travel patterns in Britain" *Environment and Planning B: Planning and Design* 28: 499 – 528.

Steiner, R.L. (1995) "Residential density and travel patterns: review of the literature" *Transportation Research Record* 1466: 37 – 43.

Train, K.E. (1986) *Qualitative Choice Analysis: Theory, Econometrics, and an Application to Automobile Demand*. Cambridge, MA: MIT Press.

APPENDIX 4: PROCESS TO AGGREGATE LAND USE DATA TO BUFFERS

Two data layers were used to construct these measures-- the buffer layer for each county and the building/parcel point layer.

The purpose of the land use measures was to calculate selected attributes (see below) of the building and parcel points that lie within the extent of each buffer and aggregate these attributes into one record that correspond with the buffer in which these building and parcel points were located. Within the build/parcels layer were a total of 22 different land use types as listed in Table 50.

Table 50: Land Use Categories

Number	Land use	Number	Land use
1	Agricultural	12	Neighborhood Retail
2	Civic	13	Office Building
3	Doctor-Dentist	14	Open Space
4	Educational	15	Other
5	Entertainment	16	Park
6	Fast Food	17	Parking
7	Grocery	18	Recreational
8	Industrial	19	Restaurant
9	Large Retail	20	Single Family
10	Multi Family	21	Unknown
11	Museum	22	Vacant

The specific attributes that make up the land use measures include:

- Identification of land uses within each buffer
- Total number of each land use within the buffer
- Total parcel area for each land use within the buffer
- Total building area for each land use within the buffer
- Total number of building/parcel records that had missing land use data within each buffer

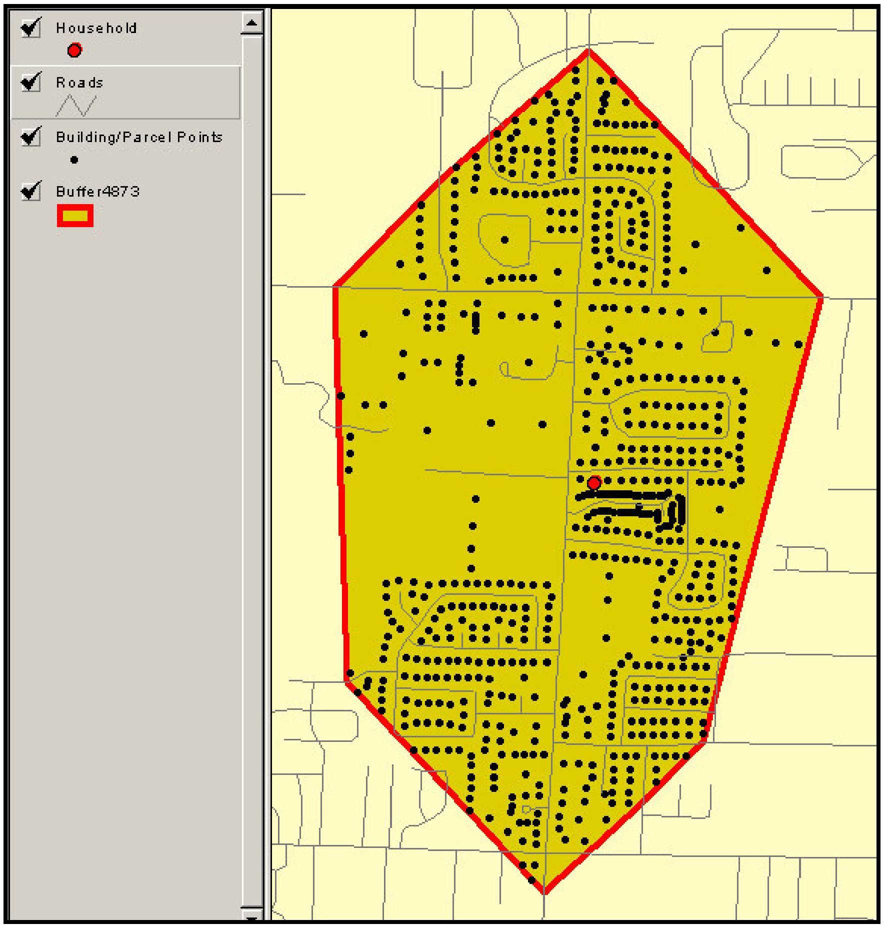
- Total number of building/parcel records that had missing latitude and longitude coordinates within each buffer
- Total number of parcel records within the buffer where there was no value for floor area
- Total number of building records where the build area was imputed

In order to calculate these measures, three main stages were followed, namely summarization, land use base table construction, and aggregation. The first step in the summarization stage was to first create a linking field between the summary tables and the soon to be land uses table, in addition to, a link back to the original buffers table. To do this, a new field was added in the Buffers table called Buffer_id and was coded as sequential numbers from 1 to 23, 654 (based on the total number of buffers) for the survey data.

Next, each record in the buffer table was intersected with the records in the building/parcel point table. Figure 1 illustrates one of the buffers and the points that lie within or on the boundary of the buffer. The buffer boarder is represented by the red outline and the buildings/parcel points are represented by the black dots.

Figure 6 illustrates the tabular form of this transaction. The table on the left shows the selected buffer while the table on the right shows the building/parcel records that intersect with the buffer.

Figure 6: Buffer (1km road network based) with Building & Parcels Points



These selected parcels were then summarized based on the land use measures listed above and exported to their own layer. An example of the summary table is illustrated in Figure 7. The name of the exported summary layers equaled the buffer_id. For example, if the buffer_id equaled 1, then the name of its output summary layer also equaled Buffer1.shp. Similarly, if the buffer_id equaled 345, then its output summary layer would equal Buffer345.shp. The end result of this step was 23,654 individual survey data layers, one for each buffer from the original buffer table.

Figure 7: Tabular View of Selected Buffer & Associated Building/Parcels Points

Attributes of Survey_buffers_kitsap...

Shape	Site_id	Xcoord	Ycoord	Buffer_
Polygon	4873	1194997.85	225216.70	
Polygon	4874	1195003.75	229882.68	
Polygon	4875	1195049.04	202932.18	
Polygon	4876	1195075.13	235848.34	
Polygon	4877	1195079.62	200804.45	
Polygon	4880	1195207.87	159269.78	
Polygon	4881	1195309.75	271592.31	
Polygon	4882	1195459.11	202745.01	
Polygon	4883	1195503.92	184693.25	
Polygon	4884	1195699.59	254115.57	
Polygon	4885	1195706.37	186159.87	
Polygon	4886	1195754.24	275666.52	
Polygon	4887	1195756.13	274920.78	
Polygon	4888	1195773.85	156150.98	
Polygon	4889	1195786.54	185079.75	

Attributes of Survey_points_kitsap.shp

Shape	Parcel_id	F_x_y	Lfc_22_cat
Point	513400001300	1.00	Single Family Residentia
Point	494800004900	1.00	Single Family Residentia
Point	494800005800	1.00	Single Family Residentia
Point	445100004000	1.00	Single Family Residentia
Point	445100003900	1.00	Single Family Residentia
Point	352501302820	1.00	Single Family Residentia
Point	445100003800	1.00	Single Family Residentia
Point	494800005100	1.00	Single Family Residentia
Point	494800005200	1.00	Single Family Residentia
Point	413700005800	1.00	Single Family Residentia
Point	413700004900	1.00	Single Family Residentia
Point	445100003700	1.00	Single Family Residentia
Point	448300000600	1.00	Single Family Residentia
Point	332502402220	1.00	Single Family Residentia
Point	352501403420	1.00	Single Family Residentia
Point	494800005700	1.00	Single Family Residentia
Point	413700003500	1.00	Single Family Residentia
Point	413700005800	1.00	Single Family Residentia
Point	352501302420	1.00	Single Family Residentia
Point	322401406620	1.00	Industrial
Point	494800005300	1.00	Single Family Residentia
Point	494800005400	1.00	Single Family Residentia
Point	494800005500	1.00	Single Family Residentia
Point	494800005600	1.00	Single Family Residentia
Point	352501409220	1.00	Multi Family Residential
Point	448300001900	1.00	Single Family Residentia

With the summary values calculated, there was the issue of condensing the data from the multi-record buffer summary tables into one record that equaled the buffer_id. To do this, the construction of a new land use base table was required (Stage 2). In this table, each land use from the summary table was used as a field in the new table. For example, the land use Civic has seven fields in the summary table in Figure 8, namely Count, Sum_built (Building Area), Sum_newarea (Parcel area), Sum_ f_miss (records or building points with missing land use data), Sum_f_x_y (records or building points with no xy coordinates), Sum_f_u200 (records or building points with no building floor area), and Sum_f_impb (records or buildings points where the build area was imputed). These fields correspond to the land use measure attribute data noted in the bullet listing above. Thus, seven new fields were added to the base table, one for each of the above seven attributes for each land use. Since there were 22 land uses and seven measures for each land use, a total of 154 fields were added to the urban measures database table. The names of each field and their definition can be found in Table 51. A buffer_id field was also added to the land use base table (as noted above) in addition to 23,654 records for the survey (one record for each household).

Figure 8: Sample of a Summary Table

Attributes of S_ks_b167.shp

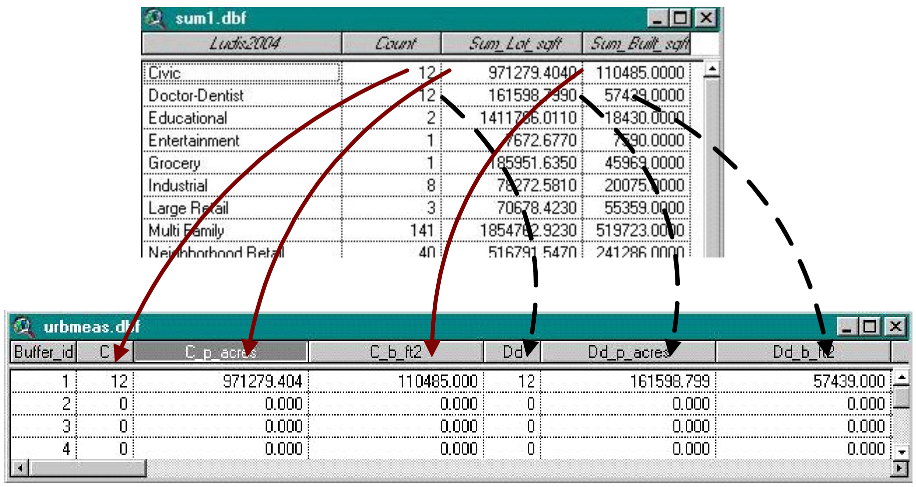
Shape	Lfc_22_cat	Count	Sum_built	Sum_newpar	Sum_f_miss	Sum_f_x_y	Sum_f_u200	Sum_f_impb
MultiPoint	Civic	15	38890.0000	402496.2360	0.0000	10.0000	0.0000	0.0000
MultiPoint	Fast Food Restaurant	1	1851.0000	8435.6950	0.0000	1.0000	0.0000	0.0000
MultiPoint	Multi Family Residential	38	21567.0000	1123519.5420	0.0000	14.0000	0.0000	0.0000
MultiPoint	Museum	1	5079.0000	4746.4090	0.0000	1.0000	0.0000	0.0000
MultiPoint	Neighborhood Retail	1	4520.0000	320.0260	0.0000	1.0000	0.0000	0.0000
MultiPoint	Office Building	3	5204.0000	61312.1470	0.0000	1.0000	0.0000	0.0000
MultiPoint	Other	10	7500.0000	520012.2590	0.0000	6.0000	0.0000	0.0000
MultiPoint	Park	6	0.0000	110779.2560	0.0000	0.0000	0.0000	0.0000
MultiPoint	Single Family Residentia	541	705569.0000	6071655.5250	0.0000	488.0000	0.0000	0.0000
MultiPoint	Unknown	6	5040.0000	74411.2540	0.0000	6.0000	0.0000	0.0000
MultiPoint	Vacant	51	0.0000	3130408.7070	0.0000	0.0000	0.0000	0.0000

Table 51: Field Definitions for Land Use Measures

#	Land Use Name	Count	Parcel Area	Building Area	Land use Missing Flag	Missing xy Flag	Bld No Floor Area Flag	Bld Floor Area Imputed Flag
1	Agriculture	AG	AG_P_ft2	AG_B_ft2	AG_f_miss	AG_f_x_y	AG_f_u200	AF_f_impb
2	Civic	C	C_P_ft2	C_B_ft2	C_f_miss	C_f_x_y	C_f_u200	C_f_impb
3	Doctor-Dentist	DD	DD_P_ft2	DD_B_ft2	DD_f_miss	DD_f_x_y	DD_f_u200	DD_f_impb
4	Educational	ED	ED_P_ft2	ED_B_ft2	ED_f_miss	ED_f_x_y	ED_f_u200	ED_f_impb
5	Entertainment	EN	EN_P_ft2	EN_B_ft2	EN_f_miss	EN_f_x_y	EN_f_u200	EN_f_impb
6	Fast Food	FF	FF_P_ft2	FF_B_ft2	FF_f_miss	FF_f_x_y	FF_f_u200	FF_f_impb
7	Grocery	G	G_P_ft2	G_B_ft2	G_f_miss	G_f_x_y	G_f_u200	G_f_impb
8	Industrial	IN	IN_P_ft2	IN_B_ft2	IN_f_miss	IN_f_x_y	IN_f_u200	IN_f_impb
9	Large Retail	LR	LR_P_ft2	LR_B_ft2	LR_f_miss	LR_f_x_y	LR_f_u200	LR_f_impb
10	Multi Family	MF	MF_P_ft2	MF_B_ft2	MF_f_miss	MF_f_x_y	MF_f_u200	MF_f_impb
11	Museum	MU	MU_P_ft2	MU_B_ft2	MU_f_miss	MU_f_x_y	MU_f_u200	MU_f_impb
12	Neighbourhood Retail	NR	NR_P_ft2	NR_B_ft2	NR_f_miss	NR_f_x_y	NR_f_u200	NR_f_impb
13	Office Building	OB	OB_P_ft2	OB_B_ft2	OB_f_miss	OB_f_x_y	OB_f_u200	OB_f_impb
14	Open Space	OS	OS_P_ft2	OS_B_ft2	OS_f_miss	OS_f_x_y	OS_f_u200	OS_f_impb
15	Other	O	O_P_ft2	O_B_ft2	O_f_miss	O_f_x_y	O_f_u200	O_f_impb
16	Park	P	P_P_ft2	P_B_ft2	P_f_miss	P_f_x_y	P_f_u200	P_f_impb
17	Parking	PK	PK_P_ft2	PK_B_ft2	PK_f_miss	PK_f_x_y	PK_f_u200	PK_f_impb
18	Recreational	RC	RC_P_ft2	RC_B_ft2	RC_f_miss	RC_f_x_y	RC_f_u200	RC_f_impb
19	Restaurant	RS	RS_P_ft2	RS_B_ft2	RS_f_miss	RS_f_x_y	RS_f_u200	RS_f_impb
20	Single Family	SF	SF_P_ft2	SF_B_ft2	SF_f_miss	SF_f_x_y	SF_f_u200	SF_f_impb
21	Unknown	UN	UN_P_ft2	UN_B_ft2	UN_f_miss	UN_f_x_y	UN_f_u200	UN_f_impb
22	Vacant	V	V_P_ft2	V_B_ft12	V_f_miss	V_f_x_y	V_f_u200	V_f_impb

The final step in the construction of the land use table was the aggregation of the summary values from stage one into its appropriate cell in the newly constructed land use base table. To do this, the name of the summary data layers were used to locate the buffers associated record in the land use table. For example, the summary values in Buffer1 would be plugged into the record containing the buffer_id of 1 in the land use table as illustrated in Figure 9.

Figure 9: Distribution of Values to Land Use Database Table



Once complete, the final products are two tables, one for each of the survey household buffers and their applicable land use measures.