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# Linking land use with household vehicle emissions in the central puget sound: methodological framework and findings

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**Abstract**

A leading cause of air pollution in many urban regions is mobile source emissions that are largely attributable to household vehicle travel. While household travel patterns have been previously related with land use in the literature (Crane, R., 1996. Journal of the American Planning Association 62 (1, Winter); Cervero, R. and Kockelman, C., 1997. Transportation Research Part D 2 (3), 199–219), little work has been conducted that effectively extends this relationship to vehicle emissions. This paper describes a methodology for quantifying relationships between land use, travel choices, and vehicle emissions within the Seattle, Washington region. Our analysis incorporates land use measures of density and mix which affect the proximity of trip origins to destinations; a measure of connectivity which impacts the directness and completeness of pedestrian and motorized linkages; vehicle trip generation by operating mode; vehicle miles/h of travel and speed; and estimated household vehicle emissions of nitrogen oxides, volatile organic compounds, and carbon monoxide. The data used for this project consists of the Puget Sound Transportation Panel Travel Survey, the 1990 US Census, employment density data from the Washington State Employment Security Office, and information on Seattle's vehicle fleet mix and climatological attributes provided by the Washington State Department of Ecology. Analyses are based on a cross-sectional research design in which comparisons are made of variations in household travel demand and emissions across alternative urban form typologies. Base emission rates from MOBILE5a and separate engine start rates are used to calculate total vehicle emissions in grams accounting for fleet characteristics and other inputs reflecting adopted transportation control measures. Emissions per trip are based on the network distance of each trip, average travel speed, and a multi-stage engine operating mode (cold start, hot start, and stabilized) function. 

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## 1. Introduction

A recent tightening of air quality standards by the Environmental Protection Agency (EPA) in conjunction with ever increasing traffic congestion within metropolitan regions has highlighted the need for a better understanding of the relationship between urban land use patterns and per capita travel demand (USEPA, 1997). [1] Factors responsible for increases in per capita miles of travel include increased auto ownership, changes in the demographic composition of households, and increases in trip distances associated with reduced density and increased separation of land uses (US Department of Transport, 1992; Frank and Pivo, 1995; Cervero, 1988). Further reductions in accessibility have occurred from the scarcity of pedestrian facilities (i.e. sidewalks), large building setbacks, and disconnected road network patterns that have characterized the latter half century of development in this country. As a result of these changes in urban form and individual travel behavior, mobile source emissions now account for over half of all emissions produced in major metropolitan regions nationwide (USEPA, 1997).

An informed inquiry of the relationship between land use and travel behavior must account for two aspects of accessibility that are impacted by development patterns: proximity and connectivity. For the purposes of this research, proximity is defined as the *linear* distance between trip origins and destinations, while connectivity describes the level of impedance or *route* directness associated with various travel options. As Fig. 1 illustrates, proximity in the absence of connectivity is often common within the familiar modern subdivision form. A product of design, the reduced connectivity of suburban street networks shown in the upper half of the diagram was developed to safeguard residential areas from "drive through" traffic. The unintended consequence of this development paradigm, however, has been an increase in the route distance between trip ends, reducing the viability of non-vehicle travel (Kulash, 1990). Ironically, our efforts to control vehicle traffic in modern urban forms have ultimately contributed greatly to vehicle use. The resulting debate over the influence of street network type (grid vs. cul-de-sac) on travel choices essentially boils down to one over the inherent levels of proximity and connectivity encompassed within each urban design framework (Crane, 1996, Frank, forthcoming).

From a transportation and air quality policy perspective, land use strategies are generally considered to be long-term approaches that are not politically viable solutions for mitigating today's traffic congestion or mobile source emissions. In the minds of many, once development is in place, it is arguably too difficult to change (McPherson, 1994). Yet, while the regional location and general form of existing development may not be substantially altered, there do exist a number of land use strategies for potentially improving air quality. These strategies include altering the design (i.e. "New Urbanism") and location (i.e. "Smart Growth") of new development and increasing the connectivity within and between existing developments (Katz, 1994; Calthorpe,

[1] In July 1997 the EPA announced a more restrictive NAAQS standard for ambient concentrations of ground-level ozone and particulate matter. Produced directly or indirectly from the combustion of fossil fuels, both pollutants are largely attributable to mobile sources within urbanized regions. In the case of ozone, "[m]any new health studies show that health effects occur at levels lower than the previous standard ..." (USEPA, 1997). The introduction of the new standard presents a greater challenge for regions that are currently out of attainment with the 1-h standard to devise strategies for compliance with the more restrictive 8-h standard. Land use approaches to reducing vehicle travel present a potentially viable compliance strategy over the long-term.

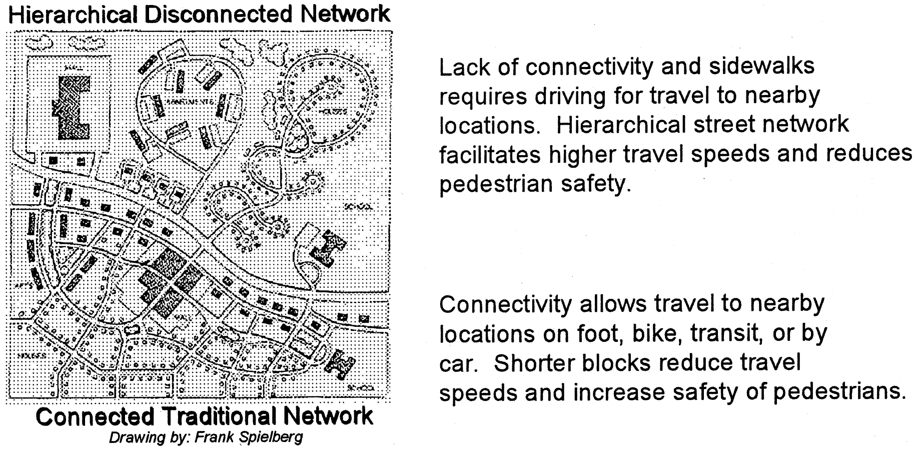


Fig. 1. Contrasting two forms of street network configuration.

1993). This research is designed to estimate the merits of improving connectivity where proximity between residential, employment and commercial areas is provided. This requires the ability to target where sufficient levels of density and land use mix are provided but there is little ability to get from "here to there", even if where you want to go is just around the corner. This approach is consistent with the theoretical premise of the gravity model which recognizes the ease of travel between two locations as a primary predictor of trip frequency or the level of travel demand between two locations (Brokke, 1958; Wilson, 1967).

This paper describes a methodology for analyzing the interaction between specific attributes of land use, household travel demand and associated vehicle emissions, while accounting for demographic factors cited as significant in the literature including income, household size, and vehicle ownership (Cervero and Radisch, 1995; Gordon, 1994; Giuliano, 1993). More recently, work has been conducted that suggests attitudes and values are largely accountable for travel patterns (and perhaps land use decisions) and that land use may merely masks these preferences (Kitamura, 1997). This line of reasoning is important because it suggests that policy implications from research presented here would be largely ineffective – that creating communities where people can accomplish some of their daily tasks without a car would have limited effect on travel demand and vehicle emissions.

This argument assumes that consumers are expressing their land use and travel preferences through their current choices. Moreover, that the locational and urban design attributes of the environments in which most live, work, and recreate are designed to meet the needs and desires of today's homeowners. We argue that it is not possible to discern actual preferences through expressed choices when the set of options are highly limited and overwhelmingly biased – in this case towards residential and employment locations that are auto-dependent (Leinberger, 1998). Any study which seeks to gauge the role of residential preference on travel must further account for the availability of a range of community options which are similar in cost, quality of education, crime rate, and address other socio-economic indicators which are independent of the physical aspects of community design. The growing popularity of neo-traditional designs with increased mix and density, smaller lot sizes, and building setbacks suggests that the true demand for a range of residential preferences is not currently being met through conventional subdivision templates.

### 1.1. Linking land use and vehicle emissions

While much disputed, a growing body of research has demonstrated that statistically significant relationships exist between the intensity of land use and the frequency and duration of vehicle travel (Cervero, 1993, 1995; Frank and Pivo, 1995; Cambridge Systematics, 1992; Holtzclaw, 1990). This project seeks to test such findings and to contribute to this area of inquiry through the development of a framework for linking land use patterns at the place of residence and employment with the generation of household vehicle emissions. The limited amount of work which has addressed the implications of land use on travel choice has not succeeded in providing a framework for the linking of land use to air quality, let alone one which can be applied to regional data in many areas of the US.

Due to the numerous variables involved in the emissions production process, including regional climate, fleet characteristics, and engine operating temperature, observed reductions in trip generation and vehicle miles of travel may not directly equate with emission reductions. For example, holding all other variables constant, a "warmed-up" vehicle will pollute at a lower rate than one that has been at rest for a period of time sufficient for the engine to cool. Thus, it is possible that a "cold start" trip will produce more emissions than a "hot start" trip, even if it is shorter in distance and duration. In consideration of the complexities of the emissions production process, it is important that an attempt be made to model emissions generation directly, rather than to assume air quality benefits necessarily accrue from vehicle travel reductions. It is the intent of this research to propose a methodology for estimating total vehicle emissions utilizing currently available data and emissions modeling techniques. This approach will further provide a platform to subsequently incorporate a wide range of factors influencing emissions including microscopic measures of vehicle operating characteristics and macroscopic measures of roadway design (Guensler et al., 1998; Bachman, 1997; NCHRP, 1997).

While previous work has established significant linkages between urban form and a range of individual travel behavior variables (i.e. trip generation, vehicle miles of travel, and vehicle hours of travel), this study presents a methodology for directly estimating vehicle emissions from travel survey data in order to better approximate the influence of land use on air quality. Using base MOBILE series emission rates, the total vehicle running exhaust emissions produced by households included in the 1996 wave of the Puget Sound Transportation Panel survey are estimated and associated with urban form characteristics of the residential and employment census tracts of survey participants. Table 1 provides a set of four general research questions and the associated hypotheses.

## 2. Research design

In consideration of the significance of mobile source emissions to regional air quality, the research design for this study provides a means of linking vehicle travel behavior to emissions directly. To do so, survey travel data is utilized as input for an emissions factor model to derive an estimate of survey household emissions of nitrogen oxides, carbon monoxide, and volatile organic

Table 1
Research questions and hypotheses

| Research question | Corresponding hypothesis |
|---|---|
| 1. Do the travel behavior variables of trip generation, vehicle miles of travel, and vehicle hours of travel provide an accurate indication of the air quality effects of vehicle travel? | Traditional measures of household travel behavior cannot be directly extended to the production of household vehicle emissions |
| 2. How responsive are total vehicle emissions per household to alternative patterns of development? | Increases in connectivity and proximity within urbanized regions are associated with overall reductions in vehicle emissions of nitrogen oxides ($NO_x$), carbon monoxide (CO), and volatile organic compounds (VOC) when controlling for household size, income, and vehicle ownership[a] |
| 3. How do the individual vehicle pollutants (CO, $NO_x$, HC) differ in their sensitivity to measures of proximity and connectivity? | Vehicle emissions of $NO_x$ exhibit a greater sensitivity to proximity and connectivity than CO or VOC |
| 4. Which land use and transportation strategies may be effective at reducing the formation of ground level ozone in $NO_x$ limited regions of the nation? | Land use strategies that reduce crow-fly distances between activities and transportation investment strategies that reduce network distances will reduce $NO_x$ and ozone formation – particularly in $NO_x$ "limited" regions of the nation |

[a] It is important to note that the emission rates generated by MOBILE5a have wide confidence intervals and may therefore only provide a rough approximation of the actual pollutant emissions produced by any single trip. The precise impacts of vehicle travel on air quality may only be conclusively addressed through the use of on-board data loggers for direct emissions monitoring. While actual emissions data has never been obtained for a large sample travel survey, the SMARTRAQ research effort currently underway at the Georgia Institute of Technology will utilize on board instrumentation for this purpose.

compounds. What follows in this section is a description of the travel survey, land use, and emissions generation components of the methodology.

### 2.1. Travel survey data

The database assembled for this research consists of three primary components including a travel survey, land use, and emissions factor dataset. The travel survey data utilized for this project was collected by the Puget Sound Transportation Panel (PSTP). "The PSTP is the first application of a general urban transportation panel survey in the US. Following the Dutch National Mobility Panel, it responds to the needs for direct data on the effects of demographic characteristics and transportation conditions on household travel behavior in an urban area" (Murakami and Watterson, 1990). Initiated in 1989, the PSTP records data from approximately 1700 households within the Puget Sound region of greater Seattle, Washington for two days each year. During the annual survey period, travel diaries are maintained by all household members over the age of fifteen. Travel data on variables such as the mode, travel time, and purpose of each trip taken are recorded. In order to obtain data on a statistically significant number of non-vehicle trips from a limited sample size, a "choice-based" sampling technique was used. Under a choice-based sampling design, households likely to utilize less common travel modes such as carpooling and transit are over-sampled in the survey. A set of weights are then applied to create a regionally representative sample for analysis. In addition to travel information, the PSTP travel survey collects information on a number of significant demographic variables such as household size, income, and vehicle ownership. The database constructed for this research incorporated the 1996 wave of PSTP data.

The emissions estimation procedure requires that five travel variables be operationalized from the raw travel survey data. These include vehicle trip generation, vehicle hours of travel, vehicle miles of travel, average trip travel speed, and the mode of engine operation. The first of these variables, vehicle trip generation, is easily constructed based upon the mode and trip generation records provided by the PSTP. Similarly, information detailing the time of day at which each trip began and ended provides the basis for determining the hours of travel for each vehicle trip. [2] As a result, trip distances were derived from a zonal network function that determines the shortest route distance between the centroids of the origin and destination census tracts. For short "intra-zonal" trips, this distance was estimated at one mile. [3] Once calculated, vehicle miles of travel were divided by the vehicle hours of travel variable to derive an estimate of average travel speed.

As noted above, the initial engine temperature is also significant to the emissions estimation process. The reason for this pertains to the effectiveness of catalytic converters, an emissions control device found in all vehicles manufactured after 1975 to reduce pollutant emissions (Boubel et al., 1994). Catalytic converters reduce emissions through a chemical reaction that increases in efficiency with increasing temperature. As a result, engines that are not sufficiently warmed-up do not reduce pollutant emissions as efficiently as hot engines. Based upon this relationship between engine temperature and emissions reduction, three modes of engine operation may be identified from the survey data. These include the cold start, hot start, and hot stabilized modes of operation. For the purposes of this research, all vehicle trips following a period of rest of 60 min or more are classified as cold starts. Periods of rest less than 60 min are classified as hot starts. The stabilized mode of engine operation reflects the highest temperature and is achieved only after the vehicle has been in operation for a period of time. EPA's Federal Test Procedure, the basis for the calculations performed by the MOBILE emission factor models, utilizes a threshold of 3.59 miles of driving to achieve the stabilized mode. This threshold was adopted here to identify trips that likely experienced more than a single mode of engine operation, and thus should have their emissions calculated in two stages.

In addition to the travel data collected by the PSTP, information on household demographics was obtained from the travel survey. As illustrated in previous work on the relationship between land use and travel choice, demographic variables such as household size, income, and vehicle ownership have clear and statistically significant relationships with expressed behavior (Holtzclaw, 1990; Kitamura et al., 1997). As a result, these variables must be controlled in an analysis of the relationship between land use and household travel behavior. In consideration of the fact that the household serves as the primary decision making unit for selecting a residential location, the household was selected as the unit of analysis for this study. The household is the unit at which the demographic and travel variables included with the survey data were collected. Table 2 presents descriptive statistics on the travel behavior and demographic information collected in the

[2] Although also collected by the PSTP, trip distance has been found to be unreliable as a self-reported variable in previous survey efforts (Frank and Stone, 1997).

[3] A distance of 1 mile was selected based upon the mean travel time estimated for trips beginning and ending in the same zone and an assumption that the mean overall travel speed of these vehicle trips is 20 miles/h.

Table 2
Household travel (two days) and demographics

| Variable | Range | Mean | S.D. |
|---|---|---|---|
| Vehicle trips | 1–96.00 | 15.19 | 9.60 |
| Cold start trips | 1–37.00 | 8.67 | 4.97 |
| Vehicle miles of travel | 1–653.90 | 121.83 | 95.42 |
| Vehicle hours of travel | 0.05–25.00 | 4.59 | 3.05 |
| Mean travel speed | 15–53.42 | 26.29 | 8.91 |
| Household size | 1–10 | 2.51 | 1.25 |
| Annual income[a] | <$10,000 – >$75,000 | $49,289 | $22,854 |
| Number of vehicles | 0–9 | 2.06 | 1.15 |

[a] Mean and standard deviations based on point estimates of categorical ranges.

PSTP's 1996 data wave. All statistics reflect household vehicle travel and are based upon two days of observation. Both the travel and the demographic data are presented.

### 2.2. Estimating vehicle emissions

The emissions estimation process requires that a stabilized rate of emissions be derived for each trip in the database in grams per second as a function of average travel speed. In addition to the stabilized emissions, engine start emissions are calculated based upon the soak time and the total trip travel time. [4] Once these modal emissions are estimated, total trip emissions are calculated by summing the stabilized and engine start emission totals. The stabilized emission rates were estimated using base MOBILE5a emission rates that were generated for 5 miles/h increments with start and evaporative emissions zeroed out, thus providing stabilized emissions as a function of average speed (Bachman, 1997). The start emissions were generated from a base cold start rate and a base 10-min soak warm start rate (USEPA, 1998). Total start emissions become a function of the total soak time, interpolating values between the 10-min rate and the cold start rate. It should be noted that both sets of stabilized and start emission rates assume a regional model year distribution for 1996.

Based upon these regional inputs, the emission rate models generate an emissions profile for an average or composite vehicle that reflects the characteristics of the region's fleet. Although not designed as a tool to associate vehicle emissions to land use, the generation of a single composite emissions profile adapts quite well to this purpose. The reason for this is that in order to isolate land use as a predictor of vehicle emissions, each of the vehicle specific characteristics relevant to

[4] The separate calculation of start and running emissions follows the framework of the forthcoming MOBILE6.

emissions must be controlled. For example, sport utility vehicles generate emissions at a higher rate than smaller, more fuel-efficient cars. Were the specifics of each vehicle driven by survey participants incorporated into the estimation process, it would be difficult to determine whether the variation in emissions across households was a product of different urban forms or different engine types. The use of a single, generic vehicle in the modeling process assumes that, all other variables remaining constant, each participant produces emissions at the same rate. This attribute of the model eliminates the need to control vehicle-specific criteria.

The emissions rates are sensitive to the travel variables of average speed and the mode of engine operation. Factors were generated for every speed falling between 5 and 80 miles/h in 5 miles/h increments. For trips in which the average speed fell between the 5 miles/h increments, interpolated emission rates were used. In addition, different emissions factors were needed for each of the three modes of engine operation: cold start, hot start, and stabilized. In order to most accurately account for the effect of engine temperature on emissions, start emissions were interpolated between the cold start rate, the 10-min warm start rate, and zero. Thus, a hot start following 20 min of engine rest resulted in a higher start emissions total than one following 10 min of rest. Fig. 2 illustrates the results of this process for the three vehicle pollutants of $NO_x$, CO, and VOC. This graph represents emission rates for a vehicle operating in the stabilized engine mode. Slightly different rates would result for a vehicle running in the cold start or hot start modes.

The final step in the emissions estimation process requires that the stabilized emissions rates be assigned to each vehicle trip and multiplied by the trip's total travel time in seconds. The engine start portion was then added to this total to generate the total trip emissions in grams for each pollutant. For trips shorter than the stabilized threshold of 3.59 miles, start emissions are adjusted to represent only the time the vehicle was running. For trips longer than 3.59 miles, start emission totals are added to the emissions for the portion of the trip dedicated to the lower stabilized rate. Emissions for these "multistage" trips were thus calculated by the following simple equation:

$$\text{Total trip emissions} = [\text{engine start rate} * [3.59/\text{average speed}]] + [\text{travel time} * \text{stabilized mode rate}].$$

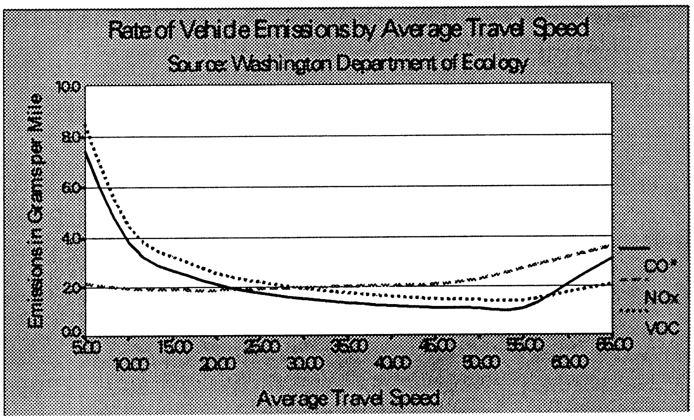


Fig. 2. Emissions profiles for stabilized mode (CO was reduced by a factor of 10 in order to present on common $y$-axis with $NO_x$ and VOC. Please note that emission rates are presented in grams per mile for display purposes. Rates in grams per second were used in the emissions modeling).

Table 3
Emissions descriptive statistics[a]

| Variable | Range | Mean | S. D. | Units |
|---|---|---|---|---|
| $NO_x$ | 2.08–693.86 | 130.76 | 100.84 | Grams |
| VOC | 2.05–365.64 | 80.84 | 48.34 | Grams |
| CO | 19.34–3812.76 | 863.20 | 531.56 | Grams |

[a] The results presented are per household over a two day travel period.

Table 3 presents descriptive statistics for household emissions of the three vehicle pollutants. Similar to the travel variables, the emissions variables represent the total emissions from all trips taken by household members over the two-day survey period.

### 2.3. Land use data

Having derived the travel behavior and emissions variables, the final component of the database to be assembled is the land use dataset. The land use information utilized for this research was obtained from federal, state, and regional sources. The survey region covers four counties in the Puget Sound region including the King, Kitsap, Pierce, and Shonomish counties. Each of the land use variables included in the analysis, its purpose, and data source follows:

- *Household density*: Household density is a measure of the number of households found per gross acre within the census tract of residence for each survey household. This variable measures the intensity of residential development and as such serves as an indicator of the proximity between non-work trip ends. The number of households is directly enumerated by the decennial census and was obtained from the 1990 Census for this research.
- *Employment density*: Employment density is a measure of the number of employees found per gross acre within the census tract of residence for each household and the census tract of employment for each employed survey household member. Employment density was used in both forms within the analysis to serve as two distinct indicators. Residential employment density serves as a proxy measure of the level of land use mix found within census tract of residence (Boarnet and Sarmiento, 1996). As such, it provides a means of estimating the level of proximity between compatible residential and commercial and office development uses of land. The employment density of the census tract of employment measures the intensity of commercial and office development around the workplace and serves as an indicator of the proximity between work-based trip ends. [5] For households with multiple workers, the employment densities of the work tracts were averaged. The employment density data was obtained from the Washington State Employment Security Office for each of the four counties.
- *Distance to work*: The distance to work variable is a measure in miles of the distance from the home census tract to the tract of employment. This variable serves as a direct measure of the proximity between residence and work for survey participants and, as such, is a proxy for

[5] Assessor's parcel level land use data measures the square footage of development by land use type and can provide the basis for an accurate measure of land use mix at the place of residence and employment. This data can also be used to address the level of proximity between complementary land uses.

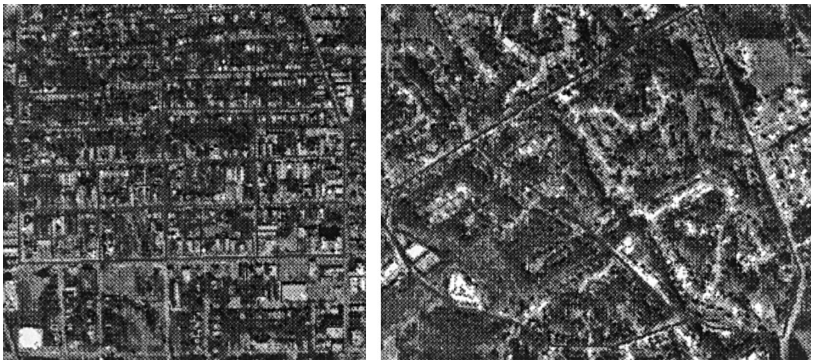

Fig. 3. Census block size by network type (photos obtained from the Georgia GIS Clearinghouse).

regional location relative to the workplace. For households with more than a single worker, the work distance variable is an average of the multiple commute distances.

- *Census block density*: Census block density is a measure of the mean number of census blocks found per square mile within each census tract of the survey region. Census blocks are typically designated as the smallest fully enclosed polygons bounded by linear cartographic features, such as roads and streams, on all sides. [6] As the street network increases in density, census block polygons decrease in size. The most highly connected network pattern, a gridiron, reduces the route distance for all modes of travel by increasing the number of route options. As illustrated in Fig. 1, hierarchical or dendritic networks limit route options through the use of disconnected streets. As a result, fully enclosed polygons are less frequent per unit of area in dendritic networks, necessitating larger census blocks (Replogle, 1992; Holtzclaw, 1990). Fig. 3 illustrates this basic relationship between street connectivity and census block size. Recorded at the same scale, these aerial photographs depict a basic gridiron and dendritic network pattern. Based upon a grid network, the neighborhood depicted on the right has a greater frequency of intersections, and thus smaller block size relative to the dendritic network which is configured around a discontinuous street design. The census block data was obtained from the US Census Bureau.

Table 4 presents descriptive statistics on the five land use measures utilized in the analysis. Statistics are presented for both the survey census tracts (in italics) and the region as a whole.

### 2.4. Database construction

The final task in constructing a land use and travel behavior database for analysis consists of linking the individual components together by a common variable and aggregating the data to a common unit of analysis. Based on the trip as the primary unit of analysis, the travel survey and

[6] Census block density is an accurate measure of street connectivity within urban locations. However, in suburban areas where street intersections are less frequent, artificial boundaries are often constructed to limit the size of census blocks. This practice can serve to artificially reduce the actual variation in street connectivity that actually exists within a given region. However, a comparison of block and intersection density in the Seattle Region revealed little difference within our analysis.

Table 4
Land use variable descriptive statistics

| Variable | Range | Mean | S.D. | Units |
|---|---|---|---|---|
| *Household density* | 0.01–48.18 | 2.75 | 3.76 | Per acre |
| Household density (Region) | 0–48.18 | 2.99 | 3.90 | Per acre |
| *Employment density (Home)* | 0–92.03 | 2.34 | 6.00 | Per acre |
| *Employment density (Work)* | 0.02–401.43 | 64.18 | 116.79 | Per acre |
| *Employment density (Region)* | 0–415.92 | 5.22 | 22.49 | Per acre |
| *Census block density* | 0.30–285.40 | 46.82 | 50.43 | Per sq. mile |
| Census block density (Region) | 0.27–295.41 | 56.73 | 59.50 | Per sq. mile |
| *Distance to work* | 0–61.20 | 12.67 | 9.42 | Miles |

emissions datasets provide the most disaggregate structure for organizing the data. Yet, the behavioral decisions affecting travel behavior do not occur at the level of the trip, but rather at the level of the individual and the household. Furthermore, the demographic information utilized for this study was obtained at the level of the household. Having selected the household as the most appropriate unit of analysis, there is a need to aggregate the trip level information to the household level. The inclusion of a person and household ID field for each trip in the dataset permits trip level information to be statistically summarized through aggregation from approximately 30,000 trip-level records into 1700 household-level records.

In contrast to the travel data, the land use information used in this analysis was collected at a geographic unit (census tract) and must be disaggregated to match the household unit of analysis. Through a geocoding process, the census tract of each trip origin and destination was provided in the PSTP survey data. In addition, the census tract of each household and employment location for survey participants has been determined. The inclusion of land use linkages at each trip end and at the residential and employment tracts, presents two options for associating the land use and travel data. One option would be to determine the value of the land use variables at the origin and destination of each trip in the database and statistically average these values. This option has the advantage of capturing land use at trip ends that do not originate from home or work, but the disadvantage of using modified values. The second option is to associate the travel data with land use only from the census tracts of residence and employment. [7]

The latter option was chosen because it more directly informs policies targeted at residential and employment locations and is further supported by the premise that the land use and travel interaction is largely driven by the environment in which one lives or works. It is assumed here that the land use characteristics of the census tract of residence and employment are most significant in influencing the creation of habitual travel patterns. As illustrated in Fig. 4, the hierarchy and coding of the travel survey structure permits land use and emissions data to be integrated into the database at the level of the trip, the individual, or the household. In addition to the vehicle emissions and land use information, the demographic variables detailed above were linked to each survey household within the original travel survey dataset.

[7] Analysis techniques using Gls can calculate land use measures at the parcel level for each household.

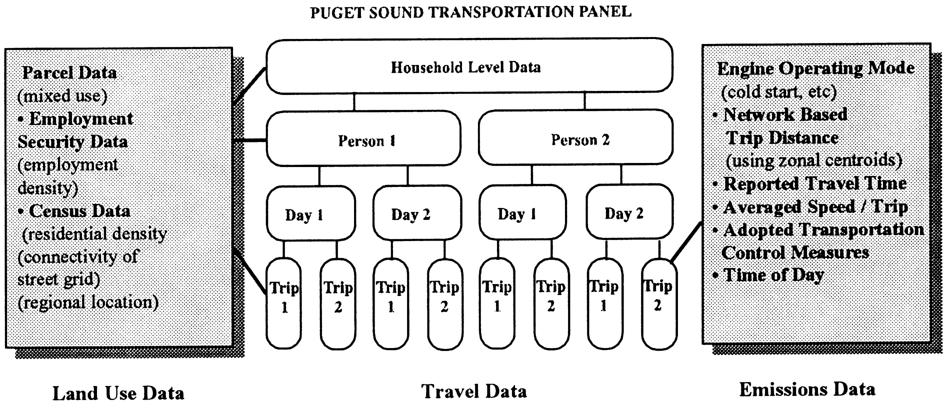


Fig. 4. Framework for database construction.

## 3. Analysis and findings

The data analysis component of this research is intended to explore the interaction between the five measures of land use and the vehicle emissions estimates. Specifically, we are interested in establishing whether or not vehicle emissions are sensitive to land use and, further, whether any measured responses differ by pollutant (see Table 1). The answers to these questions may suggest directions for targeting land use strategies towards reducing vehicle emissions as a group or individually based upon regional air quality issues. What follows in this section are the results from a series of exploratory and explanatory methods of inquiry used to isolate the interaction among the land use and travel behavior variables included in the database. The use of partial correlation and regression analysis permits these relationships to be analyzed while controlling for the three demographic variables of household size, income, and vehicle ownership. Exploratory line drawings of the covariance between the five land use variables and three vehicle pollutants are included as a means to visually display the bi-variate association between these measures. A controlled analysis follows the line drawings to permit an estimation of the strength and significance of the observed covariance.

### *3.1. Household vehicle travel*

Prior examining the interaction between land use and vehicle emissions, it is useful to consider how the vehicle travel behavior variables vary across changing land use patterns. The four travel variables of vehicle miles of travel, vehicle hours of travel, vehicle trip generation, and cold start production were selected for analysis due to their direct importance to the emissions production process. Partial correlation was used to test the relationship between these four travel variables with the land use measures of household density, home tract employment density (a proxy for land use mix), census block density (a proxy for street connectivity), work tract employment density, and the distance to work variables. In measuring the covariance between each variable pair, household size, a dummy variable for household

Table 5
Partial correlations for travel variables (controlling for household size, income, and vehicle ownership)

| Land use variable | VMT (correlation/sig.) | VHT (correlation/sig.) | Vehicle trips (correlation/sig.) | Cold starts (correlation/sig.) |
|---|---|---|---|---|
| Household density | −0.43/0.000+ | −0.16/0.000*+ | −0.09/0.008* | −0.07/0.036 |
| Employment density (H) | −0.38/0.000+ | −0.14/0.000*+ | 0.10/0.003+ | 0.08/0.018 |
| Census block density | −0.39/0.000+ | −0.16/0.000*+ | 0.11/0.002+ | 0.08/0.023+ |
| Employment density (W) | −0.23/0.000*+ | −0.22/0.000* | −0.14/0.000* | −0.26/0.000* |
| Distance to work | 0.39/0.000 | 0.19/0.000*+ | −0.17/0.000 | −0.17/0.000 |

income, [8] and the number of household vehicles were controlled in the analysis. The plotting of scatter diagrams for each of the land use and travel variable combinations revealed that most relationships are non-linear in form. In consideration of this fact, natural logarithmic transformations are utilized in the analysis to isolate the strongest interactions. These transformations are indicated by either a "+" symbol to denote a transformed land use variable or a "*" symbol to denote a transformed travel variable. Double transformations are denoted by the display of both symbols. Table 5 presents the results from this analysis.

The analysis reveals the complexity of the potential interaction between land use and air quality. The most consistent results were found for the vehicle travel distance (VMT) and time (VHT) variables. It is hypothesized that as population and network densities increase, the level of proximity and connectivity between trip ends is increased as well. These attributes of urban form minimize total route distance, reducing both the distance traveled by vehicle and potentially the number of vehicle trips generated as the viability of pedestrian modes is enhanced.

The employment density of the work tract was found to have an inverse relationship with the generation of all vehicle trips (cold start and hot start), and with overall travel time and distance per household. High employment densities are believed to be associated with reduced overall vehicle travel distance (VMT) through increased utility of transit service and reduced utility of driving stemming from increased parking costs and congestion. An inverse relationship between travel time (VHT) and employment density is curious given a higher level of congestion associated with places of higher employment density. This overall reduction in household travel time is partially attributable to the reduced level of vehicular travel for non-work trips due to increased access to nearby opportunities for the mid-day work based trip (lunch, errands, etc.) regardless of the mode utilized for the work trip. Furthermore, the distribution of employment density in the Seattle Region is highly non-linear with the Seattle CBD being nearly twice as dense as other major work centers in the region. While the Seattle CBD is the most dense and highly congested, a significant amount of high density residential housing is located within a five mile radius in Capitol Hill, First Hill, Beacon Hill, Queen Anne Hill, Magnolia, and West Seattle. Our analysis shows that a significant percent of the households in the Puget Sound Travel Survey that work in the Seattle CBD live sufficiently close to offset the increased travel time from reductions in facility performance.

[8] Due to the fact that household income was reported as a categorical variable, this measure was incorporated into the analysis as three dummy variables representing quartiles of the income range.

While the interaction between land use and "running" emissions may be inferred from these results, "start" emissions, those attributed to the initial mode of engine operation, manifest a less consistent and weaker relationship with the five land use measures. Most significantly, both vehicle trip generation and cold start generation were found to have a positive correlation with home tract employment density, our land use mix proxy, and street network density. These findings provide support for claims that compact development forms can actually serve to aggravate air quality problems through reducing the cost of travel across all modes (Crane, 1996; Boarnet and Sarmiento, 1996). It is hypothesized that a reduction in travel costs independent of mode will increase the use of vehicles for short, non-work trips due to the convenience and time savings of vehicle travel. Increases in the number of vehicle trips and cold start trips with increasing levels of land use mix and street density could certainly produce this effect. It is important to note, however, that the true impacts of urban form on vehicle emissions will result from a complex interaction among travel measures, one which may not be readily inferred from an examination of independent travel indicators alone. The deployment of an emissions modeling methodology is required to fully address such questions.

Interestingly, work trip distance was found to be negatively related to household vehicle trip generation and cold starts. This finding may indicate that households with longer work trip commutes attempt to economize their non-work vehicle travel. Another plausible explanation may concern the potential for an under-reporting of trips that occur as part of a trip chain. Frequently in travel surveys, trips that occur as part of trip chains are not recognized as independent trips. Thus, it is feasible that an individual will remember the single-purpose short home-based trip, but may forget the two errands on the way home from work when they fill out their travel diary at the end of the day. [9] Considering that trip chaining is a more prominent characteristic of travel behavior for individuals that reside within single use, lower density locations, this phenomenon could explain the findings of reduced trip generation for participants with longer commutes. The implications of such a travel pattern for air quality will be based upon the relative contributions of start and running emissions to the total household emissions profile. In general, it appears from this data that vehicle trip generation is less sensitive to land use than the amount of distance traveled or time spent traveling in a personal vehicle. Assuming this to be the case, any air quality benefits achieved through land use approaches would most likely be derived from reductions in vehicle travel distance and time.

### *3.2. Household vehicle emissions*

The exploratory component of the emissions analysis plots household emissions as a function of each of the five land use measures. In each graph, the three emissions variables are cross-tabulated against quartiles of each land use measure. As noted above, due to the fact that such cross tabulations fail to control for the influence of "third party" variables, such as household

[9] This assertion will be tested within the SMARTRAQ Travel Survey being designed for the Atlanta Regional Commission's upcoming household travel survey which will employ "in-and-out-of-vehicle" instrumentation packages for a statistically significant subset of the survey households to more accurately gauge spatial and temporal aspects of travel behavior.

demographics or related urban form measures, trends illustrated in these graphs do not provide conclusive evidence of a relationship between two variables. Cross tabulations do, however, serve as a means of visually conveying the likely covariance between the land use and three emissions variables. In order to examine the interaction between these variable sets while controlling for potential third party interactions, regression models are presented in the subsequent portion of the data analysis.

### *3.2.1. Density and vehicle emissions*

The first two sets of cross tabulations depict the covariance between home tract household density, work tract employment density, and the three pollutants. In the case of household density, the three pollutants appear to consistently decrease across increasing levels of density. Considering that each of the primary precursors to emissions, travel distance, travel time, vehicle trip generation, and cold start production, were found to have significant negative relationship with household density, this is not a surprising result. Although consistently negative, the relationship suggests that households located in census tracts within the highest quartile of residential density do not pollute much less than households located in a slightly less compact environment. In contrast, household emissions appear to decline at an increasing rate over increases in work tract employment density. A downturn in emissions of the three pollutants at the third quartile of employment density could suggest a threshold at which transit and other non-vehicle modes become a competitive option over driving to work, largely attributable to increasing costs for parking and improved levels of service for other modes.

One trend that emerges in these cross tabulations, and is repeated throughout this analysis, concerns the variability of nitrogen oxide emissions in relation to carbon monoxide and volatile organic compounds. From this illustration it is clear that carbon monoxide varies across these two density measures in a pattern parallel to volatile organic compounds. Nitrogen oxides appear to manifest a greater degree of variability across both density continuums shown in Figs. 5 and 6. This trend may indicate that emissions of $NO_x$ are more sensitive to these vectors of land use than CO or VOC. The implications of such a relationship for air quality management will be explored further below.

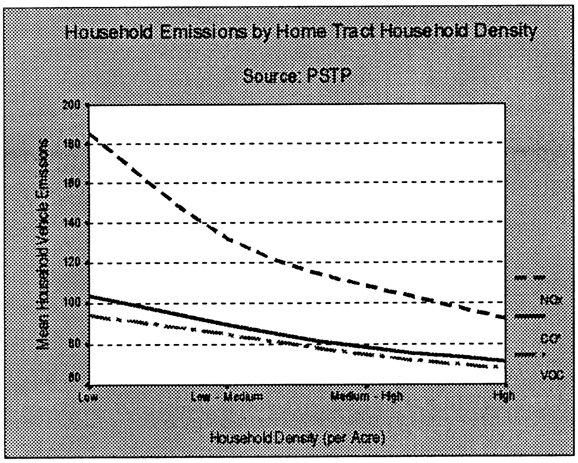


Fig. 5. Covariation between home tract household density, and vehicle emissions.

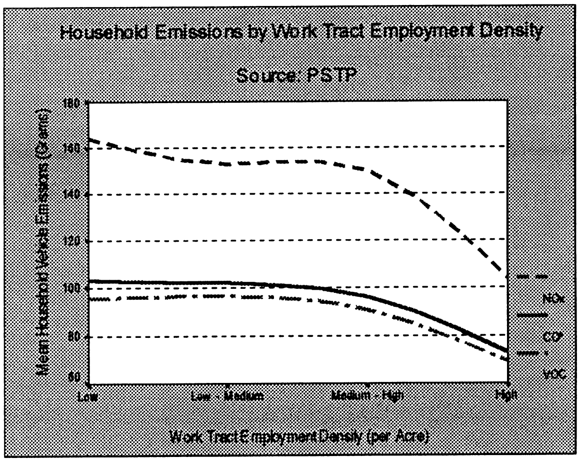


Fig. 6. Covariation between work tract employment density and vehicle emissions.

### *3.2.2. Connectivity, home tract employment density, and vehicle emissions*

The relationships between household vehicle emissions and census block density (street connectivity) and home tract employment density (land use mix) appears to be very similar to that found to exist between home tract household and work tract employment density and emissions. This is consistent with findings in the literature expressing a high degree of co-variation between these land use variables making it difficult to disentangle their interactions (Cervero and Kockelman, 1997; Frank, 1998). The inverse relationships shown in Figs. 7 and 8 are consistent with the partial correlations for VMT and VHT shown in Table 5 supporting the assertion that vehicle emissions behaves in a consistent manner with these vectors of travel behavior. However, Table 5

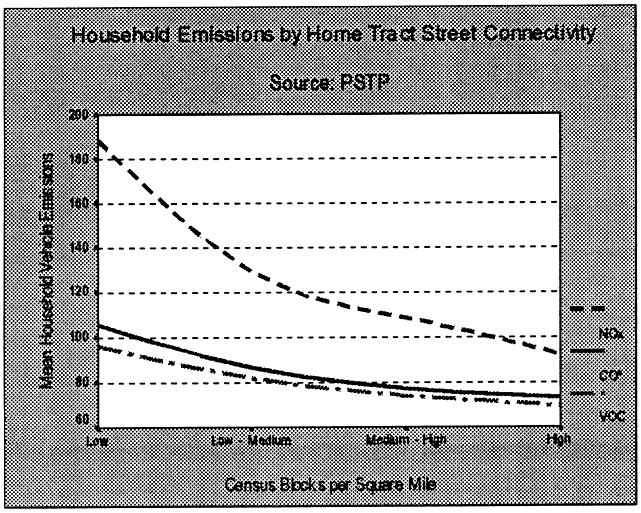


Fig. 7. Covariation between street connectivity and vehicle emissions.

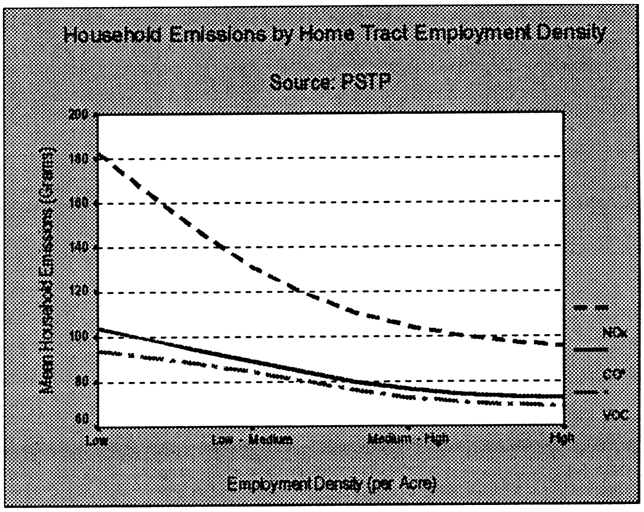


Fig. 8. Covariation between home tract employment density (mix proxy) and vehicle emissions.

shows a positive relationship between vehicle trip generation, connectivity, and home tract employment density. These findings collectively suggest that the amount of emissions produced per household cannot be inferred from vehicle trip generation – or even cold start rates. This finding is significant because it suggests that increased connectivity and efficiency of the street network is not associated with an increase in the amount of vehicle emissions generated per household. Our analysis suggests that the reductions in emissions shown in Figs. 7 and 8 are associated with less VMT and VHT overwhelming the increases in vehicle trip generation associated with increased connectivity. These findings suggest the inability to directly infer air quality implications of land use – travel behavior relationships and the need to actually model vehicle emissions at the household level. Moreover, implications of regional location and the larger land use and mobility context in which a household is located need to be addressed before assuming that a given approach to land development can or cannot offer a superior environmental performance.

### *3.2.3. Work trip distance and vehicle emissions*

The final cross tabulation shown in Fig. 9 depicts a positive co-variation between commute trip distance and household vehicle emissions. Although seemingly intuitive, the finding of an inverse relationship between the distance to work, vehicle trip generation, and cold starts indicates that households with longer commutes may reduce vehicle trip generation for other purposes. [10] While much debated, the use of commuter rail for long commutes holds the potential to reduce total $NO_x$ emissions for these households. Despite the potential emission savings of such travel patterns, however, the emissions produced by long work trips appear to offset any gains achieved through reduced vehicle trip generation.

[10] As noted above, it is also likely that chained trips that occur on the way to and from work are under-reported.

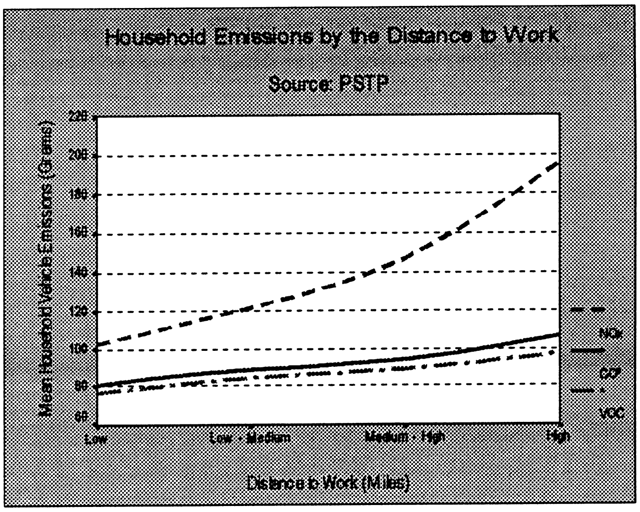


Fig. 9. Covariance between commute distance and vehicle emissions.

### 3.3. Regression analysis

The final step in the data analysis involved the construction of multivariate regression models to estimate household vehicle emissions based upon the combination of demographic and land use measures included in the database. Table 6 details the results of the analysis.

In consideration of the non-linear relationships indicated by the travel variable partial correlations, emission variable cross-tabulations, and a series of bivariate scatter plots (not presented here), a non-linear transformation was utilized for each of the emissions variables in the analysis. In addition, the land use measures of household density and street connectivity were found to have high levels of multicollinearity when incorporated into the same model. A natural log transformation of the street connectivity variable was found to eliminate this potential source of error. The demographic and land use measures were entered in separate "blocks" within the analysis to gauge the contribution of land use to the model's predictive power. Adjusted $R^2$ summary statistics for the block one models (models utilizing only the three demographic variables) are reported in brackets. Independent variables which failed to meet a significance level of 0.10 are not reported in the results and are denoted by a dash (–).

The results from the regression analysis clearly illustrate the significance of land use to the production of household vehicle emissions. In each of the three emissions models, the land use variables of home tract household density (HH DENSITY) and work tract employment density (WK EMP DENSITY) were found to have significant negative relationships, and work commute distance (WK DISTANCE) a significant positive relationship with emissions. As noted above, these findings includes the controlling for the demographic measures of household size, the number of household vehicles, and income. The employment density of the work tract, in particular, was found to have one of the strongest interactions with emissions among all variables considered. In addition, the street connectivity and land use mix proxy variables were found to have either a negative or insignificant relationship with each of the three emissions variables.

Table 6
Regression analysis results for household vehicle emissions

| Variable name | $NO_x$[a] | | | $CO$[a] | | | VOC[a] | | |
|---|---|---|---|---|---|---|---|---|---|
| | *B* | T | Sig. | *B* | T | Sig. | *B* | T | Sig. |
| HH size | 0.139 | 7.89 | 0.000 | 0.145 | 9.57 | 0.000 | 0.146 | 9.74 | 0.000 |
| # Vehicles | 0.089 | 4.41 | 0.000 | 0.088 | 5.03 | 0.000 | 0.087 | 5.08 | 0.000 |
| Income 1 | −0.404 | −4.29 | 0.000 | −0.321 | −3.97 | 0.000 | −0.336 | −4.42 | 0.000 |
| Income 2 | −0.235 | −3.87 | 0.000 | −0.211 | −4.05 | 0.000 | −0.215 | −4.19 | 0.000 |
| Income 3 | – | – | – | – | – | – | – | – | – |
| Constant | 4.41 | 35.42 | 0.000 | 6.25 | 58.54 | 0.000 | 3.87 | 36.80 | 0.000 |
| HH density | −0.018 | −2.17 | 0.030 | −0.016 | −2.24 | 0.025 | −0.017 | −2.35 | 0.019 |
| WK emp density | −0.002 | −7.61 | 0.000 | −0.001 | −7.44 | 0.000 | −0.001 | −7.50 | 0.000 |
| Block density* | −0.082 | −3.51 | 0.000 | – | – | – | – | – | – |
| HM emp density | – | – | – | – | – | – | −0.011 | −1.74 | 0.082 |
| WK distance | 0.019 | 7.10 | 0.000 | 0.007 | 2.90 | 0.004 | 0.006 | 2.55 | 0.011 |
| Summary statistics | Adj-$R^2$: (0.21)0.-38 | *F*: 54.55 | Sig: 0.000 | Adj-$R^2$: (0.24)0.-32 | *F*: 41.70 | Sig.: 0.000 | Adj-$R^2$: (0.24)0.-32 | *F*: 41.76 | Sig.: 0.000 |

[a] Denotes a natural log transformation.

These findings diminish the relevance of a weak positive covariance found to exist between these land use measures and vehicle trip generation. The strong positive covariance found to exist between connectivity, mix, and the travel variables of VMT and VHT is of greater significance to the production of emissions (especially $NO_x$) than potentially minimal increments in vehicle trip generation and cold starts which is alluded to above.

The addition of the land use measures to each of the models was found to boost predictive power. In the case of nitrogen oxides, the adjusted $R^2$ was almost doubled through the incorporation of the five land use predictors. The $NO_x$ model was further found to have the highest explanatory power of the three models constructed. The adjusted $R^2$ of 0.38 indicates that the combination of demographic and land use variables entered into the $NO_x$ model explains approximately 38% of the variation in household vehicle emissions of this pollutant. In light of the large number of variables that influence travel behavior and emissions production, the explanatory power of this model is noteworthy. The somewhat reduced explanatory power of the models for carbon monoxide and volatile organic compounds (adjusted $R^2$ of 0.32) is not surprising based upon the cross tabulations which revealed a lower response to variation in the land use measures relative to nitrogen oxides. In particular, the generation of $NO_x$ was found to be more sensitive to our measure of street connectivity (block density) than was CO or VOC. This finding is attributable to effect of street network configuration on average travel speed with lower average travel speeds per trip occurring in a more interconnected street networks which tend to be located in denser, older, more central areas of the Seattle Region. [11] As Fig. 2 illustrates, $NO_x$ emissions tend to increase with increasing travel speed. The similar regression statistics reported here between CO and VOC further suggests a parallel relationship with these measures of urban form based upon the emissions modeling framework employed in this analysis.

## 4. Summary and conclusion

This research provides two important contributions to the field of land use, transportation, and air quality research. First, it presents a methodology to link land use with vehicle emissions via travel survey data. The use of such an emissions methodology eliminates the need for guesswork concerning the relative effects of often conflicting evidence on the relationship between land use, travel choice, and air quality. Due to the complexity of the emissions production process, it is important to derive an estimate of emissions directly, rather than attempting to extrapolate air quality impacts from travel data alone. The methodology presented here may be applied with a widely available emissions factor model and travel survey data which provides information on the mode of travel, the time of day at which trips began and ended, and the travel distance.

[11] Mobile5a uses an average vehicle travel speed per trip which is a relatively poor predictor of emissions. A better predictor would be a modeling framework that captures a measure of the speed profile of the trip addressing acceleration and deceleration rates among other modal factors (Guensler et al., 1998).

Second, this research further establishes the potential role that land use strategies should play as part of a regional air quality management strategy. The application of this methodology to the Central Puget Sound Region resulted in findings that have significant policy implications. Specifically, that a significant inverse relationship exists between the land use measures of household density, work tract employment density, and, in the case of nitrogen oxides, street connectivity (census block density) and vehicle emissions. Furthermore, these relationships were significant while controlling for the effects of household size, vehicle ownership, and income. The commute trip distance, a proxy measure for regional location and jobs-housing balance, was further found to have a significant relationship with all three pollutants. These relationships suggest the efficacy for reducing vehicle emissions through the configuration and siting of future development and transportation network improvements within the Puget Sound region. Subsequent work which employs this methodological framework in Atlanta and in New Jersey confirms the results presented here (Frank, 1999).

The finding of a strong relationship between urban form and nitrogen oxides is particularly significant due to the contribution of this pollutant to the production of ozone, particularly in light of national increases in emissions of nitrogen oxides since 1970 (USEPA, 1997). [12] Produced through an interaction between nitrogen oxides, volatile organic compounds, and other atmospheric constituents in the presence of sunlight, ozone has been linked to numerous respiratory illnesses, as well as materials and vegetation damage (Boubel et al., 1994). While ozone may be reduced through either a reduction in $NO_x$ or VOC, the large-scale production of VOC by trees and urban area sources makes this pollutant difficult to control in many regions. As a result, these regions are known to be "$NO_x$-limited", a designation which indicates the need for controlling ozone through reductions in anthropogenic $NO_x$ emissions. Although currently in compliance, the Puget Sound region has fallen out of attainment with the national standards for ozone concentrations in the past. The results presented above indicate that land use strategies may serve as a component of a comprehensive approach to reducing ozone formation, especially in Seattle and other $NO_x$ limited regions of the nation.

Considerable resistance has been levied against efforts to address air quality through land use strategies. While certainly multi-faceted, the majority of this resistance has been rooted in the belief that changing land use is a long term proposition that is often incompatible with the time frame in which most decision-makers operate. In addition, several regions are looking for strategies to demonstrate the conformity of their short-term transportation improvement programs (TIPs) with federal air quality mandates. While land use is slow to change, transportation investment strategies that foster increased connectivity may take relatively less time to implement than significant changes to urban form and should be carefully considered. Increased local accessibility within centers could be accomplished in the near term through the deployment of direct linkages between complementary land uses that are relatively proximate in space while supporting improved access to transit for enhanced regional mobility. This study indicates that such a strategy could reduce emissions of nitrogen oxides and ozone formation.

Through an increased ability to gauge the impacts of urban design decisions on travel demand and vehicle emissions it will become possible to develop regional approaches to stem mobile

[12] Secondary pollutants are formed from the interaction of primary pollutants such as $NO_x$ and VOC.

source emissions that address the underlying effects of the built environment. Reducing the average vehicle miles traveled to work, for example, would require incentives to take transit and to provide residential options for a wider array of demographic profiles closer to places of employment. With two or more workers in many households, the ability to locate closer to places of employment is often difficult. Densification of the employment district, if coupled with significant improvements to the pedestrian environment, may serve to increase the viability of transit service to these areas and increase the likelihood of non-vehicle travel for work based trips. While not a new finding, our data extends this land use transportation relationship to household vehicle emissions and air quality management.

An increase in densities within existing locations would require infill development to occur and the adoption of growth management programs to foster intergovernmental coordination at the regional level. The longer-term solution is imbedded within the competition for development amongst competing jurisdictions requiring a mechanism to reward localities that support development decisions that are associated with reduced vehicle emissions at the household level. This would require strong political leadership at the regional and state levels to implement the intent within and interwoven between federal transportation (TEA-21) and air quality (CAAA) mandates.

Transportation investment would need to support the growth management principals of reduced sprawl and resource conservation. To date, most growth management programs have been based solely upon a regulatory model and implemented within a landscape where the financial rewards have stacked up against their success. For this to change, the programming of transportation investments would need to be altered to foster development in locations that support regional mobility and air quality mandates and designed in a manner that is associated with reduced overall travel demand and vehicle emissions. One potential tool that could be used to accomplish these objectives would be the creation of an institutional mechanism that makes additional transportation funds available to jurisdictions that adopt and implement development regulations that are consistent with regional transportation and environmental mandates. The newly formed Georgia Regional Transportation Authority has the capacity to implement such a model pursuant to its carefully crafted enabling legislation (Georgia General Assembly, 1999). As a model for smart growth, much of the nation will be watching this experiment to effectively bridge regional transportation investment and local land development activities.

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