Weighted Population Density as a Transportation Performance Metric

November 2, 2014

Words: 5,935 including
Abstract: 209
References: 721
Figures: 2
Tables: 4

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ABSTRACT

The study seeks to identify the correlation of weighted population density (WPD), or clustering of the built environment, with the ratio of per capita levels of personal income (PCPI)/vehicle miles traveled (PCVMT). The purpose is to determine the level of impact that polycentric urban form has on the proportion of household finances dedicated directly to transportation. The study area consists of 77 Midwestern Metropolitan Statistical Areas (MSAs) in the United States.

Using a hybrid of 2000 and 2010 cross-sectional and longitudinal multi-variable data, and controlling for other variables, regression analysis shows a statistically significant positive relationship between WPD and PCPI/PCVMT ratio. This association is evident for both static WPD and changes in the metric over time. The correlation during both measured periods is elastic as areas with 1% higher WPD can be expected to experience larger PCPI/PCVMT ratios by about 1.6% and reduced per capita transportation cost (PCTC)/PCPI ratios by about 1.7%. The latter relationship holds true for both estimated personal vehicle operating costs alone and in combination with public transportation operating costs. These dependent variables are not elastically sensitive to WPD changes between 2000 and 2010. A 1% increase in WPD during this period was found to increase PCPI/PCVMT proportion and decrease PCTC/PCPI ratio by about 0.3%.

BACKGROUND

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) required the U.S. Department of Transportation (USDOT) to establish planning regulations for federal-aid highway/bridge construction, highway safety improvements, and relieving traffic congestion in addition to addressing needs for public transit, intermodal facilities, bicycle, and pedestrian travel. ISTEA also required metropolitan planning organizations (MPOs) and state departments of transportation (DOTs) to consider planning factors in developing transportation programs. This included: consistency with/effects on land use and development; consideration of social, economic, energy, and environmental effects; techniques to expand, enhance and improve transit usage; and methodologies to improve transportation system efficiency *(1)*. The legislation was innovative in that it required MPOs and DOTs to reconsider the conventional assumption that transport planning is performed narrowly as a response to current and future land uses that are beyond their control. Subsequent transportation reauthorizations have continued the planning factors and broad quality of life theme established by ISTEA.

In June 2009, USDOT, U.S. Department of Housing and Urban Development (HUD) and the U.S. Environmental Protection Agency (EPA) joined together to form the Partnership for Sustainable Communities (PSC). Six livability principles have been established through this collaboration which include: mode choice and reduced travel costs, fuel usage, and emissions; affordable location/energy efficient housing; accessibility to amenities; revitalization of neighborhoods and increased efficiency of public works investments through transit-oriented development, mixed land uses and land recycling; enhancing unique characteristics, imageability, and walkability of the built environment; and coordination, accountability and effectiveness by all levels of government in planning for future growth *(2)*.

Moving Ahead for Progress in the 21st Century (MAP-21), signed into law in 2012, is ground-breaking in terms of the focus on performance-driven outcome-based planning. The legislation establishes seven national goals: safety, infrastructure conditions, congestion reduction, system reliability, freight movement/economic vitality, reduced project delivery delays, and environmental sustainability *(3)*.

The primary scope of the study is to determine if increases in clustered or compact development quantified by WPD in urbanized areas (UAs) and MSAs have statistically significant impacts on quality of life as measured by PCPI/PCVMT and PCTC/PCPI ratios. In addition to WPD, the study seeks to identify all independent variables having substantive correlations with these dependent variables. The purpose is to determine if they have value to planners in coordinating transportation and land use while successfully addressing the established planning factors, PSC livability principles, and environmental sustainability.

The study area consists of 88 UAs and 77 MSAs either fully or partially within the six states of Illinois, Indiana, Michigan, Minnesota, Ohio and Wisconsin. Collectively, these states are the Region 5 area for the EPA and USDOT, Federal Transit Administration. The study area consists of: 15 UAs with populations more than 500,000; 16 mid-sized UAs with populations between 200,000 to 500,000; and 57 small UAs with populations between 50,000 to 200,000. The study area was chosen in part to compare performance or planning outcomes within a specific section of the country over time. It is recognized that a broader cross section of the nation could impact the findings to some extent.

EXISTING RESEARCH

Research has generally substantiated theory regarding the effect of variables related to traditional urban form on improvements in non-single occupancy vehicle (SOV) travel (i.e. transit, walk, bicycle) such as increases/improvements in residential population densities, street connectivity, intersection densities, mixed land uses, large employment centers/densities and air quality. The elasticities tend to be marginal in a number of studies. However, changes in each of these elements can have cumulative impacts in improving overall quality of life through increased modal balance and related reductions in transportation costs, VMT and emissions *(4)(5)(6)(7)(8)(9)*. Other studies have found that improvements in quality of life as measured by per capita income is primarily determined by human capital such as education, employment rate and type, in addition to urban agglomerations. Race is no longer a significant determining factor *(10)*. What is unclear or inconsistent from past studies is the correlation between levels of population clustering, other than measured through standard population densities, and the proportion of personal income dedicated to travel and transportation costs.

Communities tend to promote population growth for the related increases in employment and economic activity. Simple regression analysis of the 77 Region 5 MSAs for 2010 using U.S. Bureau of the Census (Census) and U.S. Bureau of Economic Analysis (BEA) data finds this may be plausible as there is a significant positive relationship between population and both per capita gross domestic product (PCGDP) and PCPI. However, stronger significant relationships are evident if WPD is used instead of population to measure the effect on these dependent variables as shown in Table 1 below *(11)*. WPD is calculated by determining population density in each Census tract, weighting it by the proportion of persons in the MSA, and adding the totals.

This is consistent with other research findings that population growth in of itself does not influence per capita income. Rather, the progression in economic deterioration is: (1) decline of regional competitive capability; (2) unemployment; (3) net out-migration; (4) population loss *(12)*. A study of 2000-2009 data for the 100 largest U.S. metropolitan areas, found that areas with slow or moderate population growth rates tended to experience higher incomes, less income declines during the 2007-2009 recession, and lower poverty rates *(13)*.

Using 1990 MSA data, other research found that primary factors influencing wealth-building areas were higher education and high-tech employment levels. Geographically large, high-population metropolitan areas tended to be wealth-builders but only in the sense that they had high densities creating "urbanization economies" *(14)*. Using 1960-1990 MSA data, a study found that population growth did not have any relationship with income while educational level and wealth-building employment did have significant associations *(15)*. Another study of 1950-2000 MSA data revealed that income was primarily determined by the same factors *(16)*. Klasen and Nestmann provide a thorough analysis of the stronger relationship of GDP with population density as opposed to population growth *(17)*.

There are conflicting results from research regarding the economic value of higher VMT which is summarized by Ecola *(18)*. Pozdena concludes that PCVMT is a large and statistically significant driver of GDP based on data analysis of oil consumption in 177 countries. Consequently, any non-market-driven policies to reduce VMT would likely be harmful to the economy *(19)*. His and other studies acknowledge there are bi-directional effects between the two variables, meaning the causal effect works both ways at different times in the economic cycle.

Other studies have found that lower PCVMT is associated with higher PCGDP and related economic benefits *(20)(21)*. In a study of 98 MSAs, McMullen found no significant causal relationship between VMT and economic activity in either direction. However, that study found this relationship did not necessarily hold true in small urban and rural areas. This was attributed in part to the minimal development of these areas and the lack of transportation alternatives. The study also found that the VMT and GDP interrelationship tends to be dependent on the macroeconomy and stages of the business cycle. Additionally, transit use and population density had inverse relationships to PCVMT. The study concludes that "…in well-developed urban areas, it is reasonable that greenhouse gas (GHG)-related VMT-reduction policies would not result in significant drops in economic activity *(22)*. For comparison purposes, Figure 1 below shows PCPI and PCVMT for the Region 5 MSAs. There is no statistically significant relationship, however, the trend is inverse as PCPI tends to rise with declining PCVMT.

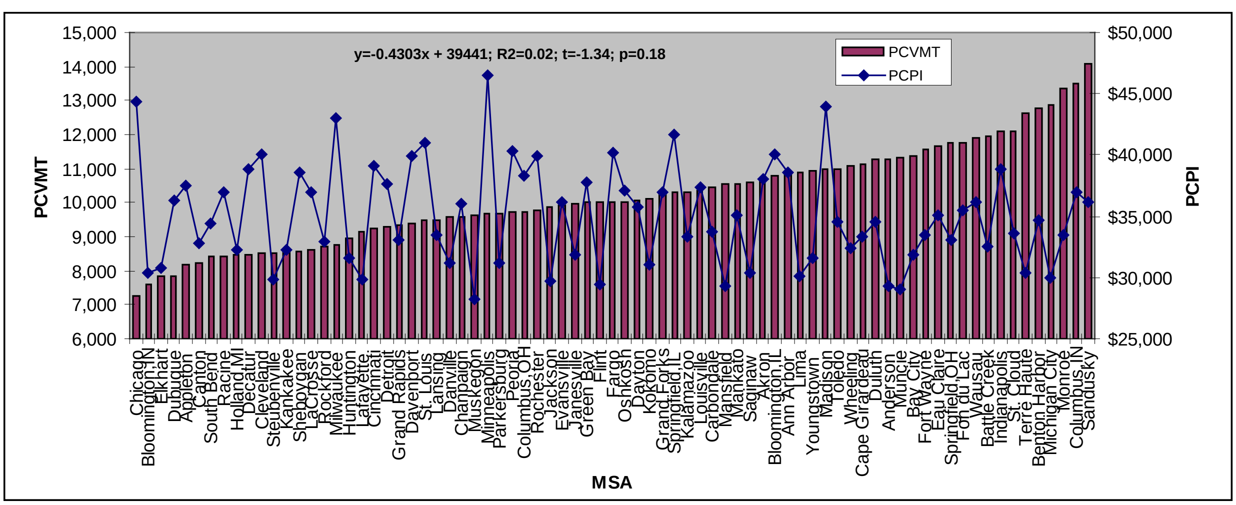

FIGURE 1 FTA Region 5 2010 MSA Per Capita VMT and Personal Income.

Pozdena also cites other voluminous research to conclude that income and demographics tend to have higher positive associations with VMT rather than population density *(19)*. It is certainly true that additional travel requires more fuel and vehicles which collectively generates economic activity. Conversely, higher vehicle travel in tandem with reduced population densities imposes externalities such as congestion, accident damages, import exchange burdens, and pollution from emissions. This increases economic activity but can reduce economic efficiency and quality of life. Other researchers have found a positive relationship between vehicle travel and economic productivity which predominantly occurs with increases from low to moderate levels of mobility. These are high-value trips such as the ability to get to employment that otherwise might not have been possible. However, at a point many additional trips are discretionary and the declining marginal benefits can become negative due to the decreases in economic efficiency *(21)*.

Findings from a study on the effects of compact development were that a doubling of population density may lower household VMT by 5 to 12 percent and perhaps by as much as 25 percent. The caveats are that the compact scenario includes higher employment densities, transit improvements, mixed land uses and other supportive demand management strategies *(23)*. In a meta-analysis of travel and urban form, research concluded that there is a relatively weak relationship between population/employment density and SOV travel. However, this was based on controlling other factors related to density such as intersection density, street connectivity, and jobs/housing balance *(7)*.

Studies have drawn conflicting conclusions on whether regions with higher population densities experience higher housing costs. Real income in terms of lower cost of living and housing affordability has been found to improve with declining urbanized area population density in addition to slower population growth rates *(24)*. Clearly, housing costs overall will rise in higher density areas if many home and lot sizes do not vary much from those in smaller areas. However, many larger areas respond to these pricing signals with smaller lot sizes and dwelling units. Controlling for other factors, a study of 452 U.S. UAs using 2000 data found small housing price decreases were associated with a more centralized urban form *(25)*. Market demand, housing availability, and local regulations on land use are the primary determinants of housing costs *(26)*. Additionally, per capita income and climate are significant factors *(27)*. While there are certainly exceptions, combined housing and transportation costs tend to decline closer to urban centers in areas with good transit systems *(28)*.

Studies have found that independent variables such as the proportion of an area that is urban, level/type of private sector employment, employment rate, and education quality and/or level have strong influences on per capita income *(29)(30)(31)(32)*.

STUDY MODEL DEVELOPMENT

Independent and dependent variable data were obtained primarily from the Census and BEA for 2010 and 2000 for the MSAs in the six-state study area. Some of the data for 2010 are five-year estimates from 2006-2010. Table 1 below shows associations of the 2010 cross-sectional data in terms of a Pearson Correlations matrix, or correlation coefficient indicating strength of the associations as measured by *R*. Additionally, the Pearson Probabilities depict the *p*-values with significance less than 0.05 highlighted in red. Most of the independent variables have statistically significant correlations when measured individually with the dependent variable of PCPI/PCVMT.

Pearson Correlations

	PCPI	PCVMT	POP	PD	WPD	PCPT	PCGDP	EMPR	LFPR	POVR	QE	MANUF	PCEX	EDUBS	GINI	RPP	BCS	PCPI/PCVMT
PCPI	1.000	-0.153	0.491	0.332	0.577	0.410	0.803	0.547	0.648	-0.471	0.547	-0.217	0.193	0.654	0.202	0.440	0.015	0.710
PCVMT		1.000	-0.284	-0.301	-0.399	-0.278	-0.135	-0.023	-0.071	-0.042	-0.112	-0.045	-0.165	-0.143	-0.177	-0.323	-0.047	-0.786
POP			1.000	0.727	0.773	0.540	0.405	-0.042	0.149	-0.127	0.558	-0.204	-0.007	0.283	0.314	0.548	0.136	0.563
PD				1.000	0.694	0.344	0.258	-0.266	0.034	-0.093	0.599	0.008	-0.037	0.172	0.265	0.472	0.240	0.463
WPD					1.000	0.780	0.516	0.156	0.317	-0.097	0.569	-0.226	-0.025	0.563	0.342	0.613	-0.161	0.672
PCPT						1.000	0.352	0.179	0.193	0.055	0.406	-0.333	0.036	0.588	0.355	0.538	-0.403	0.466
PCGDP							1.000	0.523	0.616	-0.397	0.551	-0.027	0.175	0.650	0.221	0.403	-0.050	0.568
EMPR								1.000	0.571	-0.145	0.110	-0.353	-0.058	0.584	0.166	0.003	-0.406	0.317
LFPR									1.000	-0.596	0.275	-0.016	-0.083	0.546	-0.221	0.357	-0.119	0.428
POVR										1.000	-0.280	-0.293	-0.035	-0.030	0.616	-0.247	-0.401	-0.282
QE											1.000	-0.151	-0.009	0.435	0.227	0.454	0.097	0.404
MANUF												1.000	0.244	-0.418	-0.405	-0.128	0.397	-0.063
PCEX													1.000	-0.055	0.074	0.034	0.150	0.238
EDUBS														1.000	0.451	0.485	-0.529	0.460
GINI															1.000	0.057	-0.265	0.231
RPP																1.000	-0.012	0.508
BCS																	1.000	0.074
PCPI/PCVMT																		1.000

Pearson Probabilities

	PCPI	PCVMT	POP	PD	WPD	PCPT	PCGDP	EMPR	LFPR	POVR	QE	MANUF	PCEX	EDUBS	GINI	RPP	BCS	PCPI/PCVMT
PCPI	-	0.184	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.058	0.093	0.000	0.078	0.000	0.896	0.000
PCVMT		-	0.012	0.008	0.000	0.014	0.241	0.845	0.540	0.718	0.334	0.699	0.152	0.214	0.124	0.004	0.684	0.000
POP			-	0.000	0.000	0.000	0.000	0.715	0.196	0.271	0.000	0.076	0.952	0.013	0.005	0.000	0.237	0.000
PD				-	0.000	0.002	0.024	0.019	0.772	0.423	0.000	0.946	0.748	0.135	0.020	0.000	0.035	0.000
WPD					-	0.000	0.000	0.177	0.005	0.402	0.000	0.048	0.830	0.000	0.002	0.000	0.161	0.000
PCPT						-	0.002	0.118	0.092	0.636	0.000	0.003	0.755	0.000	0.002	0.000	0.000	0.000
PCGDP							-	0.000	0.000	0.000	0.000	0.816	0.127	0.000	0.054	0.000	0.666	0.000
EMPR								-	0.000	0.207	0.341	0.002	0.618	0.000	0.148	0.981	0.000	0.005
LFPR									-	0.000	0.015	0.888	0.473	0.000	0.054	0.001	0.301	0.000
POVR										-	0.014	0.010	0.764	0.795	0.000	0.030	0.000	0.013
QE											-	0.191	0.936	0.000	0.047	0.000	0.402	0.000
MANUF												-	0.033	0.000	0.000	0.268	0.000	0.585
PCEX													-	0.634	0.523	0.767	0.192	0.037
EDUBS														-	0.000	0.000	0.000	0.000
GINI															-	0.622	0.020	0.043
RPP																-	0.916	0.000
BCS																	-	0.521
PCPI/PCVMT																		-

PCPI = per capita personal income
PD = population density
WPD = weighted population density
PCPT = per capita public transportation ridership
PCGDP = per capita gross domestic product
EMPR = employment rate
LFPR = labor force participation rate
POVR = poverty rate
QE = quality employment
MANUF = PCPI from manufacturing employment
PCEXP = per capita export value
EDUBS = proportion of population aged 25+ with a bachelors degree
GINI = gini index rating of personal income equity
RPP = regional price parity
BCS = binary value for proportion of college students >0.08
PCPI/PCVMT = per capita personal income/per capita vehicle miles traveled ratio

TABLE 1 2010 Region 5 Multiple Variable Regression Correlation Matrix

Data for a number of other independent variables, including per capita federal expenditures and average annual temperature, were gathered but not included in Table 1 due to their lack of significance when analyzed together with the other variables. The study also analyzed 2010 U.S. Bureau of Labor Statistics (BLS) employment data by proportion of worker income in the Region 5 MSAs for the following categories: manufacturing; construction, finance and real estate (FIRE); government; arts and entertainment; accommodation/food service; and the variance of these metrics. A statistically significant relationship was not identified for any of these independent variables in relation to PCPI/VMT. However, areas with less variance by employment category tended to have positive impacts on the dependent variable. Other research has found that personal income is positively correlated with industrial diversity. That research found there is weak evidence of areas with higher personal income having concentrations in any one industry when controlling for other factors *(10)*.

Weighted population densities were used to measure monocentric/polycentric population clustering *(33)*. 2010 and 2000 population densities were calculated for each of the almost 12,000 MSA Census tracts in the study area. The results for each tract were then weighted by the proportion of total regional population and then added for each MSA. Typically, the weighted densities are somewhere between the core city population densities and densities of the larger MSA areas. As shown in the correlation matrix in Table 1 for the 2010 data, WPD has stronger positive associations than population and standard population density with the following quality of life metrics: PCPI, PCGDP, EMPR, LFPR, EDUBS, and PCPI/PCVMT. Most of the independent variables in Table 1 have statistically significant relationships with PCPI/PCVMT when analyzed individually for 2010. A multi-variable regression analysis was run initially using all of these variables based on 2010 data. An iterative process was conducted on the 2010 data by removing independent variables incrementally from the initial multi-variable regression model to ensure retention of those having statistically significant correlations with PCPI/PCVMT.

INTERPRETATION OF RESULTS

The process of developing a cross-sectional model using 2010 data resulted in primarily three independent variables (WPD, PCEXP, EMPR in order of strength) having statistically significant associations with PCPI/PCVMT in this multi-variable analysis, as measured by the R^2 and *p/t*-values. Additionally, a binary value was retained due to it's significance on the dependent variables when used together with these three independent variables. The binary metric differentiates MSAs with high proportions of college students compared to the overall population >0.08 and those with less than this value.

Additional separate multi-variable cross-sectional regression was performed using the dependent variables of PCPI/PCVMT and PCTC/PCPI for both years of 2000 and 2010. Separate multi-variable longitudinal regression was also calculated for both dependent variables using data for the changes between these years. Finally, a hybrid of cross-sectional and longitudinal data was used in an effort to improve performance of the model. Data was converted to log values for all models in part to address non-constant variance due primarily to outliers such as the Chicago MSA which has WPD much higher than all of the other MSAs. Multicollinearity is not a concern in any of the models as the four dependent variables do not have statistically significant or substantive relationships with each other.

Results from the eight regression models for the 76 Region 5 MSAs are in Table 2 below at the 0.05 level of significance. The output consists in part of the R^2 values showing fractions of the variation in PCPI/PCVMT and PCTC/PCPI that are explained by the equations. PCTC includes public transportation operating expenses obtained from the National Transit Database (NTD)*(34)*. Excluding the NTD statistics from PCTC did not have any substantive effect on the relationship. With the exception of the longitudinal models, all R^2 values are near to or more than 0.50. Output includes the *F*-ratio, or the regression mean square divided by the mean square residual, and its *p*-value, *Significance F*. All of the models are statistically significant as these metrics are above and below the respective critical values. *Significance F* under 0.05 means there is less than a 5% chance that the dependent variable observations occurred by chance.

Dependent Variable	Cross-sectional model								Longitudinal Model				Hybrid Model			
	2010 PCPI/PCVMT		2010 PCTC/PCPI		2000 PCPI/PCVMT		2000 PCTC/PCPI		Δ 00'-10' PCPI/PCVMT		Δ 00'-10' PCTC/PCPI		2010 PCPI/PCVMT		2010 PCTC/PCPI	
	Coefficient	T stat	Coefficient	T stat	Coefficient	T stat	Coefficient	T stat	Coefficient	T stat	Coefficient	T stat	Coefficient	T stat	Coefficient	T stat
Intercept	-2.60	-4.32	1.62	5.26	-2.19	-0.35	0.65	0.74	0.13	3.92	0.63	3.74	-5.92	-5.53	1.07	7.40
WPD 2010	0.22	6.31	-0.03	-6.25												
EMPR 2010	1.90	2.88	-1.10	-3.83												
PCEXP 2010	0.06	3.24	-0.01	-2.60									0.05	2.68	0.01	-2.77
Binary			-0.04	-2.37	0.37	3.38	-0.05	-3.20					0.30	2.60	0.04	-2.21
Δ WPD									0.10	1.16	0.02	0.53	0.54	2.05	-0.06	-1.74
Δ EMPR									1.61	3.15	-0.76	-2.97	6.27	4.31	0.84	-4.28
WPD 2000					0.28	7.83	-0.04	-7.30					0.26	7.54	-0.03	-6.81
EMPR 2000					0.84	0.14	-0.16	-0.20								
R^2	0.52		0.53		0.50		0.47		0.14		0.11		0.59		0.55	
F	26.11		20.45		24.40		21.38		6.14		4.43		20.12		17.68	
Significance F	1.40E-11		2.74E-11		4.82E-11		4.84E-10		3.41E-03		1.53E-02		1.92E-12		2.42886E-11	

PCPI = per capita personal income
PCVMT = per capita vehicle miles traveled
PCTC = per capita transportation costs
a = the y intercept
b = slope associated with x variable
WPD = weighted population density
EMPR = employment rate
PCEXP = per capita exports
Binary = proportion of college students > 0.08

TABLE 2 Estimating transportation cost impacts of polycentric development.

Table 2 also exhibits the *t* stats, which is the coefficient divided by the standard error, for the independent variables in each of the regression models. The associated *p*-values are not included. Generally, the respective *t* stats and *p*-values are above and below the critical levels of significance at the 0.05 level of confidence with the following exceptions: EMPR in the 2000 cross-sectional regression analysis; and WPD change between 2000 and 2010 in the longitudinal model. All eight models demonstrate statistically significant positive correlations between polycentricity as measured by WPD and the proportion of personal income dedicated to transportation costs measured both as PCPI/PCVMT and PCTC/PCPI. The two respective hybrid model equations for the dependent variables of PCPI/PCVMT and PCTC/PCPI exhibited the highest R^2 values and are shown below for the 77 Region 5 MSAs. Their *F* statistic was not quite as high as the cross-sectional models. However, the hybrid models allowed the use of both cross-sectional 00'WPD and the change in WPD (longitudinal) from 00'-10'.

Hybrid Equation 1

$$10'\ PCPI / PCVMT = \sum a + (b_1)00'\ WPD + (b_2)\Delta 00'\text{-}10'\ WPD + (b_3)\Delta 00'\text{-}10'\ EMPR + (b_4)10'PCEXP + Binary$$

Hybrid Equation 2

$$10'\ PCTC / PCPI = \sum a + (b_1)00'\ WPD + (b_2)\Delta 00'\text{-}10'\ WPD + (b_3)\Delta 00'\text{-}10'\ EMPR + (b_4)10'PCEXP + Binary$$

These models were then tested for the following assumptions of multiple regression: normality, linearity, homoscedasticity, and reliability of measurement. Separate normal probability plots or P-plots of the residuals or errors and the independent variables shows they are all in a fairly straight line with slight tailing at the ends. This held true with both the standard and log data but there is an improvement with the latter. Consequently, there appears to be no problem with the normality assumption.

The standardized residuals or errors were then plotted with the predicted log values for each of the dependent variables and the actual log values of the non-binary independent variables. All of the plots tended to be distributed randomly around the horizontal line of 0 with no noticeable pattern. In other words, the errors appeared to exhibit traits of linearity and homoscedasticity or similar amounts of variance across the range of independent and dependent variable values. A Goldfeld-Quandt (GQ) test was performed to further analyze the assumption of linearity and homoscedasticity. The data was sorted by the independent variable of 2000 WPD. Separate regressions were performed on both the upper and lower one-third of the data while excluding the middle portion. The ratio of the Residuals Sum of Squares ($R = RSS2/RSS1$) was calculated and compared to F*((n-c-2k)/2, (n-c-2k)/2 degrees of freedom*, where n is the sample size, c is the number of dropped observations, and k is the number of regressors in the model. $R<F$ is the null hypothesis of homoscedasticity. Since $R>F$, the null hypothesis of homoscedasticity is rejected and heteroscedasticity was found to be present as depicted in the Unadjusted section of Table 3 below.

DV	Unadjusted		Adjusted	
PCPI/PCVMT	R = RSS2 / RSS1 R = 0.42899 / 0.18059 R = 2.38	F((n-c-2k)/2, (n-c-2k)/2 F((77-25-2*5)/2, (77-25-2*5)/2 F(21,21,.05) F = 2.10	R = RSS2 / RSS1 R = 0.34593 / 0.18052 R = 1.92	F((n-c-2k)/2, (n-c-2k)/2 F((75-25-2*5)/2, (75-25-2*5)/2 F(20,20,.05) F = 2.12
PCTC/PCPI	R = RSS2 / RSS1 R = 0.00937/ 0.00256 R = 3.66	F((n-c-2k)/2, (n-c-2k)/2 F((77-25-2*5)/2, (77-25-2*5)/2 F(21,21,.05) F = 2.10	R = RSS2 / RSS1 R = 0.00445/ 0.00219 R = 2.03	F((n-c-2k)/2, (n-c-2k)/2 F((72-24-2*5)/2, (72-24-2*5)/2 F(19,19,.05) F = 2.17

TABLE 3 Goldfield-Quandt Test Summary

The problem was addressed in each model through sorting by the residuals and eliminating outlier data or MSAs with the highest errors. Sandusky and Elkhart were eliminated from *Hybrid Equation 1* while these locations in addition to Steubenville, Michigan City, and Terre Haute were removed from *Hybrid Equation 2*. The GQ test was performed again with separate regressions on both the upper and lower one-third of the data, excluding the middle portion. Since $R<F$, the null hypothesis of homoscedasticity is retained as heteroscedasticity was eliminated as shown in the Adjusted section of Table 3. The adjusted metrics for *Hybrid Equations 1 and 2* are depicted in Table 4 below. Strength of the models is increased and all dependent variables remain statistically significant.

Elasticity measures sensitivity of the dependent variables to a change in one or more of the independent variables. The dependent variables were not found to be elastic in relation to PCEXP. Differences in levels of personal vehicle usage and transportation costs as a proportion of income amongst the MSAs are elastic to changes in employment rate and existing urban form. A 1% increase in employment rate can be expected to increase PCPI/PCVMT ratio by 3.9% and reduce PCTC/PCPI ratio by 4.4%. An area with 1% higher WPD than another region can be expected to experience a 1.6% larger PCPI/PCVMT ratio and 1.7% lower transportation costs as a proportion of income when measured by PCTC/PCPI.

Changes in WPD from 00'-10' for the 76 Region 5 MSAs are statistically significant in terms of the *t* and *p* values but were not found to be elastic. A 1% increase in the WPD change independent variable can be expected to alter the dependent variables by 0.3%: positively for PCPI/PCVMT; and negatively for PCTC/PCPI. Almost all MSAs analyzed exhibited decreases in WPD between the two periods. The mean decrease was -8.6% with a range of about -43% to +32%. Only 6 MSAs experienced double-digit WPD increases and 4 of them were small to medium size areas with college students making up >0.08 of the population. A possible partial explanation is that college students tend to reside in clusters on or near campus. In addition, they usually have minimal income and may be dedicating a much higher proportion of it to transportation. As a result, impact on the dependent variables is minimized.

Dependent Variable	Hybrid Model Adjusted					
	2010 PCPI/PCVMT		2010 PCTC/PCPI		2014 HUD/DOT Transport Costs	
	Coefficient	T stat	Coefficient	T stat	Coefficient	T stat
Intercept	-6.61	-6.44	1.15	8.88	0.62	4.72
WPD 2010						
EMPR 2010						
PCEXP 2010	0.04	2.39	0.01	-2.82	-0.002	-1.09
Binary	0.34	3.08	0.04	-3.01	-0.03	-2.05
Δ WPD	0.51	2.09	-0.07	-2.16	-0.07	-2.36
Δ EMPR	7.29	5.20	-0.95	-5.42	-0.08	-0.44
WPD 2000	0.26	8.35	-0.03	-7.89	-0.03	-8.66
EMPR 2000						
R^2	0.64		0.63		0.57	
F	24.39		22.88		17.3	
Significance F	4.72E-14		3.00E-13		6.59E-11	

TABLE 4 Final Model Output and Validation

Another potential reason for the lack of elasticity in the dependent variables to WPD changes over time is that very few urban areas, if any, likely have aggressive land use policies that focus non-student growth and development geographically inward rather than outward. These findings appear to demonstrate the challenge in significantly revamping conventional low-density land use patterns that have evolved in exurban areas since the post-World II period.

As shown in Table 1, MSA population (POP) and standard population density (SPD) have statistically significant positive associations with PCPI/PCVMT measured through single-variable regression that are not quite as strong as for WPD. For comparison purposes, POP and SPD were substituted for WPD in separate multivariable regressions using the above *Hybrid Equation 2*. In both cases, R^2 is 0.50 and the equations are statistically significant as demonstrated by F values of about 14. These are not quite as strong as the values for WPD in Table 2. The POP and SPD values for 2000 and the changes between the two periods are also statistically significant. The *t* and *p*-values are not as strong for 2000 as with WPD but they are stronger for changes between periods. This comparison can be interpreted to show the strength of the existing built environment and population clustering over population and SPD in predicting the proportion of income spent on transportation. Further, changes in the dependent variable from 2000 to 2010 are likely less influenced by WPD due to heavy continuation of exurban development in conventional low density form. Again, impacts of any increases in clustering may be minimized by a substantive amount occurring due to college student population increases.

For validation purposes, Figure 2 below depicts a scatterplot of Region 5 MSA 2010 WPD against HUD/DOT Location Affordability Portal (LAP) transportation costs as a proportion of household income for the study area. The LAP uses both regression and structural equation modeling to estimate housing and transportation costs by location. These estimates are based primarily on a number of Census databases/surveys relating to household and employment characteristics at the block level. Data used includes selected home features/ownership costs, household and job densities in addition to vehicles per residence and means of transportation to work *(35)*. There is a strong significant negative relationship between the 2010 WPD data and LAP transportation costs estimates as depicted by the following values: R^2=0.53, t=-9.0, p=1.7E-13. Further, the HUD/DOT transportation costs data was substituted for the PCTC/PCPI data as the dependent variable in the final hybrid multi-variable regression analysis. The output is included in Table 4 above. This test showed comparable statistically significant relationships in terms of the overall model and two WPD independent variables. The EMPR change and EXPR independent variables are not statistically significant. Data for these variables are not used in the LAP methodology.

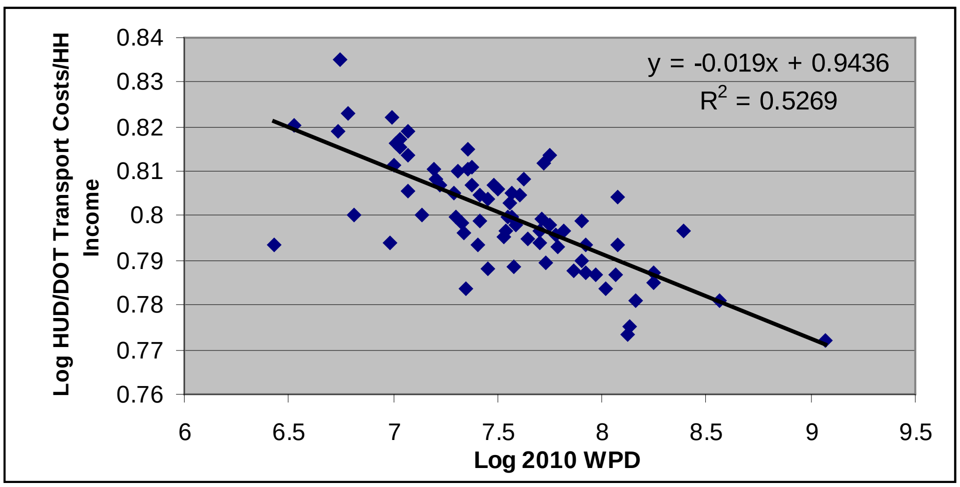

Figure 2 Comparison of Region 5 MSA 2010 WPD and HUD/DOT Transportation Costs/Household Income Ratio

CONCLUSION

WPD data has value in measuring the association of alternate urban form scenarios on quality of life, particularly in terms of increasing land use polycentricity and reducing the proportion of personal income used to meet transportation demand. Further use of the WPD metric can be meaningful in addressing and predicting outcomes associated with the USDOT planning factors and PSC livability principles including energy conservation, emissions, transportation system efficiency, and revitalization of neighborhoods. A hybrid of cross-sectional and 2000-2010 longitudinal data in 77 Midwestern MSAs demonstrate that higher WPD is statistically significant with the proportion of income dedicated to transportation. MSAs with a 1% higher WPD than others can be expected to have larger PCPI/PCVMT ratios by about 1.6% and smaller PCTC/PCPI ratios by about 1.7%. Consequently, the ratio of income dedicated to transportation is elastic or sensitive to differences in form of the built environment. A 1% increase in WPD over the measured 10-year period is also statistically significant but not elastic as it can only be expected to change the independent variables by 0.3%.

The WPD metric itself is not a panacea for urban planning as it is not measuring underlying features that tend to influence attractiveness of the built environment and travel mode split. Sterile and isolated high-rise public housing developments would equate to higher WPD measures but general consensus has been that they are not a component of desirable urban form. Measures such as mixed land uses, building form and setbacks, and street/sidewalk connectivity indexes including intersection densities and block lengths will continue to provide more specificity. Nevertheless, the value of WPD is in its simplicity and potential in guiding the planning of these other characteristics.

The study does not model the association of increased WPD on property values. Research is clear that land prices generally rise with increasing development intensity. Conflicting studies exist on the association of higher property values with the proportion of income dedicated to housing costs. However, WPD can be an indicator of improved quality of life, as measured by combined housing and transportation costs and exhibited in analysis of HUD/DOT Location Affordability data. The caveat is that land use policies are in place to facilitate both inward growth/development and provide adequate housing to meet demand.

Generally, it takes many years to change the existing built environment once any particular urban form is established. Consequently, the changes measured over the 10-year period are not relatively substantive compared to what could occur over much longer periods. This is an area for further research. However, there could be challenges in availability of older comparable Census tract data. Such analysis could also include housing costs to understand a more long-term association of these combined expenditures as a proportion of PCPI. Future research could also focus on a larger sample for the United States to identify potential differences with the six-state study area.

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