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Road Expansion, Urban Growth, and Induced Travel: A Path Analysis

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Abstract

Claims that roadway investments spur new travel and thus fail to relieve traffic congestion, known as induced demand, have thwarted road development in both the United States and abroad. Most past studies point to a significant induced demand effect. This research challenges past results by employing a path model to causally sort out the links between freeway investments and traffic increases, using data for 24 California freeway projects across 15 years. Traffic increases are explained in terms of both faster travel speeds and land-use shifts that occur in response to adding freeway lanes. While the path model confirms the presence of induced travel in both the short- and longer-run, estimated elasticities are generally lower than those of earlier studies. This research also reveals significant “induced growth” and “induced investment” effects – real-estate development has gravitated to improved freeway corridors and road investments have been shaped by traffic trends in California. Fighting road projects on the grounds of induced-demand should be carefully considered. Energies might be better directed at curbing mis-pricing in the highway sector and managing land-use changes spawn by road investments.

Road Expansion, Urban Growth, and Induced Travel: A Path Analysis

Few issues in the urban transportation field have sparked as much controversy and threatened proposed road projects as claims of "induced demand". For decades, highway critics have charged that building new roads or expanding existing ones to relieve traffic congestion is a futile exercise. Improved roads simply spur additional travel or divert trips from parallel routes, quickly returning a facility to its original congested condition. Traffic is thought to behave more like a gas than a liquid – it expands to fill available space. Regional transportation plans, such as in the San Francisco Bay Area, have been mired in legal and political squabbles on the very grounds that they failed to account for the possibility that new roads might induce sprawl and the extra trips associated with it. Claims of induced demand have spawned such clichés as "build it and they will come" and "you can't pave our way out of traffic congestion".

The preponderance of empirical evidence to date suggests that induced effects are substantial. A widely cited study by Hansen and Huang (1997), based on 18 years of data from 14 California metropolitan areas, found every 10 percent increase in lane miles was associated with a 9 percent increase in vehicle miles traveled (VMT) four years after road expansion, controlling for other factors. Another study of 70 U.S. metropolitan areas over a 15-year time period concluded that areas investing heavily in road capacity fared no better in easing traffic congestion than areas that did not (Surface Transportation Policy Project, 1998). Based on a meta-analysis of more than 100 road expansion projects in the United Kingdom, Goodwin (1996) found that proportional savings in travel time were matched by proportional increases in traffic on almost a one to one basis, a finding that prompted the U.K. government to jettison its longstanding policy, "predict and provide", of responding to traffic-growth forecasts by building more motorways.

With the cumulative weight of evidence on induced demand threatening road projects in many parts of the United States, it bears noting that past research has recently come under fire on methodological grounds. Many studies can be faulted for failing to introduce a normative behavioral framework for tracing impacts, one that accounts for intermediate steps between road improvements and traffic growth and that allows for two-way causality (DeCorla-Souza and Cohen, 1999; Cohen, 2001; Pickrell, 2001; Cervero, 2001).

Using data for a panel of California freeways, this paper aims to fill past methodological gaps by postulating and empirically testing a path model of induced travel. A short-run model, which focuses on relationships within a one-year time frame, holds that changes in road supply affect travel speeds, which nearly instantaneously affect traffic levels. In contrast to most recent analyses of induced demand that measure VMT growth as a direct function of lane-mile additions, this analysis introduces an important intermediate step – namely, that road improvements confer benefits, in the form of higher travel speeds, and that it is changes in operating conditions that influence demand, not the physical attributes (e.g., lane miles) of a project. A longer-run model traces how road investments induce major building activities over a multi-year time horizon, and how resulting land-use shifts in turn lead to increased travel. A feedback loop is also modeled, capturing how traffic growth influences road investment decisions.

Econometric models are called upon to sort out the relative influences of land-use shifts in stimulating traffic vis-à-vis travel behavioral adjustments that are normally associated with induced demand. To the degree that induced travel is found to be a consequence of long-term structural adjustments, land-use management and planning gains all the importance as a tool for managing traffic levels.

1. The Anatomy of Induced Demand

Road improvements are thought to have distinct near- and longer-term impacts. In the short run, increased capacity prompts *behavioral* shifts – some formerly suppressed trips are now made (i.e., latent demand), and some motorists switch modes, routes, and times of travel to exploit available capacity, what Downs (1962, 1992) calls “triple convergence”. For example, those who previously patronized transit to work might decide to drive once they see traffic flowing more smoothly. Some who previously commuted on the shoulders of the peak might start filling freeway slots that are vacant in the heart of the peak. Over the longer term, *structural* changes can be expected. Notably, people and firms locate to exploit the accessibility benefits created when freeways are upgraded. The consequences dot America’s landscape: fast-food restaurants, gas stations, and other auto-oriented uses cluster around interchanges, warehouses align themselves along frontage roads, and new residential subdivisions spring up along connecting arterials (Hartgen and Kim, 1998; Hartgen and Curley, 1999).

Some of the traffic gains spawn by a new or improved road are *generative* in nature and some are *redistributive*. The former represents new travel that did not previously exist in any form. Included here are formerly suppressed trips, longer trips as motorists opt to travel farther because of freer flowing traffic, and modal shifts. Route and schedule changes, on the other hand, are redistributive in the sense that they do not increase total miles traveled (assuming trips do not become more circuitous).

Short of placing an electronic tag on each traveler affected by a new road and monitoring his or her travel, disentangling the many contributors to increased travel – at least to a high degree of precision – can be a futile exercise (Bonsall, 1996). For this reason, many past studies have examined the magnitude of traffic increases following a road improvement for *all* sources combined. Some studies have employed county- or metropolitan-level data to trace the influences of aggregate increases in lane-miles on aggregate increases in vehicle miles traveled (VMT) (for example: Hansen and Huang, 1997; Noland and Cowart, 2000; Fulton, *et al*., 2000). This helps to net out redistributive trips since route diversions occur largely within the unit of analysis, although the downside of such aggregate analyses is they are more easily prone to ecological fallacies when drawing statistical inferences.

Many past empirical studies have applied simplified model structures to gauge "induced demand" effects. Often, traffic increases are treated as a direct consequence of lane-mile additions. It is not the lane miles of roads that prompt people to travel more, however. Rather it is the benefits that the lane miles confer. Only if travel speeds increase and travel times fall will motorists gravitate to an improved corridor. Adding a 12-foot lane matters along a highly congested urban corridor; adding one to a lightly trafficked exurban stretch really does not. A firmer econometric framework is needed to help unravel the imbedded, often intricate relationship between road investments and traffic conditions.

2. Toward a Normative Theory: A Path Model

Figure 1 presents a path model for tracing the effects of road improvements on travel demand as well as urban development. The diagram's solid lines represent near-instantaneous impacts, occurring within a year's time. The dashed lines represent longer-term adjustments, signifying the need for a lagged model structure. In the transportation and land-use arena, delayed responses to “stimuli” like road improvements reflect

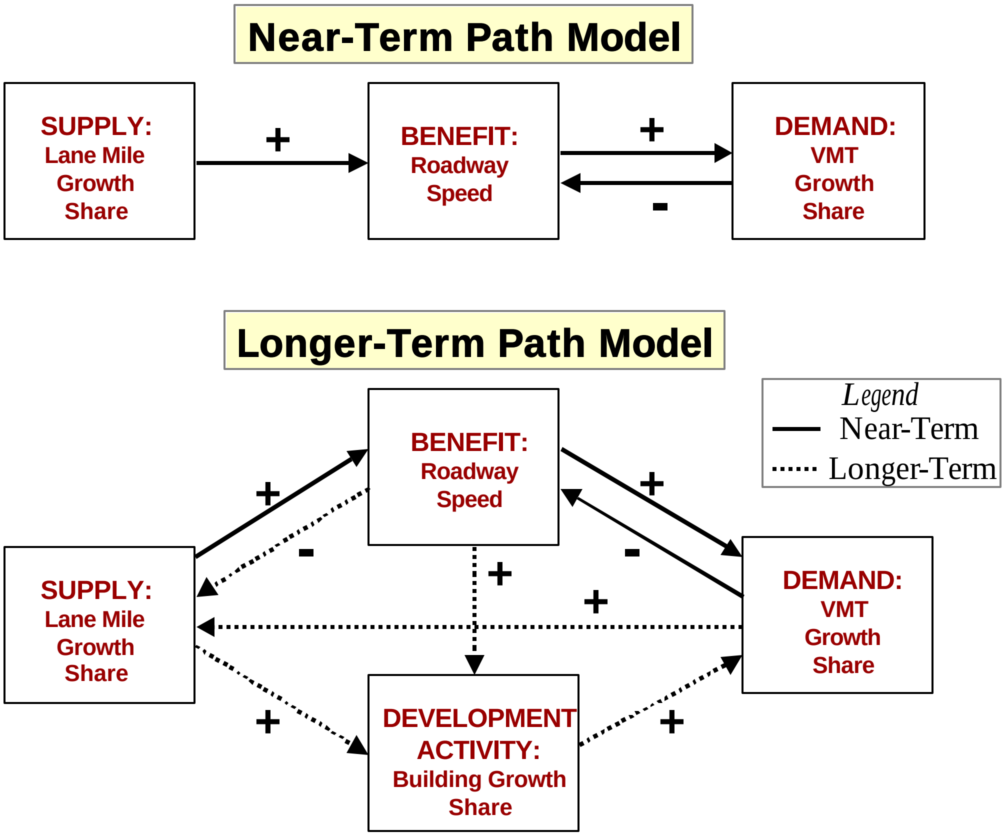


Figure 1. Hypothesized Path Model

institutional lags – such as the need for local planning agencies to rezone land to accommodate new growth or time spent by real-estate developers securing building permits and bank loans.

The path diagram also informs the model estimation process. In the case of uni-directional relationships (in both the near-term and longer-term models), ordinary least squares (OLS) provides efficient, unbiased estimates (as long as OLS assumptions are met). Estimation of two-way, co-dependent relationships hinges on the time structure. Where two variables, like travel speed and demand, nearly instantaneously influence each other, OLS will produce biased parameter estimates. This is because speed and demand are endogenously related. Accordingly, instrumental variables are needed to reduce simultaneous-equation biases. Where two variables are jointly related, and variable X influences variable Y nearly instantaneously but Y's effect on X is delayed over several years, OLS will generally provide suitable parameter estimates. Because the co-dependence is not contemporaneous, the value of one variable, by definition, will be pre-determined in relation to that of the other. For example, while a road improvement can be expected to have a near-immediate effect on travel speed, the effects of eroding speeds over time (once travel demand has risen) on the decision to further expand a facility unfold over a number of years. Econometrically, the values of travel speed in time period (t-n) are already known in relation to the values of road capacity in the current time period (t). Thus, wherever a solid path-line operates in both directions between two variables, multi-stage (e.g., two-stage or three-stage) estimation is called for. Wherever one path-line is solid and the other is dashed in a two-way relationship, instrumentation is unnecessary.

Effects of Road Improvements on Travel Speeds

This link is missing from most past studies of induced demand. Economic theory holds that road improvements spur behavioral changes in travel by reducing "generalized costs", expressed mainly in terms of travel times. Over a fixed distance, there is a one-to-one correspondence between changes in average travel times and average speeds. In this study, average recorded operating speeds over a one-year period for each study corridor is used to gauge reductions in generalized costs.

Effects of Road Improvements and Travel Speeds on Urban Development

In congested urban settings with reasonably vibrant economies, real estate developers scramble to acquire and develop properties with good regional roadway access. Parcels well-served by roads can yield handsome profits (Voith, 1993; Boarnet and Chalermpong, 2001). Two forces are set into motion that influence the decision to develop a parcel, and for modeling purposes help to define a time-lag structure. One is the announcement and construction of road improvements. Developers are well aware of roadway projects slated for construction under regional Transportation Improvement Programs and position themselves to take advantage of planned public improvements. Due to institutional delays, however, it can take several years before necessary permits are secured. A five-plus year time lag between project announcement and new development is not uncommon. The time lapse between when capacity is actually added and induced development occurs is likely shorter, often on the order of two to three years.

Besides the opening of new lanes, actual operating conditions are also thought to influence the scale of land-use changes, at least at the margin. Higher speeds provide confirmation, demonstrating first-hand that there are advantages to owning or leasing properties along a particular stretch of roads. The combination of past-year road investments and recent trends in operating speeds are thought to influence the amount of development added within a buffer zone of a freeway.

Effects of Travel Speeds and Urban Development on Travel Demand

It is this link of the path diagram that encapsulates the idea of induced demand. The model postulates that the combination of current operating speeds on a roadway and previous-year changes in urban development influence current-period demand levels. Both factors are thought to increase VMT -- the former in the near term, the latter over the longer run.

Effects of Travel Demand and Speeds on Road Improvements

Figure 1 also accounts for “induced investment” effects. Notably, changes in a project’s share of countywide VMT over time can be expected to influence future shares of countywide road improvements targeted at the corridor, as will trends in travel speeds. Indeed, a criticism leveled at past induced demand studies is they ignored this feedback loop. Roads not only stimulate but also respond to demand. Using 60 years of data, a study by the Urban Transportation Center (1999) found that road improvements in metropolitan Chicago could be better explained by population growth a decade earlier than vice-versa. Over time, it is this combination of “induced demand” and “induced investment” effects that yields some degree of partial equilibrium between road supply and demand.

3. Methodology and Data

For purposes of empirically testing the hypothesized path model, a system of log-linear equations was specified and estimated. In this functional form, coefficient estimates represented elasticities, revealing the proportional change in one variable as a function of a proportional change in another, all else being equal. For the longer-run analysis, the estimated equations took the following form (with all except the fixed effect variables expressed as natural logarithms):

Speed Model: $B_{it} = f(S_{i,t}\ \ D_{i,t}\ \ C_{i,t}\ \ T_t\ \ P_i)$
Development Model: $L_{it} = f(B_{i,t-n}\ \ S_{it-n}\ \ C_{i,t}\ \ T_t\ \ P_i)$
Demand Model: $D_{it} = f(B_{i,t}\ \ L_{i,t-n}\ \ C_{it}\ \ T_t\ \ P_i)$
Supply Model: $S_{it} = f(D_{i,t-n}\ \ B_{i,t-n}\ \ C_{it}\ \ T_t\ \ P_i)$

Where:

B = Benefit vector (e.g., mean operating speed)
S = Supply vector (e.g., lane miles)
D = Demand vector (e.g., vehicle miles traveled)
L = Land-Use vector (e.g., building square footage)
C = Control vector (e.g., median personal income in area)
T = Time-series fixed effect (0-1 “dummy variable”)
P = Project fixed effect (0-1 “dummy variable”)
i = Project cross-sectional observation
t = Time-series observation
n = Length of time lag

With this formulation, benefits and demand are jointly related, thus endogenous variables (i.e., operating speed and VMT) were predicted as functions of pre-determined (exogenous and lagged-endogenous) variables. Given the lagged, pre-determined nature of other endogenous variables, other equations were predicted using ordinary least squares. Also, various time-lag specifications were attempted in the analyses that follow. Before turning to the results, background information on data sources, the sampling frame, and approaches used to measure and impute certain variables are reviewed below.

Data Sources

Records on freeway expansions throughout California were obtained from the California Department of Highways (CalTrans) for years that matched the time span (1980 to 1994) of annual records on building activities obtained from the U.S. Census Bureau. Census records on land-use additions were turned to because, among available secondary sources, they provided the most disaggregate and consistently reported time-series data. Project contracts archived by CalTrans supplied needed information on freeway improvements: the project name and location, number of lanes added, and the length of improved segments.

Sampling Frame

Only freeway expansion projects that occurred in small to medium-size municipalities in suburban settings were chosen for the analysis. This constraint was necessary because of how land-use changes were measured and how building activities were reported. A two-mile “impact zone” around the centerline of each improved freeway project was chosen to gauge development impacts, forming a four-mile wide buffer. However, building data from the census bureau were available only down to the municipal level. To ensure that the impact zone encompassed a significant share of a municipality’s land area, only freeway projects that traversed or skirted small-to-medium size cities were considered for the analysis. In all, 24 freeway-expansion projects over the 1980 to 1994 period (representing 360 data points) were chosen on the grounds that four-mile buffers encompassed at least 40 percent of the land area of municipalities that were either traversed or that directly bordered the improved facility.

Variable Measurement

The core variables from Figure 1 that were measured in aggregate units -- notably, lane-mile of roads, building-permit additions, and VMT – were expressed in proportional terms for carrying out the path analysis. Specifically, these variables were defined as shares of countywide totals – e.g., “VMT proportion” represented the share of VMT on all state-owned freeways and highways in a county that occurred on a particular facility for a particular year. In this sense, core variables were expressed as “market shares”. If the countywide share of total road-mile additions along a freeway corridor increases, this research hypothesizes that this will be followed by an increase in the share of countywide building activities within a four-mile buffer and that this in turn will be followed by increases in the share of countywide VMT recorded along the facility. Expressing aggregate variables in proportional terms meant that sub-regional trends and conditions were imbedded in the analysis.

The biggest measurement challenge involved estimating building activity within four-mile buffer zones. Using a Geographic Information Systems (GIS) street layer as a guide, paths of the 24 selected freeway projects were digitally traced. Next, four-mile buffers were formed around each project segment and superimposed onto a GIS layer of municipal boundaries. From this, the percentage of land area of each affected municipality that lied within the four-mile buffer was determined. It was assumed that the share of a municipality's building activities within a four-mile buffer matched the share of that municipality's land area within the same buffer. This implicitly assumed that land-use densities were uniform within a municipality. This was felt to be a reasonable assumption given that densities tend to be fairly similar in most small-to-medium size suburban municipalities – the places traversed or bordered by the freeway projects that were studied. To the degree that errors were introduced in imputing building activities within four-mile buffers, there was no reason to suspect such errors were systematically biased.

Census records contained fairly detailed information (e.g., square-footage, number of units) on building activities, drawn from municipal and county building-permit records, across major residential and commercial land-use categories. To empirically test the "induced growth" hypothesis, a composite variable of "building activity" was created for each freeway corridor, gauging the relative degree of countywide development that occurred within a four-mile-wide impact zone. Creating such a variable was necessary since VMT changes were thought to be less sensitive to particular land uses than the overall amount of building activity that took place within a corridor. Because building-permit data on the "scale" of activities reported by the Census Bureau differed among land uses, a composite variable was needed. (For example, residential development is report by number of housing units whereas industrial growth is tracked in terms of building square footage.) The composite represented a weighted average of countywide proportions of each of the six land-use categories: single-family residential; multi-family residential; offices; retail; industrial; and other (representing mainly public and institutional uses). Weights were based on total square footage estimates for each land-use category. Local data on average building sizes were used to estimate total square footage of housing units, offices, and retail establishments.[i]

Induced Travel Versus Induced Demand

As noted previously, not all of the changes in VMT that occur along an improved roadway are truly "induced demand" since some of the traffic growth migrates from other facilities, and will thus be redistributed. The term "induced travel" is often used to represent all changes in trip-making that are unleashed when a road is improved, not only in terms of newly added traffic but also in terms of diverted trips from other routes (Hills, 1996; Lee, *et* *al*., 1999). This distinction is important, and many previous studies have failed to carefully distinguish "induced demand" from "induced travel". Because this study examines VMT at the facility level, and there is no way to know from reported VMT data how much is diverted, "induced travel" is the focus of the research that follows.

4. Project List, Variables, and Descriptive Statistics

Table 1 lists the 24 freeway projects that formed the panel used to carry out the analyses, and Map 1 shows their locations within nine of California's 56 counties. Nineteen of the freeway segments studied were in four "mature suburban" counties: Contra Costa, Santa Clara, Orange, and Alameda. As limited-access, high-performance facilities, freeways provide favorable contexts for gauging induced travel and land-use impacts, particularly in fairly congested, fast-growing settings such as many of the California corridors studied.

Background data on segment length (in centerline miles) and lane expansions are also shown in Table 1. For each project, lane-miles of capacity were estimated by simply multiplying number of lanes by number of centerline miles. For example, the capacity of Project 15 increased from 15.6 lane miles (4 * 3.9) to 31.2 lane miles (8 * 3.9) when the 3.9-mile segment along Interstate-580 in Alameda County was expanded by one lane in each direction in 1986. In the data base, the number of lane miles for Project 15 was recorded as 15.6 for the period of 1980 to 1985 and 31.2 for the period of 1986 to 1994. Table 1 also shows the "variable name" used in the predictive models to account for each project's fixed effects (based on 0-1 coding). Fixed-effect variables help to capture the unique characteristics of certain places that are not expressed by other variables in an equation. Noland and Lem (2000) maintain that the inclusion of fixed-effect variables is absolutely essential in induced travel studies since so many exogenous, difficult-to-measure factors (e.g., entry of women into the workplace) have propelled VMT growth over the past several decades [see Heanue (1997) for further discussions].

Table 2 presents key variables used in conducting the path analysis, with variables organized across seven dimensions. Summary statistics for 360 data points (15 years of data pooled over 24 projects) are also shown. Over the 15-year study period, the 24 freeway segments constituted, on average, less than 3 percent of countywide VMT and lane-mile capacity. Office buildings constituted the highest average share (21 percent) of countywide

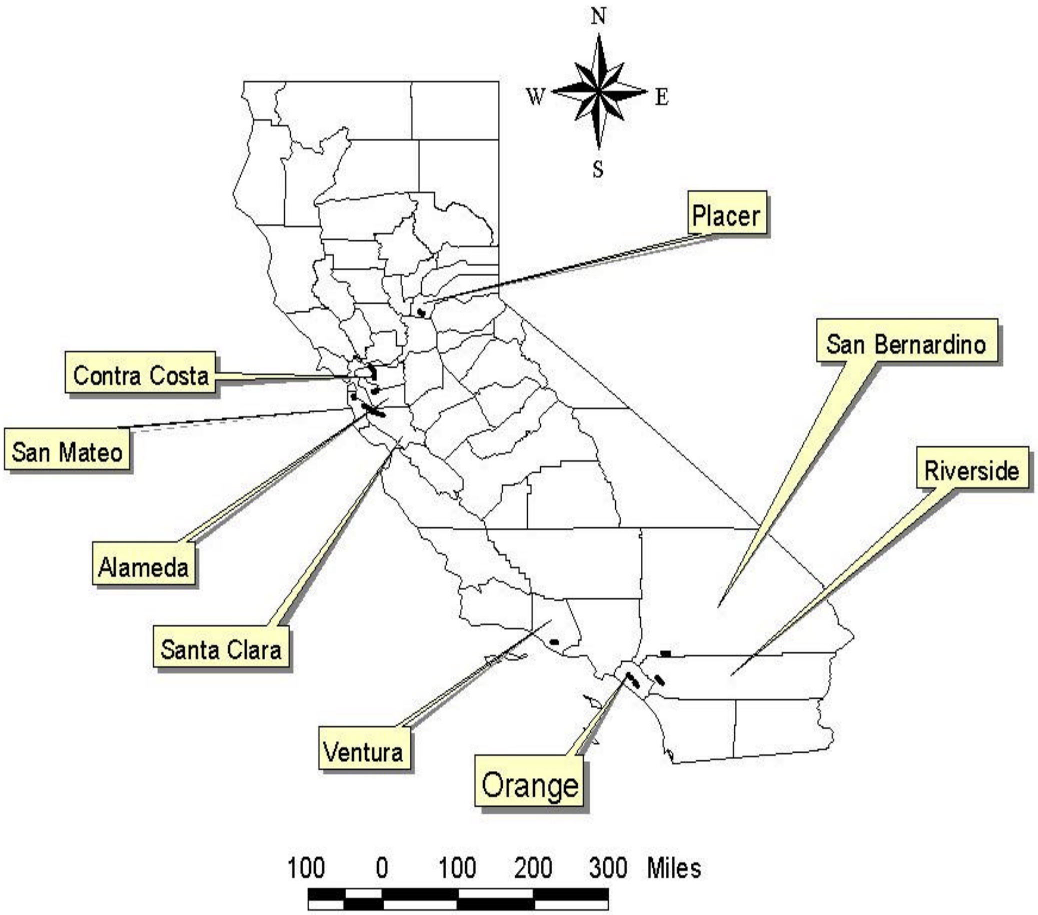
Table 1. Freeway Projects: Locations, Centerline Miles, Lane Expansions, and Variable Name

Project: Facility & County	Centerline Miles	Lane Expansion	Variable Name
1. Interstate-5, Orange County	4.9	8 to 10 lanes	Project1
2. Interstate-5, Orange County	2.6	8 to 16 lanes	Project2
3. Interstate-5, Orange County	2.7	6 to 10 lanes	Project3
4. Interstate-5, Orange County	2.1	6 to 14 lanes	Project4
5. Interstate-10, San Bernardino County	1.0	8 to 10 lanes	Project5
6. Interstate-15, Riverside County	3.6	4 to 6 lanes	Project6
7. U.S.-65, Placer County	3.5	2 to 4 lanes	Project7
8. U.S.-101, Ventura County	3.9	4 to 6 lanes	Project8
9. U.S.-101, Santa Clara County	1.3	6 to 8 lanes	Project9
10. U.S.-101, Santa Clara County	1.9	6 to 8 lanes	Project10
11. U.S.-101, Santa Clara County	1.2	6 to 8 lanes	Project11
12. U.S.-101, Santa Clara County	5.9	6 to 8 lanes	Project12
13. U.S.-101, Santa Clara County	6.4	6 to 8 lanes	Project13
14. U.S.-101, San Mateo County	5.4	6 to 8 lanes	Project14
15. Interstate-580, Alameda County	3.9	4 to 8 lanes	Project15
16. Interstate-580, Alameda County	2.1	4 to 8 lanes	Project16
17. Interstate-580, Alameda County	3.4	4 to 6 lanes	Project17
18. Interstate-680, Alameda County	2.8	4 to 8 lanes	Project18
19. Interstate-680, Contra Costa County	1.3	6 to 8 lanes	Project19
20. Interstate-680, Contra Costa County	1.2	6 to 7 lanes	Project20
21. Interstate-680, Contra Costa County	3.1	4 to 6 lanes	Project21
22. Interstate-680, Contra Costa County	2.7	4 to 6 lanes	Project22
23. Interstate-680, Contra Costa County	1.5	4 to 6 lanes	Project23
24. Interstate-680, Contra Costa County	1.8	4 to 6 lanes	Project24

land-use activities within the freeway buffers. Because study corridors were in suburban settings, gross densities tended to be fairly low for municipalities served by the freeways studied. Whites made up a majority of households among the freeway-served municipalities. Also, an appreciable share of households -- one out of six – was Hispanic.

5. Near-Term Path Model

The near-term model shown in Figure 1 postulates that the influences of freeway expansions on VMT are channeled through an intermediate step – operating speed. Only if speeds increase can traffic levels also be expected to rise, reflecting both newly generated trips (e.g., latent trips unleashed by faster moving traffic) and route diversions. And in due time, an equilibrium is reached as rising traffic volumes erode the travel-time savings, some trips are again suppressed, and motorists stop switching routes and modes.



Map 1. Location of 24 Freeway Projects Across Nine California Counties

Table 2. Key Endogenous and Predictor Variables: Summary Statistics and Data Sources

Dimension	Variable	Mean or Proportion	Std. Deviation
Demand	VMT on facility, proportion of countywide total[1]	0.028	0.019
Supply	Lane Miles on facility, proportion of countywide total[1]	0.021	0.011
Benefit	Operating speed on facility, mean mph[1]	38.1	7.5
Land Use	Total building activity[2], buffer proportion of countywide total[3]	0.093	0.111
	Single-family units, buffer proportion of countywide total[3]	0.022	0.057
	Multi-family units, buffer proportion of countywide total[3]	0.016	0.022
	Office valuation, buffer proportion of countywide total[3]	0.211	0.432
	Retail-commercial valuation, buffer proportion of countywide total[3]	0.073	0.137
	Industrial building square footage, buffer proportion of countywide total[3]	0.080	0.125
	Other building square footage, buffer proportion of countywide total[3]	0.010	0.045
Density	Population, persons per square mile, municipality[4]	1,308.5	842.3
	Employment, workers per square mile, municipality[4]	744.2	531.1
Policy	Air Quality, Maximum CO, one hour, parts per million, county[5]	14.17	4.78
Population	Personal Income, mean ($000), municipality[6]	20.605	5.199
	Race: White, proportion, municipality[6]	0.669	0.082
	Race: Black, proportion, muncipality[6]	0.067	0.051
	Race: Asian, proportion, municipality[6]	0.093	0.045
	Ethnicity: Hispanic, proportion, municipality[6]	0.166	0.057

Notes: 1 *Source:* California Department of Transportation, agency data files

2 Defined as weighted average of countywide proportions for six land-use categories, with weights for each category measured by the number of units (residential uses) or establishments (non-residential uses).

3 *Source:* U.S. Census Bureau, *Construction-Building Permits*, Residential Construction Branch, Manufacturing Construction Division, Building Permit Branch.

4 *Source:* California Department of Finance, agency data files

5 *Source:* California Air Resources Board, agency data files

6 *Source:* U.S. Department of Commerce, Bureau of Economic Analysis

Operating Speed Model

The left-hand side of Table 3 presents a best-fitting log-linear model that predicts operating speeds for any time period as a function of predictor variables for the same time period. The coefficients for all but the fixed-effect control variables represent point elasticities. Values of the endogenous variable “VMT proportion” were estimated using instrumental variables (consisting of all exogenous and fixed-effect variables used in the simultaneous predictions of “operating speed” and “VMT proportion”). The estimated model explained over two-thirds of the variation in operating speeds across the 360 pooled time series and cross-sectional observations.

The results clearly show that operating speeds increased in step with gains in the share of countywide lane-miles along the study corridors. On average, every 10 percent increase in a facility’s share of countywide freeway lane mileage was associated with a 4.2 percent increase in mean operating speed on that facility. As hypothesized, rising travel eroded some of the speed benefits conferred by a road. Based on elasticity values, however, it appears that VMT increases were not totally offsetting – that is, the speed-enhancing benefits of freeway expansions exceeded the speed-eroding impacts of rising VMT.

Consistent with theory, Table 3 also shows that operating speeds tended to fall in higher density settings. Moreover, there appeared to be secular declines in average freeway speeds, reflected by the consistent negative signs of time-series fixed effect variables (relative to the prior-year suppressed categories of 1980 and 1981).

Induced Travel Model

The near-term model that predicted VMT shares as a function of mean operating speeds is shown in the left-hand column of Table 4. Two-stage least squares (2SLS) estimation was used to provide instrumental-variable estimates of the endogenous variable, “operating speed”, to reduce possible simultaneous-equation biases.

Statistically significant and positive induced travel effects were found, though it is noted that the estimated elasticity of 0.238 is considerably smaller than elasticities estimated in previous county-level studies drawn from California experiences that used lane-miles as a direct predictor (e.g., Hansen, *et al*., 1993; Hansen and Huang, 1996; Cervero and Hansen, 2001). It is also smaller than “induced demand” elasticities estimated using project-level data

Table 3. Operating Speed Model: Natural Logarithm of Mean Operating Speed on Freeway, 24 California Freeway Segments, 1980 to 1994; 2SLS Estimation; See Tables 1 and 2 for Variable Definitions

	NEAR-TERM MODEL			LONGER-TERM MODEL		
	Coefficient	**Std. Error**	**Prob.**	**Coefficient**	**Std. Error**	**Prob.**
Natural Log of:						
Lane Mile Proportion	0.418	0.033	0.000	0.385	0.085	0.000
VMT Proportion	-0.184	0.027	0.000	-0.165	0.078	0.036
Employment Density	-0.173	0.011	0.000	-0.173	0.016	0.000
Time-Series Fixed Effects:						
1982	-0.032	0.024	0.198	0.247	0.221	0.272
1983	-0.045	0.025	0.069	0.201	0.183	0.280
1985	-0.091	0.025	0.000	0.161	0.144	0.276
1986	-0.047	0.025	0.064	0.212	0.170	0.226
1987	-0.046	0.025	0.069	0.214	0.169	0.220
1988	-0.037	0.025	0.142	0.224	0.170	0.217
1989	-0.058	0.026	0.024	0.206	0.181	0.267
1990	-0.056	0.025	0.028	0.204	0.180	0.269
1991	-0.046	0.025	0.070	0.210	0.177	0.248
1992	-0.037	0.026	0.147	0.226	0.178	0.212
1993	-0.052	0.026	0.050	0.219	0.183	0.239
1994	-0.038	0.027	0.142	0.245	0.185	0.195
Project Fixed Effects:						
Project1	0.188	0.035	0.000	0.199	0.051	0.000
Project2	0.315	0.036	0.000	0.304	0.052	0.000
Project3	0.453	0.039	0.000	0.430	0.057	0.000
Project4	0.494	0.040	0.000	0.452	0.063	0.000
Project5	0.473	0.067	0.000	0.340	0.140	0.016
Project7	-0.219	0.039	0.000	-0.191	0.059	0.001
Project9	0.377	0.040	0.000	0.356	0.067	0.000
Project10	0.380	0.041	0.000	0.324	0.070	0.000
Project11	0.300	0.035	0.000	0.304	0.036	0.000
Project15	0.099	0.034	0.004	0.112	0.050	0.026
Project16	0.176	0.038	0.000	0.167	0.054	0.002
Project17	0.102	0.034	0.003	0.109	0.050	0.028
Project18	-0.071	0.031	0.021	-0.074	0.033	0.023
Project19	0.122	0.031	0.000	0.109	0.045	0.016
Project20	0.191	0.032	0.000	0.161	0.050	0.001
Project21	-0.117	0.029	0.000	-0.119	0.042	0.005
Project22	-0.126	0.030	0.000	-0.125	0.043	0.004
Constant	5.630	0.107	0.000	5.223	0.374	0.000
Summary Statistics						
No. of Cases	360			360		
F Statistic (prob.)	21.22 (.000)			9.47 (.000)		
R Square	.675			.632		

Table 4. ***Induced Travel Model*****: Natural Logarithm of Vehicle Miles Traveled on Freeway as a Proportion of Countywide VMT on State Freeway and Highway Facilities, 24 California Freeway Segments, 1980 to 1994; 2SLS Estimation;** See Tables 1 and 2 for Variable Definitions

	NEAR-TERM MODEL			**LONGER-TERM MODEL**		
	Coefficient	**Std. Error**	**Prob.**	**Coefficient**	**Std. Error**	**Prob.**
Natural Log of:						
Operating Speed	0.238	0.083	0.004	0.637	0.374	0.089
Building Activity (T-2)	--	--	--	0.107	0.055	0.059
Building Activity (T-3)	--	--	--	0.065	0.034	0.064
Employment Density	0.394	0.149	0.009	--	--	--
Population Density	0.834	0.219	0.000	1.071	0.211	0.000
Black Proportion	-1.244	0.060	0.000	-0.631	0.114	0.000
Hispanic Proportion	--	--	--	-0.791	0.224	0.001
Time-Series Fixed Effects:						
1982	0.162	0.028	0.000	-0.038	0.012	0.000
1983	0.128	0.027	0.000	-0.040	0.015	0.000
1984	0.108	0.029	0.000	-0.095	0.039	0.018
1985	0.092	0.026	0.000	-0.075	0.048	0.121
1986	0.046	0.026	0.074	-0.063	0.032	0.049
1987	-0.034	0.026	0.193	-0.117	0.033	0.000
1988	-0.035	0.026	0.175	-0.067	0.030	0.028
1989	-0.036	0.026	0.169	-0.054	0.031	0.079
1990	0.016	0.008	0.058	0.017	0.009	0.060
1991	0.054	0.026	0.038	0.079	0.035	0.025
Project Fixed Effects:						
Project1	-2.809	0.143	0.000	-0.831	0.283	0.004
Project2	-3.220	0.144	0.000	-1.288	0.295	0.000
Project3	-3.571	0.144	0.000	-1.695	0.314	0.000
Project4	-3.577	0.143	0.000	-1.681	0.300	0.000
Project5	2.089	0.238	0.000	2.307	0.671	0.001
Project6	2.347	0.167	0.000	2.846	0.418	0.000
Project7	-1.020	0.180	0.000	-1.051	0.179	0.000
Project8	0.705	0.093	0.000	2.048	0.227	0.000
Project9	-1.708	0.042	0.000	-0.423	0.047	0.000
Project10	-1.733	0.042	0.000	-0.459	0.047	0.000
Project11	-1.303	0.043	0.000	-1.205	0.039	0.000
Project12	0.068	0.042	0.108	1.208	0.047	0.000
Project14	0.482	0.042	0.000	1.230	0.072	0.000
Project15	0.485	0.067	0.000	0.398	0.082	0.000
Project16	-0.120	0.066	0.069	-0.179	0.063	0.005
Project17	0.377	0.066	0.000	0.298	0.071	0.000
Project18	0.937	0.039	0.021	0.968	0.054	0.000
Project19	0.304	0.038	0.000	0.183	0.059	0.002
Project20	0.386	0.038	0.000	0.398	0.051	0.000
Project21	1.178	0.037	0.000	1.272	0.043	0.000
Project22	0.678	0.037	0.000	0.716	0.042	0.004
Constant	-16.257	0.837	0.000	-17.143	3.244	0.000
Summary Statistics						
No. of Cases	360			360		
F Statistic (prob.)	339.99 (.000)			257.00 (.000)		
R Square	.971			.973		

(Pells, 1989; Hansen, *et al.*,, 1993). The lower estimate supports the arguments of Cohen (1995), DeCorla-Souza (2000), Pickrell (2001), and others that lane-mile elasticities tend to overstate induced demand effects.

Signs for the other major predictor variables used in the model generally match *a priori* expectations. The proportion of countywide VMT along a freeway tended to increase where the population and employment densities of municipalities traversed or flanked by the freeway were comparatively high. The racial composition of a corridor (likely reflecting income and possibly cultural factors) also tended to have some bearing on traffic volumes, all else being equal.

Short-Run Model Summary

Overall, the short-term path model postulated in Figure 1 was confirmed by the empirical results. Notably, added capacity increases speeds, which in turn raises the countywide share of traffic, which then erodes some of the speed benefits, thereby moderating the growth in traffic until more or less an equilibrium condition is reached. Based on California experiences along 24 freeway corridors over the 1980 to 1994 period, a near-term "induced travel" elasticity of 0.24 was estimated. In that some of this travel increase represents route diversions, the "induced demand" elasticity of newly produced VMT is likely even smaller. These results, which are more in line with those of several recent disaggregate, person-level studies of induced demand (Strathman, *et al.*, 2000; Barr, 2000), suggest that past estimates of induced demand derived from lane-mile elasticities have overstated near-term impacts.

6. Longer-Term Path Model

The results of subjecting the longer-term path model to empirical scrutiny are summarized in Tables 3 through 7. Current VMT is treated as a product of both immediate- and delayed-response influences, the former consisting mainly of behavior shifts (i.e., latent trips, route diversion) and the latter comprising structural adjustments (i.e., land-use changes).

Operating Speed Model

From the right-hand side columns of Table 3, model outputs for predicting mean operating speeds paralleled those of the near-term model. Differences in coefficient estimates reflect the influences of a different (and larger) set of instrumental variables in the longer-term model. In the longer-term specification, the elasticity of operating speed as a function of relative road capacity and traffic levels was slightly smaller.

Induced Growth Model

The hypothesis of "induced growth" – i.e., road improvements and the resulting swifter travel speeds spur real-estate construction along a corridor -- was substantially confirmed. The model presented in Table 5 represents the lagged structure that yielded the best-fitting statistical results. The model, which explained around two-thirds of variation in total building activity as a share of countywide totals, reveals the presence of institutional delays, as postulated. Notably, the share of countywide building square footage and valuations along a corridor increased with the share of countywide freeway lane-mileage added three years earlier. Building activities were also highly responsive to average operating speeds two years before. Evidently, lane-mile additions in previous years, confirmed by increased operating speeds, spurred developers to build more housing, offices, shops, and other establishments within several miles of improved freeways. Based on elasticity estimates, the influences of operating speeds on the decision to build were more than twice as great as the influences of lane-mile additions. Far more important than either factor was the control variable "personal income". All things being equal, growth among the California municipalities studied tended to gravitate to areas with relatively high incomes.

As noted, a composite variable was created to represent "building activities" within the two-mile buffers. While this variable proved to be statistically robust, it masked the relative influences of capacity expansions and speed improvements on development activities for specific land uses. To shed light on which uses were most sensitive to road improvements, individual OLS regression models were also estimated that predicted the shares of countywide units, valuations, or building square footage within freeway impact zones for specific land uses. The same variables considered in estimating the best-fitting "building activity" model were candidates for entry into each of the specific land-use models.

Table 5. *Induced Growth Model*: Natural Logarithm of Building Activity in Two-Mile Buffer as a Proportion of Countywide Building Activity, 24 California Freeway Segments, 1980 to 1994; OLS Estimation; See Tables 1 and 2 for Variable Definitions

	Coefficient	Std. Error	Prob.
Natural Log of:			
Lane Miles Proportion (T-3)	0.443	0.137	0.001
Operating Speed (T-2)	1.052	0.267	0.000
Personal Income	1.655	0.259	0.000
Time-Series Fixed Effects:			
1985	-0.430	0.280	0.125
1986	-1.113	0.297	0.000
1987	-1.485	0.322	0.000
1988	-2.295	0.380	0.000
1989	-2.848	0.416	0.000
1990	-3.375	0.460	0.000
1991	-4.176	0.470	0.000
1992	-4.518	0.499	0.000
1993	-5.771	0.513	0.000
1994	-4.889	0.551	0.000
Project Fixed Effects:			
Project1	-0.864	0.321	0.008
Project2	-0.518	0.313	0.098
Project4	0.557	0.335	0.096
Project5	3.891	0.558	0.000
Project7	2.957	0.339	0.000
Project8	1.403	0.348	0.000
Project15	-2.278	0.340	0.000
Project16	-0.853	0.351	0.016
Project17	-0.806	0.344	0.020
Project18	-0.884	0.328	0.008
Project19	1.765	0.317	0.000
Constant	-77.261	11.313	0.000
Summary Statistics			
No. of Cases		360	
F Statistic (prob.)		21.90 (.000)	
R Square		.666	

Table 6 presents elasticities for designated time-lag periods for the path model's two key predictor variables – lane miles and operating speed. Overall, development seemed to be fairly sensitive to freeway improvements across all six land-use categories. Home-building was most responsive. Lane-mile additions two to four years previously, and in the case of apartments and multi-family units, operating speeds two years earlier, significantly explained residential construction, with elasticity estimates well above one. Barring restrictive zoning or Not-in-my-Backyard (NIMBY)resistance, housing developers clearly reacted to capacity expansions along most of the freeway corridors studied. The opening of new lanes and the ensuing higher travel speeds appear to have prompted housing developers to draft plans and seek building permits, with actual housing additions occurring several years later.

Non-residential activities were most responsive to changes in operating speeds two to four years previously, with lane-mile additions three to four years earlier exerting more modest effects on office, industrial, and public-use construction. Consistent with theories of "highest and best use", offices and public buildings appeared to value accessibility benefits conferred by freeway expansions more than industrial uses. These results square with the finding of Hansen, *et al*. (1993) that from 1966 to 1989, commercial-office construction in California urban areas was more sensitive to freeway expansions than were other types of land uses. Table 5 also shows that prior-year operating speeds, but not lane-mile additions, spurred retail development. The lower elasticity could reflect the relatively higher premium many retailers place on visibility and exposure to pass-by traffic, regardless of the operating speeds, rather than on roadway capacity *per se* (see, for example, Bonsignore and Roach, 1992).

Induced Travel Model

Table 4 also provides elasticity estimates of "induced travel" over a longer-term time horizon, which consistent with theory and past research are higher than short-run effects. Still, the longer-run elasticity estimate of 0.637 is smaller in absolute terms than elasticities estimated in previous studies that used lane miles as direct predictors (Hansen, *et al*., 1993; Hansen and Huang, 1997; Noland and Cowart, 2000; Cervero and Hansen, 2001).

Table 6. Summary Elasticities of Building Activities as Functions of Predictor Variables on Lane Miles and Operating Speeds, and Model Goodness-of-Fit Statistic.

All variables expressed in natural log form, thus coefficients denote elasticities. See Tables 1 and 2 for definitions of variables.

Building Activity Dependent Variable:	**Key Predictor Variables** (in natural log form)				R Square
	Lane Miles		**Operating Speed**		
	No. Years Lagged	**Coefficient**	**No. Years Lagged**	**Coefficient**	
Residential:					
Single-Family[1]	2	1.311***	--	--	0.804
Multi-Family[2]	4	1.252**	2	1.260***	0.747
***Non-Residential*:**					
Office[3]	3	0.655*	3	0.916*	0.638
Retail[4]	--	--	4	0.544*	0.566
Industrial[5]	3	0.405*	2	0.762*	0.708
Other[6]	4	0.576*	2	0.900*	0.533

***Key*:**

*** = Significant at the 0.01 probability level

** = Significant at the 0.05 probability level

* = Significant at the 0.01 probability level

1 = Other predictor variables in the model: Time Series: 1984-1997; Project7 through Project15; Project 18.

2 = Other predictor variables in the model: Time Series: 1996-1997; Project1 through Project4; Project 6 through Project9; Project12; Project13; Project18 through Project21.

3 = Other predictor variables in the model: Natural logs of Personal Income, Population Density, and Asian Proportion; Time Series: 1983 through 1993; Project1 through Project4; Project7 through Project19.

4 = Other predictor variables in the model: Natural logs of Personal Income, Population Density, White Proportion, and Asian Proportion; Times Series: 1985 through 1994; Project1; Project2; Project5 through Project11; Project14; Project16 through Project19; Project21.

5 = Other predictor variables in the model: Natural log of Employment Density; Time Series: 1983 through 1994; Project4 through Project11; Project14; Project15; Project18 through Project21.

6 = Other predictor variables in the model: Natural logs of Personal Income, Population Density, and Black Proportion; Time Series: 1984 through 1994; Project2; Project5 through Project15; Project18; Project19.

The longer-term model also reveals that a smaller but nonetheless appreciable increase in VMT is attributable to heightened development activity along impacted corridors. Notably, traffic generated by new residential and commercial-industrial-institutional development accounted for some of the VMT gains, with the additive elasticity for building activities two and three years previously estimated to be 0.172. The output suggests that the influences of behavioral shifts (e.g., latent trips, modal changes, route diversions) are nearly four times as strong as those of structural changes (e.g., land-use shifts).

While longer-run induced travel effects were corroborated by the model, it is worth noting that other "control" factors, such as population density and racial-economic attributes (presumably as proxies for income and cultural factors), tended to exert even stronger influences on VMT shares. All else being equal, dense corridors made up predominantly of non-black and non-Hispanic households tended to account for relatively high shares of countywide VMT.

Induced Investment Model

To bring the analysis of freeway demand-supply relationships full circle, a model was estimated on how road investments respond to traffic increases. Table 7 reveals a significant induced-investment effect. Every 10 percent increase in the share of countywide VMT on a corridor two years previously is associated with a 4.9 percent increase in the current share of countywide lane-mile capacity, *ceteris paribus*. While the induced-investment effect appears smaller than the induced-travel effect, the estimated elasticity is considerably larger than that estimated by Cervero and Hansen (2001) using countywide data from California over a similar time span. This finding further suggests an over-statement of induced demand effects from past studies. That is, a significant share of the statistical correlation between travel demand and road supply has long been assigned to induced demand effects; however, when a path-model framework is adopted that accounts for intermediate steps and induced investment effects, longer-run elasticities of VMT growth tend to be smaller, matched by higher "induced investment" elasticities.

Besides VMT levels, previous-year operating speeds were also statistically associated with freeway expansion. The fact that variables measuring both VMT and operating speeds appeared as direct and statistically significant predictors of freeway expansion could reflect

Table 7. ***Induced Investment Model*****: Natural Logarithm of Lane Miles of Freeway Capacity as a Proportion of Countywide Lane Miles of Capacity for State Freeways, 24 California Freeway Segments, 1980 to 1994; OLS Estimation;** See Tables 1 and 2 for Variable Definitions

	Coefficient	Std. Error	Prob.
Natural Log of:			
VMT Proportion (T-2)	0.490	0.049	0.000
Operating Speed (T-2)	-0.425	0.084	0.000
Maximum CO Level	-0.316	0.042	0.000
Time-Series Fixed Effects:			
1982	-0.055	0.040	0.164
1983	-0.113	0.038	0.003
1984	-0.143	0.037	0.000
1985	-0.131	0.037	0.000
1986	-0.568	0.042	0.179
1987	-0.063	0.402	0.140
1988	-0.104	0.040	0.010
1989	-0.071	0.041	0.085
1990	-0.059	0.041	0.147
1991	-0.058	0.037	0.133
1992	-0.032	0.022	0.128
Project Fixed Effects:			
Project1	0.440	0.064	0.000
Project2	0.204	0.055	0.000
Project5	-1.643	0.082	0.000
Project6	0.289	0.070	0.000
Project7	0.138	0.081	0.091
Project8	-0.152	0.074	0.042
Project9	-0.427	0.053	0.000
Project10	-0.472	0.053	0.000
Project11	-0.243	0.050	0.000
Project12	0.417	0.080	0.000
Project13	0.434	0.085	0.000
Project14	0.240	0.088	0.007
Project15	0.257	0.052	0.000
Project17	0.190	0.051	0.000
Project18	0.432	0.065	0.000
Project20	-0.229	0.053	0.000
Project21	0.286	0.070	0.000
Constant	-2.917	0.353	0.000
Summary Statistics			
No. of Cases	360		
F Statistic (prob.)	217.20 (.000)		
R Square	.949		

the influences of multiple criteria in investment decisions – that is, a combination of both traffic growth and performance levels could have played into political decisions to expand freeway capacity. Table 7 also shows that concerns over air-quality may have deterred freeway expansion, possibly out of fear that freeway-induced growth would ultimately exacerbate air quality. This stands in contrast to research by Cervero and Hansen (2001) that found deterioration in air-quality tended to spur road investments in California under the premise that congestion relief ultimately produces cleaner air. The fact that these two studies were carried out using different grains of analysis – county-level data in the case of the Cervero and Hansen study versus project-level data for this current study – could partly explain the differences.

Longer-Term Model Summary

Overall, the longer-term model performed fairly well in accounting for VMT growth along sampled California freeway segments. Evidence of "induced travel", "induced growth", and "induced investment" was uncovered. Elasticity estimates of induced travel were lower than what was found in most previous studies, including those focused on California freeways.

The long-run model suggests that it takes around 5 to 6 years before the full-brunt of traffic increases spurred by land-use shifts to be felt. Based on model outputs, it generally takes 2 to 3 years for development activity to respond to the addition of lane miles, and another 3 years for VMT to respond to development activity. The model also suggests that VMT growth feeds back to influence freeway investments several years later. The entire lagged structure, then, covers a 7 to 8 year period.

Based on beta weights, about 55 percent of the association between freeway expansion and VMT growth was accounted for by the path model.[ii] Thus while the postulated path model was supported by empirical analysis, more research is needed in different settings and at different resolutions of analysis to further refine our understanding of the co-dependencies between road investments, land-use shifts, and induced travel – hopefully research that is firmly rooted in behavioral and economic theories, and that adopts a casual modeling framework.

7. Conclusion

In recent years, concerns over induced demand have seemingly paralyzed the ability to rationalize road development in the United States. "Build it and they will come" has become a rallying cry of environmentalists, New Urbanists, and many others opposed to "sprawl-inducing" freeways.

Fairly firm positions have been taken on the induced demand debate despite the methodological shortcomings of past research. Simple mode structures have often been used to reach the conclusion that road investments provide only ephemeral congestion relief, with most added road capacity absorbed by increases in traffic. The path model presented in this paper attempts to sort through the ways in which road improvements affect travel demand, and vice-versa. As with past research, evidence of induced demand, induced growth, and induced investment was uncovered. Roads and the prominent fixtures of America's landscape that they serve – e.g., big-box retail, edge cities, and corporate campuses – are clearly co-dependent. While the magnitude of induced growth effects found in this study is generally consistent with that of previous research, the magnitude of induced demand effects is generally less. To the degree the path model better captures causal relationships than previous studies, many past elasticity estimates are likely inflated. The contention that capacity additions are quickly absorbed by increases in traffic and that "you can't build yourself out of traffic congestion" might not hold in all settings. Houston is a case in point. Over the past 15 years when the city invested around a billion dollars annually in freeway improvements (see Dunphy, 1997), Houston has made greater headway in relieving traffic congestion than most of its U.S. counterparts (Shrank and Lomax, 2000).

The problems people associate with roads – congestion, air pollution, and the like – are not the fault of road investments *per se*. These problems stem mainly from the unborne externalities from the *use* of roads, new and old alike. They also stem from the absence of thoughtful and integrated land-use planning and growth management around new interchanges and along new corridors. While the induced demand phenomenon is important and not to be trivialized, far more energies need to go toward figuring out how to best invest and manage scarce transportation and land resources – e.g., should we be building more bus rapid transit systems, applying "value-pricing" on current carpool lanes, and more closely integrating transportation and land use, and if so, when, where, and under what conditions? Whether new roads are on balance beneficial to society cannot be informed by studies of induced demand, but rather only through a full accounting and weighing of social costs and benefits.

Critics of any and all highway investments, even those backed by credible benefit-cost analyses, should more carefully choose their battles. Energies might be better directed at curbing mis-pricing in the highway sector and managing land-use changes spawn by road investments.

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Notes

[i] Square footage statistics were already known from the census source for industrial and "other" land uses.

[ii] This was based on the application of "Wright's Rules" for decomposing correlation coefficients, as reviewed in Asher (1983). For the long-term model, the Pearson Product-Moment correlation between the natural logarithms of the "lane mile" variable and the "VMT" variable lagged by 5 years (to reflect the 2-year lag in lane-miles influencing building activities and the 3-year lag in building activities influencing VMT) was 0.898. If the model were completely specified, this correlation could be re-expressed as the sum of the products of beta weights (i.e., standardized regression coefficients) across all bona fide indirect paths. For the four indirect paths, the products of beta-weights are: Lane-miles → Speed → VMT [(1.294*0.265) = 0.342]; Lane-miles → Development Activity → VMT [(0.239*0.284) = 0.068]; Lane-miles → Speed → Development Activity → VMT [(1.294* 0.218*0.284) = 0.080]; Lane-Mile → Speed → VMT → Speed → Development Activity → VMT [(1.294* 0.265* 0.337*0.218*0.284) = 0.007]. Thus, the total product of beta weights among indirect path equals 0.497, or 55 percent, of the total correlation of 0.898.