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Induced Supply

A Model of Highway Network Expansion at the Microscopic Level

David Levinson and Ramachandra Karamalaputi

Address for correspondence: Assistant Professor David Levinson, 500 Pillsbury Drive SE, Department of Civil Engineering, University of Minnesota, Minneapolis, MN 55455 USA. Ramachandra Karamalaputi is a Graduate Student in the same department.

Abstract

This paper examines the growth of a highway network based on the present and historical conditions of the network, traffic demand, demographic characteristics, project costs, and budget. The effects of expanding a link on its upstream and downstream neighbours, as well as on parallel links, are also considered. Data span two decades and consist of physical attributes of the network, their construction and expansion history, and traffic levels on each of the links. An observation of this research is that the rate of network expansion has decreased over time. The pattern of expansion for each type of highway was found to differ only marginally, indicating that the model estimated is reliable for general use. The models developed here have important implications for planning and forecasting.

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Introduction

Traffic demand is shaped by investments in new infrastructure and changes in public policy, while investment in highway network supply is itself induced by demand. Although highway agencies choose to expand small segments of the transport network, those investments are limited by decisions that have gone before; and perhaps more importantly, today's decisions constrain tomorrow's choices. This paper explicitly considers the growth of highway networks as an endogenous process, in contrast with current transport planning practice that strives to direct that growth exogenously. A 20-year database of network expansion is constructed to analyse the dynamics of network expansion decisions, which has been largely unstudied at the microscopic level.

Previous research on network expansion is limited. Grübler (1990) has looked at long-term technology diffusion issues, considering, for instance, the total length of roadway, vehicle kilometres travelled, or vehicles owned over the span of decades. Taaffe *et al.* (1963) study the economic, political and social forces behind infrastructure expansion in underdeveloped countries. Several studies have examined specific networks, for example the London Underground (Barker and Robbins, 1975), but no general theoretical framework has been given for network growth at the microscopic level.

Furthermore, increasing the capacity of a link in the network increases travel on that link due to re-routing and re-scheduling and also due to what is often called induced or latent demand (Noland 1999, Strathman *et al.*, 2000). In contrast, the process of *induced supply*, how highway agencies respond to increasing travel demand, population, income, and demography has been largely ignored, but is crucial in our understanding of the decision process leading to infrastructure improvements. Transport infrastructure supply is inelastic in the short term but varies in the long term. Transport infrastructure and economic development are interrelated, particularly in under-developed and emerging regions.

The objective of this paper is to develop insight into the growth of transport networks. Specifically, to aid in planning and design, we want to know the investment rules governing agency decisions to expand transport networks. However, available (annual) budgets limit network growth. When an existing link is improved, we need to establish the conditions of single-lane versus double-lane expansion. We want to find whether improving one link will cause upstream and downstream links to have greater demand, and parallel links to have lower demand. We posit that the pressure to expand a link will decrease if we expand parallel links. The underlying question in this research is whether network changes can be predicted, and if so, to what extent. In a sense, this paper is about modelling the behaviour of bureaucracies in response to the factors hypothesised to be the driving forces of network growth. The discrete nature of capacity expansion complicates the issue. This model can be used as a policy tool to predict how government transport agencies direct network growth as a function of projected future traffic, given demographic characteristics and budget.

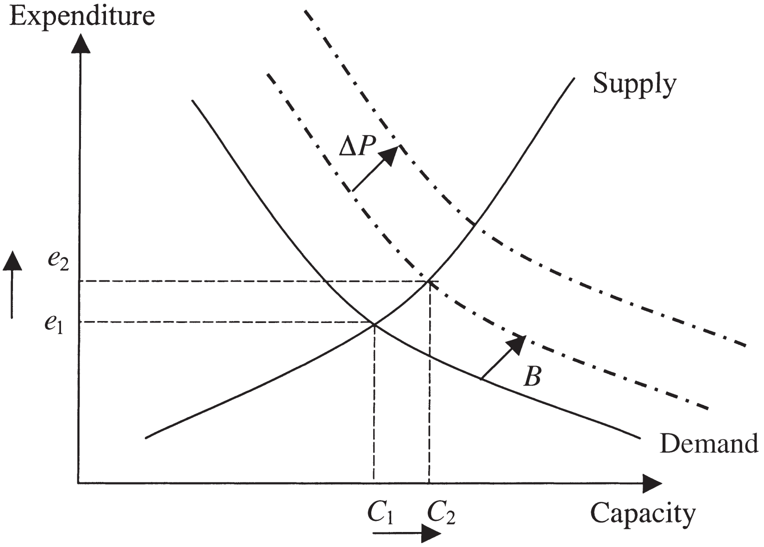
The next section describes the underlying economic theory of network expansion. The following section consists of data used in this study. Some of the issues with regard to designating adjacent and parallel links in a transport network are dealt with. In the fourth section, a cost function is developed to estimate the cost of expanding a link given the year of construction, length of the section, number of lanes to be constructed, and hierarchical level of the road. A cost function is necessary to obtain a cost estimate for expanding links on which we do not have data. The fifth section describes the model used to predict network expansion, and poses the specific hypothesis. Results are presented in the sixth section while a final section summarises and concludes.

Theory

The decision by transport agencies to increase the capacity of a link often comes in the wake of congested flow conditions on the link or as an attempt to divert the traffic from other competing routes. Alternatively, in undeveloped areas, capacity expansion anticipates the development of that area. However, expansion of links is constrained by the available annual budget for such purposes. Specifically, we want to test if capacity increases on the network depend on the capacity of the link in consideration, flow present and previous, and flows and capacities of connected and parallel links.

The traditional supply and demand curves for infrastructure supply are shown in Figure 1. The X-axis in the figure is new lane kms of capacity (C), the Y-axis shows the unit cost per lane km (e). Each of the above variables affects either the supply or the demand curve resulting in a new equilibrium. A higher annual budget (B) is agency income (allotted by the residents of the community the agency serves) that increases the willingness and ability to pay to expand or construct highways. A higher income results in a shift of the demand curve to the right. From the curve, it can be seen that higher cost of expansion per lane mile (e) decreases the

Figure 1
Infrastructure Supply-Demand Curve



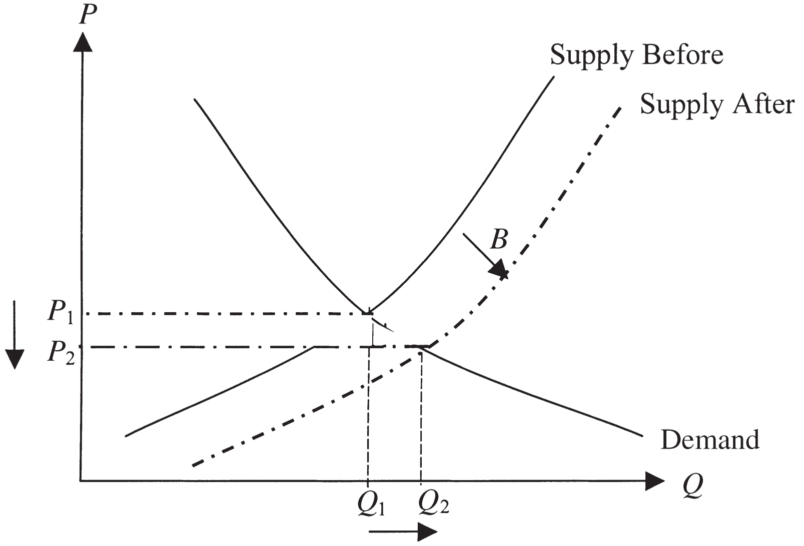
willingness and ability of agencies to construct new infrastructure. Studies have shown that infrastructure growth rates in mature systems decline with time (Grübler, 1990), that is, the supply curve becomes more inelastic (more vertical) with time.

Due to diminishing marginal returns, the likelihood of widening a highway decreases with its capacity. There are diminishing returns because costs rise with the scarcity of land for expansion. Increasing road use over time due to population growth (ΔP) or changes in travel demand is also reflected by the outward shift of the demand curve. Due to the shift in the demand curve, a new equilibrium is reached with an increased supply of infrastructure (more capacity). Note that the new equilibrium has a higher equilibrium price (unit cost of infrastructure).

Changes in capacity of the network induce additional trips on that link due to re-routing and re-scheduling of the trips (Fulton, 2000; Noland, 1999). Although the presence of induced demand is now widely accepted, the exact relationship between a capacity increase and induced demand is not clear. Parthasarathi *et al.* (2003) has studied this relationship at the link level using the same dataset as we consider for this study.

The shaded area in Figure 2 is the consumer surplus resulting from the lower price and additional demand after an increase in infrastructure supply. Although consumers' surplus increases after construction, traffic is

Figure 2
Induced Demand and Consumers' Surplus



inconvenienced during construction. If the project takes a long time to be executed, the negative effects might overrun the consumers' surplus of future years. Duration of construction is then an important consideration in the benefit-cost analysis of the expansion. Since we do not have data on duration for unbuilt projects, length of the link is used as a surrogate. Regressions on available data showed length to be a good indicator of the duration of the project. In view of this, longer road segments are less likely to be expanded. Networks tend to grow more in the peripheries once they reach saturation levels near downtown areas. Land scarcity and heavy traffic in the downtown areas make it an inconvenient place to expand the network. Higher capacity is needed to cater to the traffic need, but again land acquisition problems in such areas act as a deterrent.

Data

To study network dynamics, data have been collected on construction of new links and on expansion of existing links spanning two decades (1978–1998). Data were obtained from the following sources:

(a) Network data from the Twin Cities Metropolitan Council.

(b) Average Annual Daily Traffic (AADT) data on each link from the Minnesota Department of Transportation.

(c) Link investment data was obtained from two sources:

  Twin Cities Transportation Improvement Program published by the Metropolitan Council.

  Hennepin County Capital Budget published by Hennepin County.

(d) Population of Minor Civil Divisions (MCD) from the State Demography Center, Minnesota Planning.

Network data obtained from the Metropolitan Council gave a physical description of each link in the network in terms of number of lanes, length of the link, capacity of the link, type of highway, and its physical position. Each link is uniquely identified by its start node and end node. Each node is associated with a set of geometric coordinates that define the orientation of a link. The Twin Cities network has around 15,000 links of which 1,525 links are interstate highways, 2,362 links are trunk highways, and 4,394 are county highways. Of the county highway links, only those in Hennepin County are used for analysis, which reduces the number to 1,802 links, as investment data on other county highway links could not be obtained. Hennepin is the largest county of the seven in the Metro area and contains the city of Minneapolis. Remaining links are local roads and ramps to highways that are not considered for the analysis because investment data and AADT data could not be obtained for these links. Each type of road is analysed separately because of the inherent differences in the utilisation and financing of these roads. Table 1 summarises investment data, and Table 2 shows the number of links added in each hierarchy of the road during this period.

New construction projects follow different criteria and are not dealt with in this paper. Data in the four separate data sets were merged using ArcView GIS and through some custom computer programs. The database was then split by road type to form separate databases for interstate highways, trunk highways, and county highways.

Adjacent and parallel links in a network

To input the surrounding conditions for each link in the network, we need to identify links connected to it and its most nearly parallel link. Each two-way link is divided into two one-way links. Adjacent links are divided into two categories: supplier links, and consumer links. Supplier links have traffic flow in the same direction as the link in consideration and are physically attached to the start node of the link under consideration. Consumer links are similar to supplier links but are attached to the end node of the link under consideration. A computer program was written to

Table 1
Summary of Investment Data

Year	*No: of projects in TIPS**	*Total cost of projects in TIPS ($ 1000's)*	*No: of projects in Hennepin County Budget**	*Total cost of projects in County ($ 1000's)*
1979	11	229633	–	–
1980	7	80197	–	–
1981	5	132176	3	2780
1982	8	27120	1	6124
1983	2	38980	2	7760
1984	6	50711	3	13655
1985	3	214031	2	3677
1986	2	8538	4	13577
1987	0	0	1	2436
1988	0	0	3	10370
1989	1	55300	4	8338
1990	0	0	2	15312
1991	0	0	3	15443
1992	0	0	2	7158
1993	7	253700	3	38353
1994	1	8600	3	10380
1995	4	187500	5	16991
1996	0	0	7	35835
1997	0	0	8	35762
1998	0	0	4	22435
1999	4	268200	6	21647
2000	1	70000	4	18606

*Only projects costing more than $1 million or of more than 1 mile have been included.
Sources: *Local Transportation Improvement Program* and *Hennepin County Capital Budget*.
– Data unavailable.

Table 2
Number of Links Expanded or Constructed by Road Type (1978–Present)

	One-lane expansion	*Two-lane expansion*	*New construction*	*Total*
Interstate	104	43	35	182
TH	53	–	40	93
County Highway	86	–	3	89
Total	243	43	78	364

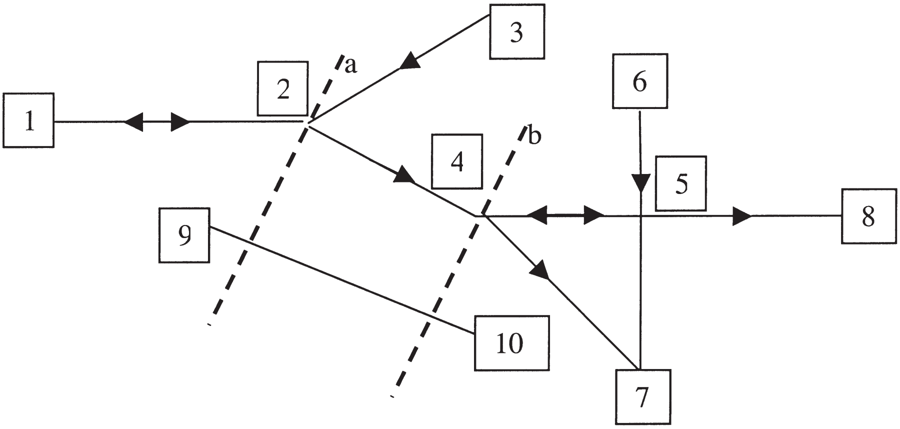
enumerate the adjacent and parallel links. Figure 3 shows supplier and consumer links of a link in a hypothetical network. For link 2–4: 1–2 and 3–2 are supplier links, and links 4–5 and 4–7 are consumer links.

Parallel link description is a little more complicated. A parallel link can be thought of as the link that would bear the maximum brunt of diverted traffic if the link under consideration was closed. Note that a parallel link may or may not be in physical contact with the link in consideration. Merely looking at the mapped data and selecting a parallel link to a given link is a subjective choice. We need to define the attributes of parallel link to have a "feel" of the type of link to be identified as a parallel link. Crudely put, we are searching for a link that is in the proximity of the link L, approximately parallel to L in the literal sense, and of comparable length. Attributes have been defined based on this definition. The first attribute is how parallel the links are. The angular difference between the two links should be as small as possible.

The second attribute is the perpendicular distance from the mid-point of link L to the other link, divided by length of link L. The third attribute is the sum of distances between start nodes and end nodes of the two links being compared. The final attribute takes the ratio of lengths of the two links into consideration. Note that each of the attributes takes a range of values. Fuzzy logic has proven useful in this kind of case.

Fuzzy theory assumes a continuous truth-value rather than the deterministic Boolean values used conventionally. The sum composition method combined with appropriate weights has been found suitable for our purposes. In sum composition, the combined fuzzy output is obtained by computing the truth-value of each attribute and summing these values.

Figure 3
Adjacent and Parallel Links in a Network



Here, we modified this method by weighing the truth-values of the attributes based on the importance of that attribute in relation to others.

The algorithm to find the parallel link needs some explanation. For a link L in consideration, we need to throw out links that are highly unlikely to be parallel. In no case should we identify a link in the continuous chain of links of which link L is a part as the parallel link. For instance, in Figure 3, link 5–8 should never be identified as parallel link to 2–4.

We need to remove all links of this type before evaluating attributes. One way to do this would be to drop perpendiculars from the nodes of the link L and check if the link we are comparing with has any point on it that falls between these perpendiculars. Further, all the links whose angular difference with link L is greater than 45 degrees are removed. The values of the attributes are given by:

(1) $Para = 1 - (angular\ difference)/45$;
(2) $Perp = 1 - \mathrm{a} * (perpendicular\ distance)/\text{length of link L}$;
(3) $Dist = 1 - \mathrm{b} * (sum\ of\ node\ distances)/\text{length of link L}$;
(4) $Comp = 1 - \mathrm{c} * (lratio - 1)$;

where:
perpendicular distance is from the centre of link *L* to the other link; *node distances* are distances between the corresponding start nodes and end nodes; *lratio* is the ratio of length of probable parallel link to the length of link L or the inverse of it, whichever is greater.

Each of the attributes is also given a weight when determining the parallel link. It was found that giving a smaller weight to attribute *Para* led to favourable results. The values of parameters *a*,*b*,*c* and weights used are given in Table 3. The programme was run for the Twin Cities network and the results have been manually inspected for accuracy.

Table 3
Values of Weights and Parameters of Parallel link Attributes

Attribute	*Weight*	*Parameter*
Para	0.5	–
Perp	0.5	$a = 0.40$
Shift	1.0	$b = 0.25$
Comp	0.5	$c = 0.50$

Cost Function

To frame the network investment decision, a cost function is needed to estimate the cost of new construction or expansion of an existing facility. Data collected on previous investments are used to estimate a cost function for the Twin Cities network. Cost of construction can be modelled as:

$$E_{ij} = f(L_{ij} * \Delta C_{ij}, F, N, T, Y, D, X) \tag{1}$$

where:

E_{ij} = cost to construct or expand the link (in 1000's of dollars);
$L_{ij} * \Delta C_{ij}$ = lane kilometres of construction;
F = dummy variable for type of funding source;
N = dummy variable to check if it is a new construction or expansion;
T = dummy variables for interstate highways and state highways;
Y = year of completion — 1979;
D = duration of construction;
X = distance of the link from the nearest town centre (in km).

A Cobb–Douglas model is estimated to predict the cost of expanding a link. Initially, all the variables mentioned above were entered into the model. It was found that both funding source and road type were insignificant. However, examining the data reveals that most interstate highway construction is built under one funding source and non-interstate highways under a different programme. To overcome this problem, funding source was dropped, as road type was sufficient for segregation. Also, subsequent models suggested that reconstruction, widening, and so on, could be grouped into one category. The model was re-estimated to give the implicit rate of inflation with respect to the highway construction sector, shown in Table 4 (Model 1).

Note that the modified year variable has been introduced into the model in a non-logarithmic fashion. If the model was written in exponential form, $(\exp .(0.078) - 1) * 100 = 8.14$ gives the rate of inflation. This is quite high compared to the overall rate of inflation in the United States. One of the reasons may be due to an increase in the costs of transport materials at a rate higher than general goods and services. Increase in labour costs, additional attributes on roads such as bike and pedestrian features, and evolving safety measures, also contribute to it. Also, highways are being constructed with better materials due to improvements in technology resulting in an increase in cost. Cost per lane km was also considered as the dependent variable, but it did not improve results.

Table 4

Coefficients of Regression for Cost Models

$\mathrm{Ln}(E_{ij})$		*Model 1*		*Model 2*	
Description of the variable	*Variable*	*Coef.*	*Std. Dev*	*Coef.*	*Std. Dev*
Lane kilometres of construction	$\mathrm{Ln}(L_{ij} * \Delta C_{ij})$	0.48	0.114*	0.50	0.118*
Dummy for new constructions	N	0.38	0.184*	0.39	0.187*
Dummy for interstate roads	*Inter*	1.68	0.271*	1.97	0.300*
Dummy for state roads	*TH*	0.57	0.212*	0.56	0.226*
Year −1979	Y	0.08	0.009*	–	–
Log of year −1979	$\mathrm{Ln}(Y)$	–	–	0.75	0.110*
Log of duration of construction	$\mathrm{Ln}(D)$	–	–	0.16	0.142
Distance from nearest town centre	X	–	–	−0.03	0.016*
	_constant	6.17	0.248*	5.56	0.329*
	Number of Observations	110		76	
	Adj. R-squared	0.65		0.77	

*Significant at 90% confidence interval
– Variable not present in that model

Finally, duration of construction (D) and distance from the nearest town centre (X) variables were also introduced into the regression. In general, other than interstate highways, construction was only one year in duration. One might then be tempted to say that duration would also be accounted for by the road type variable. However, interstate construction projects took a variable amount of time. Distance from nearest town centre was negative and significant indicating that the project cost would decrease as we move away from town centre areas. The best model taking duration of construction and distance from the nearest town centre into consideration, with all the variables significant at the 5 per cent level, is shown in Table 4 (Model 2).

The coefficient of lane kilometres of construction is less than one, indicating economies of scale in construction. As can be expected, a new construction project is more costly than expanding an existing link. The cost of construction increases with the hierarchy of the road. This is so because of the greater thickness of pavements on higher-class roads, the use of concrete rather than asphalt, and their larger width including shoulders. Higher duration projects cost more and construction becomes costlier over time. Distance from the nearest town centre, which was entered as a linear variable, shows that the project cost would decrease as we move away from town centre areas. Town centre areas have higher traffic flows and land costs, and hence restrict the construction flexibility justifying the extra cost. Note that in the final model, modified year has been entered as a logarithmic variable. This may be a better model due to the non-linear increase in costs with date of construction. According to Model 2, a lane-km of interstate highway taking three years to construct in the year 2000 would cost approximately 21.8 million dollars.

Model

Capacity in the next time period ($C_{ijt} + 1$) can be modelled as a function:

$$C_{ijt+1} = f(C_{ij}, L_{ij}, Q_{ij}/C_{ij}, Q_p/C_p, \Delta(Q_{ij} * L_{ij}), B, \hat{E}_{ij}, Y, X, (Q_{hi} + Q_{jk}), (C_{hi} + C_{jk} - C_{ij}), \Delta(Q_{hi} + Q_{jk}), \Delta(C_{hi} + C_{jk}), P, \Delta P) \quad (2)$$

where:

C_{ijt+1} = Capacity on arc ij (arc running from node i to node j) at time $t+1$;
C_{ij} = Capacity on arc ij;
L_{ij} = Length of arc ij;
Q_{ij} = Flow on arc ij;
Q_p = Flow on parallel link;
C_p = Capacity of parallel link;
$\hat{E}_{ij}$ = Unit expense of construction of improvements on arc ij (from cost function);
B = Budget for year t;
Y = Year of proposed construction −1979;
X = Distance from the nearest town centre;
Q_{hi} = Sum of flows on arcs hi;
Q_{jk} = Sum of flows on arcs jk;
C_{hi} = Sum of capacities on arcs hi (arcs supplying flow);
C_{jk} = Sum of capacities on arcs jk (arcs receiving flow);
P = Population of the surrounding Minor Civil Division (MCD).

All variables are vectors; Flows are bi-directional; Δ indicates change between time period t and $(t - n)$.

Budget is pre-determined for a particular year but it varies over years. For each year, the budget is simply the total expenditure on the link expansions considered in the model. Only a few links are expanded in the network in a given year. There have been no instances of expanding the same link twice in the years considered for this study. Since previous expansion of a link predicts failure to expand in a given year perfectly, observations of such links are dropped from the data after its expansion. A strict capacity measure was unavailable and hence the number of lanes was used as a surrogate for capacity in modelling. Modelling was directed at predicting the increase in the number of lanes rather than predicting the absolute number of lanes in the next time period as a whole. This is because the number of lanes in the previous time period largely explains the number of lanes for a given period (since most links do not change each year). It should be noted that the increase in number of lanes is a discrete number and the increase is zero for most of the links in a given time period. To overcome this problem and to consider the discrete nature of the increase in number of lanes, discrete choice modelling was considered appropriate.

While logit models have been successfully used in a wide variety of multivariate discrete choice contexts, multinomial logit models exhibit the restrictive property of Independence of Irrelevant Alternatives (IIA). IIA states that the presence of a third alternative does not affect the relative probabilities of any two alternatives. Also, coefficients of variables are assumed fixed across individuals in this setting. In mixed logit models, the coefficients are random across individuals with a specified distribution (McFadden and Train, 2000; Train and Brownstone, 1999; Hensher, 2000). This relaxes the IIA property of multinomial logit models and allows for correlation across alternatives. Mixed logit models are estimated by integrating the likelihood function of the multinomial logit model over the distributions of the random coefficients. The mixed logit likelihood function is given by:

$$\int \frac{\exp(\beta' x_{ij})}{\sum_j \exp(\beta' x_{ij})} f(\beta/\Omega)\, d\eta. \tag{3}$$

The parameters are estimated using simulated maximum likelihood due to the lack of a closed form solution to these integrals. Halton sequences, which are shown to be more efficient and guarantee uniform coverage of the distribution, are used for this study (Bhat, 2001, 2002).

The presence of induced demand presents the problem of a circular relationship between capacity increase and change in demand, that is, the problem of endogeneity. The problem is overcome by substituting the endogenous variables in the model with instrumented variables. For the purpose of this study, change in demand has been instrumented using models estimated by Parthasarathi *et al.* (2003) on the same dataset. The change in demand predicted there was in terms of change in vehicle kilometres travelled and the same is used in our study. Based on the theory described above, the hypotheses are as follows:

- It is posited that the links with higher capacity (C_{ij}) and longer length (L_{ij}) are less likely to be expanded.

- Congestion on a link (Q_{ij}/C_{ij}) increases the probability of its expansion or of the link parallel to it. The same is expected to be reflected in the congestion measure of the parallel link (Q_p/C_p).
- Increase in VKT on a link ($\Delta Q_{ij} * L_{ij}$) should increase the likelihood of its expansion.
- The higher the cost of a link expansion (E_{ij}), the lower is its probability of expansion.
- A higher budget for a year would result in more links being expanded and thus increase the probability of expansion for a particular link.
- Capacity expansion on a parallel link decreases the chances of the link under consideration to be expanded.
- Higher VKT of upstream and downstream links increases the chances of link expansion to facilitate the incoming traffic.
- Increase in capacity of a downstream link or an upstream link (ΔC_{hi} or ΔC_{jk}) would cause the link in consideration also to be expanded to take the burden of the resulting traffic.
- Chances of re-expansion of a link are assumed to be low since alternative routes will also be considered for expansion.
- Distance from the nearest town centre favours the expansion of a link.
- Increase in population in an area (ΔP) would result in expansion of the links in that area to accommodate the excess traffic.

As can be observed, expansions are decreasing over time. This may be due to costs rising faster than budgets, or it may be due to some other factors (for example, network saturation or declining benefits of new expansions over time), and this should be reflected in the time variable (Y) of the regression.

Each of the road types was modelled separately due to their functional differences. The decision to construct or expand county highways differs from state highways, as they have separate funding sources. Also, in the data set considered, there were no two-lane expansions of trunk highways and county highways, warranting separate modelling for each hierarchy of the network.

Results

A multinomial logit model was used to model the increase in number of lanes (ΔC_{ijt+1}) over the previous year. Results of the regression for interstate highway are given in Table 5. Variables $C_{ij}, L_{ij}, Q_{ij}/C_{ij}, E_{ij}, C_{hi} + C_{jk} - C_{ij}$, and Y are negative and significant while the

Table 5

Multinomial Logit Model for Interstate Highways

	$\Delta C_{ijt+1}=1$			$\Delta C_{ijt+1}=2$		
Variable	*Hypo.*	*Coef.*	$P>\|z\|$	*Hypo.*	*Coef.*	$P>\|z\|$
Cij	−S	−1.92E+00	5.25E−01*	−S	−2.22E+00	5.46E−01*
Lij	−S	−2.20E+00	9.98E−01*	−S	−3.54E+00	1.21E+00*
Qij/Cij	+S	−1.82E−05	8.28E−06*	+S	−3.84E−05	1.13E−05*
Qp/Cp	+S	1.82E−05	8.30E−06*	+S	1.79E−06	1.09E−05
$\Delta 02(Qij*Lij)$	+S	4.58E−04	1.22E−04*	+S	3.63E−04	1.01E−04*
$\Delta 24(Qij*Lij)$	+S	5.34E−04	6.97E−05*	+S	5.33E−04	7.27E−05*
$\Delta 46(Qij*Lij)$	+S	5.34E−04	6.97E−05*	+S	5.33E−04	7.27E−05*
$\Delta 68(Qij*Lij)$	+S	−8.04E−04	2.22E−04*	+S	−3.53E−04	2.06E−04
Eij	−S	−6.54E−09	1.29E−09*	−S	−3.19E−09	6.25E−10*
B	+S	4.16E−06	1.63E−06*	+S	7.83E−06	3.15E−06*
Y	−S	−1.12E+00	1.57E−01*	−S	−1.72E+00	2.59E−01*
X	+S	2.09E−01	6.04E−02*	+S	−1.54E−01	6.28E−02*
$Qhi+Qjk$	+S	1.17E−05	2.60E−06*	+S	1.13E−05	2.97E−06*
$Chi+Cjk-Cij$	−S	−7.18E−01	1.41E−01*	−S	−5.27E−01	1.52E−01*
P	–	7.78E−06	1.81E−06*	–	−3.09E−06	2.35E−06
ΔP	+S	1.63E−04	1.63E−05*	–	4.97E−04	2.37E−05*
_cons		3.02E+00	1.48E+00*		7.59E+00	1.64E+00*

Number of Observations: 10986

Initial LL = − 572.29 Final LL = − 277.65

LR chi^2 = 575.55 Psuedo R^2: 0.51

* Significant at 90% confidence interval

variables $\Delta 02(Qij*Lij)$, $\Delta 24(Qij*Lij)$, $\Delta 46(Qij*Lij)$, $Q_{hi}+Q_{jk}$, B, and ΔP are positive and significant. This shows that as the number of lanes increases, the probability of its expansion decreases and the probability of a two-lane increase is still lower in this case, supporting the hypotheses. Thus we find that links that already have higher capacities are less likely to be expanded due to decreasing marginal returns. Links with lower capacities would then be more likely to be expanded in order to achieve uniformity in the network. Long links that take more time to build tend to be overlooked for expansion in favour of other shorter links. It is difficult to divert traffic for the long period required for construction on longer links. It has been noted in previous studies (Miyagi, 1998) that the overall welfare can be negative in some cases if high volumes of traffic are inconvenienced for a longer period of time. Higher capacity on downstream and upstream links deters link expansion, again indicating decreasing marginal returns.

Increasing traffic demand for a particular link increases its probability for both one-lane expansion and two-lane expansion. Here we see the response of infrastructure supply to increases in travel demand. The probability of a link expansion increases if the flow on downstream and upstream links is high, showing again that links with greater inflow demand are expanded. Cost is negative and significant showing that links that involve higher expenditure are less likely to be expanded. The budget available is positive and significant as expected; a higher budget favours expansion of more links.

A very interesting trend comes into light with the linear variable year of construction (Y). The negative coefficient on the year of construction for two-lane expansion is considerably higher than that of single lane expansion. The expansion rate of the network has decreased and the relative probability of two-lane expansions (compared with one-lane expansions) declines with time.

Surprisingly, the congestion measure on the link is negative and significant for both one-lane and two-lane expansions. However, congestion on the parallel link is positive and significant for one-lane expansion. Interstate highways are less likely to be expanded and their parallel links, typically of a lower level of the hierarchy, tend to be expanded in the wake of congestion on an interstate highway.

Distance from a town centre is positive and significant for one-lane expansion and negative and significant for two-lane expansions. This implies that two-lane expansions are preferred near town centres where traffic demand is high and one-lane expansions are sufficient in the peripheries where traffic demand is comparatively low, although this may have to do with nonlinear effects of distance. Improvements may be favoured in first or second ring suburbs over both the town centre and the exurban fringe. Population in the adjacent jurisdiction (MCD) has a positive effect on one-lane expansions. Since rights for land acquisition would be costly in such areas, a one-lane increase is feasible to cater to the traffic generated, but a two-lane expansion might overrun the budget. A higher population increase in a MCD favours expansion to meet the additional demand generated as expected.

Results with the trunk highway network are as expected. All the trunk highway expansions are one-lane expansions in each direction and only new construction had two lanes built in each direction. The results of this binomial logit model are given in Table 6. Capacity and length of the link are negative and significant as earlier. Flow and capacity variables of its adjacent links also behave in the same manner as for interstate highways. Again congestion on the link under consideration is negative and

Table 6
Logit Model for Trunk Highways and County Highways

		Trunk Highways		*County Highways*	
Variable	*Hypo.*	*Coef.*	*Std. Dev*	*Coef.*	*Std. Dev*
Cij	−S	−8.15E+00	2.07E+00*		
Lij	−S	−2.28E+01	3.91E+00*	−5.52E−01	5.46E−01
Qij/Cij	+S	−9.30E−05	3.74E−05*	1.97E−04	2.85E−05*
Qp/Cp	+S	1.05E−05	3.81E−05	−1.99E−05	1.53E−05
$\Delta 02(Qij * Lij)$	+S	1.67E−03	6.09E−04*	2.81E−03	2.99E−04*
$\Delta 24(Qij * Lij)$	+S	4.89E−04	3.40E−04	2.72E−03	2.41E−04*
$\Delta 46(Qij * Lij)$	+S	4.89E−04	3.40E−04	2.72E−03	2.41E−04*
$\Delta 68(Qij * Lij)$	+S	4.54E−03	1.10E−03*	3.80E−03	3.05E−04*
Eij	−S	−8.18E−10	6.15E−09	6.84E−10	2.49E−09
B	+S	7.32E−05	1.92E−05*	1.07E−05	4.44E−06*
Y	−S	−1.17E+00	5.02E−01*	8.37E−02	1.02E−01
X	+S	1.13E−01	6.47E−02	5.19E−02	3.69E−02
$Qhi + Qjk$	+S	2.37E−05	6.15E−06*	−1.71E−05	6.10E−06*
$Chi + Cjk - Cij$	−S	−5.49E−01	2.46E−01*	5.43E−02	9.88E−02
P	–	1.28E−05	5.35E−06*	−1.63E−05	2.00E−06*
ΔP	+S	1.17E−03	1.95E−05*	−1.40E−04	5.73E−06*
_cons	–	3.86E+00	4.73E+00	−1.40E+01	1.25E+01
		No. of Obs: 17926		No. of Obs: 6531	
		Initial LL = −108.46		Initial LL = −366.42	
		Final LL = −41.34		Final LL = −202.98	
		LR $\mathrm{chi}^2 = 114.75$		LR $\mathrm{chi}^2 = 284.98$	
		Psuedo $R^2 = 0.61$		Psuedo $R^2 = 0.29$	

* Significant at 90% confidence interval

significant but it is insignificant on the parallel link. Some of the changes in VKT in the last eight years are positive and significant. Cost of expansion is insignificant and budget is positive and significant as usual. Both population and increase in population have the effect of favouring an expansion. Year is again negative and significant, indicating gradual decline in network growth with time, after controlling for budget and expenditure.

Results of the county highways network in Hennepin County are also given in Table 7. As before, capacity and length of the link are negative and significant. This is the first network in which the congestion measure is positive and significant. As in the case of trunk highways, the spillover effects on the parallel link are not significant. This is because trunk highways and county highways have lower capacity compared to interstate highways and their expansion does not interrupt traffic significantly. Change in VKT has a positive effect on its expansion. Higher flow on adjacent links decreases its chances of expansion. Cost of expansion is

Table 7
Comparison of Elasticities of Highway

		Interstate		Trunk Highways		County Highways	
Variable	*Hypo.*	*Coef.*	*Elasticity*	*Coef.*	*Elasticity*	*Coef.*	*Elasticity*
Cij	−S	−2.06E+00*	−4.04E+00	−8.15E+00*	−1.40E+01		
Lij	−S	−2.62E+00*	−9.39E−01	−2.28E+01*	−1.19E+01	−5.52E−01	−2.87E−01
Qij/Cij	+S	−2.50E−05*	−9.40E−01	−9.30E−05*	−1.48E+00	1.97E−04*	1.72E+00
Qp/Cp	+S	1.57E−05*	4.55E−01	1.05E−05	1.54E−01	−1.99E−05	−2.99E−01
$\Delta02(Qij * Lij)$	+S	3.98E−04*	7.12E−01	1.67E−03*	2.03E+00	2.81E−03*	1.66E+00
$\Delta24(Qij * \mathrm{Lij})$	+S	5.10E−04*	−9.63E+03	4.89E−04	−4.10E+03	2.72E−03*	2.96E+04
$\Delta46(Qij * \mathrm{Lij})$	+S	5.10E−04*	9.63E+03	4.89E−04	4.10E+03	2.72E−03*	−2.96E+04
$\Delta68(Qij * \mathrm{Lij})$	+S	−5.96E−04*	−1.55E+00	4.54E−03*	6.60E+00	3.80E−03*	3.74E+00
Eij	−S	−3.21E−09*	−1.22E+00	−8.18E−10	−8.25E−02	6.84E−10	4.32E−02
B	+S	4.38E−06*	6.68E−01	7.32E−05*	1.41E+00	1.07E−05*	4.05E−01
Y	−S	−1.09E+00*	−7.26E+00	−1.17E+00*	−7.77E+00	8.37E−02	5.50E−01
X	+S	−6.23E−03	−5.28E−02	1.13E−01	1.21E+00	5.19E−02	5.53E−01
$Qhi + Qjk$	+S	1.09E−05*	1.50E+00	2.37E−05*	1.52E+00	−1.71E−05*	−5.58E−01
$Chi + Cjk - Cij$	−S	−6.07E−01*	−2.64E+00	−5.49E−01*	−2.31E+00	5.43E−02	1.95E−01
P	–	2.56E−06*	3.24E−01	1.28E−05*	9.45E−01	−1.63E−05*	−1.47E+00
ΔP	+S	2.54E−04*	1.23E−01	1.17E−03*	7.26E−01	−1.40E−04*	−1.18E−01
_cons	–	5.22E+00	–	3.86E+00	–	−1.40E+01	–
			No. of Obs:10986 LL = − 293.92 Psuedo $R^2 = 0.46$		No. of Obs:17926 LL = − 41.34 Psuedo $R^2 = 0.61$		No. of Obs:6531 LL = − 202.98 Psuedo $R^2 = 0.29$

* Significant at 90% confidence level

again insignificant and the reason might be the necessity to expand lower capacity links (compared to interstate highways) to facilitate smoother traffic flow within the metropolitan area. Surprisingly, both population and population increase have a negative effect on the chances of expanding.

Results of the mixed logit models are as given in Table 8. Standard deviations of only two variables, change in demand over the previous two years and length of the link, were found to be significant. Initially, models were estimated assuming the coefficients to be distributed independently and normally across the population. This resulted in non-significance of the standard deviations. The assumption of a normal distribution places an important constraint on the behaviour of the links, although theory suggests the same sign on the coefficients for all the links. Another approach is to specify a distribution that may result in negative coefficients but does not necessarily impose such a situation. The triangular distribution satisfies this property and was chosen here. The two-year change in VKT ($\Delta 02(Qij * Lij)$) has a standard deviation comparable to the coefficient itself, indicating a wide range of response of individual links to this variable. In the time period considered, there were 73 lane expansions in the interstate highway network of 1,525 links. Of the 73 most probable link expansions predicted by the models, multinomial logit identified 52 links that were actually expanded, while mixed logit predicted the same 52 links and an additional 3 links correctly. Standard deviation of random variables for trunk highways is comparatively small although significant. County highways did not have any significant standard deviations in the coefficients. This shows that links on the hierarchy below interstates have a fixed response to the variables. Mixed logit models with unobserved taste as a random parameter failed to converge for all the highways. It should be noted that the final model significance depends on the significance of the input variables as well as the significance of the cost and induced demand models.

Conclusions

This paper developed for the first time a model to predict how transport agencies expand their networks as a function of traffic flow, flow on adjacent and competitor links, flow on parallel links, and estimated cost using data from the Twin Cities metropolitan area. In all the three models, capacity, length, change in VKT, total inflow, and budget have similar coefficients and significance. It is interesting to note the differences in the models. While expansion of interstate highways depends on both the budget and cost of expansion, the lower hierarchies of roads are seemingly unaffected by cost (over the range of values observed). Congestion positively and significantly affects agency decisions to expand county highways, while being negative and significant for other highways. Interstate and trunk highways show a decline in their growth with time that is not reflected in county highways. The elasticities of variables for trunk highways are generally higher, except for the population variables. These differences by type of highway give us a picture of the change in policy for each type of road.

The results are promising and suggest that a number of measurable properties drive network expansion. While it is obvious that politics factors into network expansion decisions, this model is based on empirically measurable attributes. The importance of this is in extension for modelling the implications of transport planning decisions. Any

Table 8
Mixed Logit Model for Interstate and State Highways

		Interstate		*Trunk Highways*
Variable	*Hypo.*	$\Delta C_{ijt+1} = 1$	$\Delta C_{ijt+1} = 2$	ΔC_{ijt+1}
Cij	−S	−2.15E + 00*	−2.27E + 00*	−6.83E + 00*
Lij	−S	−2.21E + 00*	−3.69E + 00*	−1.55E + 01*
Qij/Cij	+S	−1.12E − 05*	−2.94E − 05*	−6.17E − 05*
Qp/Cp	+S	2.12E − 05*	8.62E − 06	1.26E − 05
Δ02(*Qij* ∗ Lij)	+S	5.41E − 04*	2.29E − 04*	−1.20E − 03*
Δ24(*Qij* ∗ Lij)	+S	6.51E − 04*	5.10E − 04*	3.99E − 04
Δ46(*Qij* ∗ Lij)	+S	6.51E − 04*	5.10E − 04*	3.99E − 04
Δ68(*Qij* ∗ Lij)	+S	−1.24E − 03*	−2.13E − 04	3.51E − 03*
Eij	−S	−7.39E − 09*	−3.35E − 09*	−1.22E − 08
B	+S	4.73E − 06*	8.59E − 06*	−1.34E − 05*
Y	−S	−1.20E + 00*	−1.82E + 00*	−1.69E + 00*
X	+S	2.44E − 01*	−1.46E − 01*	8.62E − 02
Qhi + *Qjk*	+S	1.17E − 05*	1.15E − 05*	1.91E − 05*
Chi + *Cjk* − *Cij*	−S	−7.35E − 01*	−6.46E − 01*	−4.80E − 01*
P	–	7.65E − 06*	−3.50E − 06	1.12E − 05*
Δ*P*	+S	1.34E − 04*	5.27E − 04*	8.62E − 04*
_cons		3.47E + 00*	8.79E + 00*	1.18E + 01
Triangular Variances				
Lij		6.13E − 02*	7.45E − 01*	1.21E − 07*
Δ02(Qij*Lij)		2.92E − 04*	4.41E − 05*	2.13E − 10*
			No. of Obs:10986	No. of Obs:17926
			LL = − 232.99	LL = − 38.27

* Significant at 90% confidence interval

decision made today will lead to a chain of events, future network expansion decisions that are not considered in most static modelling frameworks. Endogenous network growth, and the pressures placed on future decision-makers because of today's decision are critical factors for planning and modelling.

Future research can be directed towards analysis of the allocation of resources in the Transportation Improvement Plans that US Metropolitan Planning Organizations are required to conduct (Crain and Oakley, 1995; Dueker, 2002). In particular, the model could be extended to treat the budget within the model endogenously.

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