

Quantifying the Impact of New Freeway Segments

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Arizona Department of Transportation
Research Center

Quantifying the Impact of New Freeway Segments

**Final Report 613
May 2013**

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16. Abstract <p>Many freeway users complain that new freeway segments immediately fill up with traffic after they are constructed. This diminishes the advantages of reduced costs and reduced driving time that would make freeways theoretically superior to arterial streets. According to previous literature, however, this phenomenon is to be expected and is not an indicator of the efficiency or inefficiency of having new freeways. Due to Downs's Law of Peak-hour Traffic Congestion, we expect freeways to immediately fill upon construction, simply because they do offer superior benefits to roadway users compared to the alternative arterial streets. Rational drivers choose to enjoy these benefits. Another phenomenon cited in the literature review is that of induced travel, which states that with the reduction in travel time posed by using freeway segments, it can also be expected that more commuters will choose to travel on them than otherwise would.</p> <p>When Downs's Law works synergistically with the phenomenon of induced travel, more vehicles can be accommodated in a given geographical area, thus increasing the total number of trips taken. This adds to the overall value of our transportation system, since after all, the value of that system is predicated on its ability to facilitate increased volume of travel.</p> <p>This report is based on data acquired from the State of Arizona, the City of Phoenix and Maricopa County, Arizona, and other sources. Through our analysis of Maricopa County traffic count data we are able to show a significant increase in traffic volume resulting from adding new freeways. This increase in traffic volume accounts for a net benefit of over \$18 million dollars per year for a given mile-long stretch of roadway. Over a freeway design-life of 20 years this is far in excess of the average of \$72 million needed to construct that mile of freeway.</p> <p>Ultimately, any evaluation of the freeway system must take into consideration the explicit and implicit benefits of the system. We know that congestion is going to be present whether new freeways are constructed or not. Before freeway segments are constructed, the existing arterial streets are congested. After the completion of freeway segments, some drivers shift from arterial streets to the new freeway. This lessens traffic on the arterials, leading to more drivers taking trips they previously avoided (i.e. induced travel). Even though congestion is an inevitable condition, even on freeway segments post-construction, freeways still offer a clear net benefit.</p>					
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
<u>LENGTH</u>					<u>LENGTH</u>				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
<u>AREA</u>					<u>AREA</u>				
in ²	square inches	645.2	square millimeters	mm ²	mm ²	square millimeters	0.0016	square inches	in ²
ft ²	square feet	0.093	square meters	m ²	m ²	square meters	10.764	square feet	ft ²
yd ²	square yards	0.836	square meters	m ²	m ²	square meters	1.195	square yards	yd ²
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi ²	square miles	2.59	square kilometers	km ²	km ²	square kilometers	0.386	square miles	mi ²
<u>VOLUME</u>					<u>VOLUME</u>				
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft ³	cubic feet	0.028	cubic meters	m ³	m ³	cubic meters	35.315	cubic feet	ft ³
yd ³	cubic yards	0.765	cubic meters	m ³	m ³	cubic meters	1.308	cubic yards	yd ³
NOTE: Volumes greater than 1000L shall be shown in m ³ .									
<u>MASS</u>					<u>MASS</u>				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000lb)	0.907	megagrams (or "metric ton")	mg (or "t")	mg (or "t")	megagrams (or "metric ton")	1.102	short tons (2000lb)	T
<u>TEMPERATURE (exact)</u>					<u>TEMPERATURE (exact)</u>				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
<u>ILLUMINATION</u>					<u>ILLUMINATION</u>				
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²	cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
<u>FORCE AND PRESSURE OR STRESS</u>					<u>FORCE AND PRESSURE OR STRESS</u>				
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

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List of Abbreviations, Acronyms, and Symbols

' (primed)	Symbol for matrix transposition
⁻¹	Symbol for matrix inversion
ADOA	Arizona Department of Administration
<i>AFTER</i>	An instance of x ; binary 1 if freeway is present or 0 otherwise
b	Independent variable, or covariate, in a regression equation of k terms
β	k -row-by-one-column vector of b_k for all covariates k under consideration
e	Base of the natural logarithm, approximately equal to 2.718
ε	Error in fit of line through a particular data observation n
E	n -row-by-one-column vector of ε_n for all data observations n
F-Value	Significance measurement for determined values of b
FHWA	Federal Highway Administration
HOV	High-Occupancy Vehicle
k	Subscript to distinguish a particular b and to distinguish x belonging to that b
\ln	Natural logarithm (to the base e)
MAG	Maricopa Association of Governments
<i>MILES</i>	An instance of x ; miles between freeway and street
n	Subscript to distinguish y and x belonging to a particular data observation
<i>POP</i>	An instance of x ; population
R^2	Fit-closeness measurement for all best-fit lines considered in regression
RARF	Regional Area Road Fund
Regression	Determination of b by matrix solution of n simultaneous best-fit-line equations
t Value	Confidence measurement for determined values of b
<i>TOTART</i>	An instance of y ; sum of multiple-arterial traffic volumes
<i>TOTARTFWY</i>	An instance of y ; sum of freeway and multiple-arterial traffic volumes
<i>TOTRAF</i>	An instance of y ; sum of freeway and one-arterial traffic volumes
<i>TOTMILES</i>	An instance of x ; total freeway stock in miles
U.S.	United States
USDOT	United States Department of Transportation
x	Independent variable of the equation of a best-fit line through a particular data observation n
X	n -row-by- k -column matrix of $x_{n,k}$ for all data observations n and covariates k
y	Dependent variable of the equation of a best-fit line through a particular data observation n
Y	n -row-by-one-column vector of y_n for all data observations n

Executive Summary

Some freeway users complain that new freeway segments fill up with traffic during peak hours immediately after construction. Because of this concern, the debate about the costs and benefits of freeways often centers on relieving congestion. The literature states that the long-term relief of congestion is an elusive goal. While congestion is a pervasive feature of freeways, it does not mean that constructing them is useless. This study helps to demonstrate that the great benefit of freeways is to facilitate travel rather than reduce peak-hour congestion. The study finds that the facilitated travel far outweighs the cost of freeway construction. Even if new freeway capacity becomes congested during peak travel hours, there is still great benefit in the increased travel mobility that can be accommodated.

Introduction

For regular commuters as well as other drivers of motor vehicles, driving on urban freeways has some inherent advantages to driving on arterial streets. The first benefit that many people may think of is the time they save going to a particular destination at a higher posted speed than that typically posted on arterial streets. When driving on urban freeways, drivers can travel safely at posted speed limits of 65 mph, where the design and operational considerations accommodate such speed, whereas most arterial streets have posted speed limits of 45 mph, or even less, in residential areas or school zones. Besides having higher posted speed limits, urban freeways also lack, absent rush-hour traffic or incidents, the constant cycle of stop and go that drivers experience at the intersections of busy arterial streets, where the flow of traffic is regulated by the constant use of traffic lights or stop signs. Additionally, and possibly a lesser known fact to the transportation-using public, urban freeways have also been shown to be statistically much safer than arterial streets. The Federal Highway Administration (FHWA) has shown that the fatality rate on urban freeways is much lower than the fatality rate on urban arterial streets. (FHWA 2005, Table FI-20) These types of clear and significant benefits should undoubtedly motivate drivers to choose urban freeways as substitutes for parallel streets whenever and wherever possible. It is reasonable to assume that discerning drivers, when confronted with two possible routes of travel from one point to another, should be expected to take the faster and more predictable route, which could be arterial streets if the trip is only a few miles.

Because urban freeways pose such advantages over arterial streets, where substantial distances must be traveled, governments commit considerable time, planning, and resources to building more of them. As segments of these new freeways are finished, drivers should be expected to start using them immediately over the alternative mode of nearby arterial surface streets. While this substitution behavior should tend to increase traffic on the newly opened freeway segments, it should also consequently reduce congestion on parallel arterials, thus increasing space and mobility there. Along with the reduction in surface-street congestion, travel time to destinations that would involve the use of these parallel streets is shortened. For drivers choosing to use the arterial streets, this should reduce the cost of traveling to such destinations, thereby motivating more drivers to travel. Moreover, as freeways have lower fatality rates than those on arterial streets, (FHWA 2005, Tables VM-2 and FI-20) there are additional public benefits to transferring traffic away from parallel streets.

Despite all of the anticipated benefits of urban freeway use over arterial streets, many drivers on new freeway segments complain that the new segments fill up with new drivers, become congested, and thus increase average driving times. This is understandable, as congestion can be thought of as a “time tax”—a tax that is paid by individual drivers with the extra time they spend in the car. Increased congestion and driving time will naturally diminish some of the benefits of using new freeway segments in the first place. Hypothetically, a point could be reached where congestion and increased driving times on new freeways get so bad that there is no longer a significant advantage to a driver of using the freeways over arterial streets. If it is manifest that new freeway segments simply “fill up” with drivers during peak hours to the point where their advantages over arterial streets become nullified, what is the value of building more of them? The purpose of this research project is to investigate and try to quantify the benefits that are derived from the construction of these new urban freeway segments.

Literature Review

As pointed out in the introduction, freeways offer a great series of benefits to roadway travelers. They allow people to save time, and drivers can travel safely at higher posted speeds than those on arterial streets. This is corroborated by Lin and Niemeier (2003), who find that actual average speeds at various levels of service (LOS) are higher on urban freeways than on arterial streets. Additionally, urban freeways are safer than arterial streets. According to the Federal Highway Administration, (FHWA 2005, Tables VM-2 and FI-20) the national urban freeway fatality rate is 0.63 persons per 100 million vehicle miles traveled compared with a rate of 1.07 persons per 100 million vehicle miles traveled on urban arterial streets. In Arizona, the 2004 urban freeway fatality rate was 57 fatalities on interstate highways, 36 on non-interstate highways, and 446 on other streets. Thus, avoidance of fatalities adds a bonus benefit to the time saved.

These significant benefits of freeways are diluted by peak-hour congestion. The obvious intent of building a freeway is to move traffic. Yet, as soon as they are built, urban freeways seem to become congested with peak-hour traffic. While little has been written, theoretically or empirically, about this behavior, there have been some attempts to provide a framework for analyzing the behavior of drivers concerning urban freeways. As early as 1962, economist Anthony Downs (1962) observed that the construction of new urban freeway segments doesn't seem to reduce peak-hour traffic congestion on these freeways. Downs coined the phrase "Downs's Law of Peak-hour Traffic Congestion" to describe the phenomenon.

Downs's Law states that any expressway that does not require a toll and has capacity made available by trip-reduction programs will soon be utilized by new trips, as people formerly discouraged from driving on the freeways are attracted to them (Gordon and Richardson 1993). Cervero and Hansen (2002) and Parry (2002) named this new-trip generation phenomenon "latent demand," and other authors have also called it "induced demand" (Noland 2001) and "underlying demand" (Noland and Lem 2002). This has led many people to believe that building new urban freeway segments does not alleviate congestion effectively. Downs notes that this fact seems to frustrate the average commuter and may convey the impression of poor highway planning. He argues, though, that the failure of new urban freeway segments to reduce congestion is not a function of poor planning, but rather is due to the nature of traffic equilibrium.

Downs begins with a few assumptions about commuters. His first assumption is that they attempt to minimize their travel time and are limited by current technology and income when doing so. Secondly, he assumes that a commuter won't change his means of transportation or route unless there is some alteration in his environment. In other words, his preferences exhibit habit persistence.

Downs also describes how travel times on certain routes tend to equalize. For example, if there are two routes, A and B, from the same origin to the same destination, where travel times on both routes are equal (assuming away other differences that may influence behavior such as scenery, etc.), then there is a balance between the two routes. If there is a change in the environment that results in a reduction in travel time for commuters who choose route A, then the change will result in the traffic from these roads being unbalanced. Once drivers on route B become aware that route A provides a shorter travel time, they will begin to switch from route B to route A,

thus increasing congestion on route A, and reducing congestion on route B. This continues until travel time on the two routes equalizes. Due to commuters' habit persistence, their route preference will tend to stay the same unless there is some event that alters the travel time on one route or the other (Downs 1962).

The extension of the above example to the construction of new urban freeway segments is straightforward. The freeway segment offers a faster route to relevant destinations, and therefore commuters will shift to that route until they gain no benefit from switching. Due to habit persistence, those who gain no additional benefit will feel most comfortable staying with their original route. Following this logic, if the addition of an urban freeway segment adds to the overall capacity between the origin and destination, then traffic will begin to shift away from surface streets to the freeway. This shift will reduce travel time on surface streets. With the reduced travel time, it can also be expected that more commuters will choose to travel than otherwise would, which results in a higher flow of traffic between the origin and destination. This increase in traffic flow is known as induced travel. Downs's concepts of Downs's Law and induced travel appear extensively in the literature (Arnott, de Palma, and Lindsey 1993; Small 1982; Calfee and Winston 1998).

DeCorla-Souza and Cohen (1999) demonstrate how induced travel can be estimated for incorporation into the evaluation process for highway expansion projects. Their approach is particularly useful when it is difficult to forecast how many additional commuters will travel due to the construction of new freeways. They apply this methodology in order to study the benefits resulting from the hypothetical construction of a new urban freeway segment. Their analysis suggests that the increase in travel induced by highway expansion not only depends on initial congestion levels prior to expansion, but is greatly compounded when the congestion is heavy.

This makes sense. If a particular roadway is heavily congested, and drive times on it are relatively long, then it is clearly a route that is heavily demanded by drivers. Since this road is in high demand, more drivers will tend to use it when congestion is relieved by an urban freeway segment than they would a roadway that was relatively less congested to begin with. DeCorla-Souza and Cohen demonstrate that, even when initial high-level congestion is worsened by the resulting induced travel, the new segment still makes a large positive impact on congestion relief. This empirically supports Downs's traffic equilibrium hypothesis and further illustrates the benefits of the construction of new urban freeway segments.

Even if induced travel does coincide with the construction of new urban freeway segments, it does not necessarily lead to a conclusion that the benefits of those new segments are offset. The Thoreau Institute (2006) used a straightforward statistical analysis of Texas Transportation Institute data from 68 different urban areas from 1982 to 1999 to show that freeway construction shifts driving from ordinary streets to freeways. Since freeway driving is statistically safer than driving on arterial or surface streets, shifting more drivers onto the freeways provides a clear benefit. Thoreau also showed that increases in traffic are not correlated with utilization of public transit, and therefore spending should be focused on the form of transportation that does get used more with more congestion, i.e., freeways. Admittedly, Thoreau claimed to have found that, while freeway per-capita driving increases, arterial- and surface-street driving decreases, causing total per-capita driving to not necessarily increase. This conclusion differs from that of this paper, which uses a different data set and methodology.

While congestion is virtually inevitable, it can be somewhat alleviated, as is illustrated by Downs (1992). Downs states that, due to rapid growth, demand-side policies for reducing congestion can be overwhelmed, thus motivating the application of supply-side remedies. He argues that, while the intensity of congestion during the zenith of peak periods may not be reduced by adding to urban freeway capacity, which is explicitly stated in Downs's Law, the additional capacity may shorten the overall length of the peak period itself. This alone, however, is not a panacea. Assuming that there is continued rapid growth, as more people move to a metropolitan area, the peak period will again lengthen in the absence of a corresponding increase in roadway capacity.

Downs (1992) continues on to suggest that it is important to properly manage the efficiency of traffic flows using such techniques as roving repair vehicles, proper maintenance of roadways, and electronically controlled signs to inform drivers about conditions ahead. He cites several studies that show how these techniques, as well as ramp controls, high-occupancy vehicle (HOV) lanes, and park-and-ride lots, have had a noticeable impact on reducing congestion in Seattle. In particular, HOV lanes encourage drivers to carpool or ride the bus, in part because the additional commute time that is generally associated with traveling in such a manner is mitigated by transferring car pool vehicles or buses from slow-moving congested lanes to faster-moving HOV lanes. Additionally, commuting via ride-sharing or buses costs less per commuter than driving alone. Such cost savings, compounded with the time savings, motivate drivers to ride-share or take buses and, therefore, contribute to reducing congestion. While congestion cannot be completely eliminated, its negative effects can be reduced by such supply-side remedies.

These remedies are needed all the more as it is certainly clear that there is no end in sight to the ever-increasing rate of growth in vehicle miles traveled in the United States. Between 1980 and 2005, urban road mileage increased 62 percent, while vehicle miles traveled in urban areas have increased by 130 percent. (FHWA [1981?], Tables VM-1 and HM-10; FHWA 2006, Tables VM-1 and HM-10) This is also supported by Parry (2002), who notes that increases in vehicle miles traveled are exceeding increases in urban freeway capacity. While this established trend lends support to the need for increased urban freeway capacity, Parry aims to formalize this fact by analyzing how commuters perceive the tradeoff between urban freeways and other modes of transportation. He develops a model in which he characterizes this tradeoff by finding the various points at which the cost to commuters of driving on the freeway during peak periods is equal to the cost of utilizing various alternative modes of transportation. This resulting set of tradeoffs is known as the commuters' "marginal rate of substitution." Ultimately, the driver is indifferent between driving on the freeway and traveling via all other substitutes.

Drivers, however, fail to consider many of the costs of driving that don't fully affect them. In particular, individuals fail to consider the costs that their additional vehicles bring about by increasing the total volume of traffic. Parry (2002) calls these costs "marginal external costs." When drivers fail to consider marginal external costs, driving on urban freeways during peak periods appears less costly to the commuter than it actually is to society. Consequently, this leads to an inordinately high number of drivers choosing urban freeways as their mode of transportation during peak periods, which leads to congestion.

Parry (2002) numerically analyzes this phenomenon. After making some simple assumptions about drivers' preferences, he derives the equilibrium conditions described above. Using previous literature and relevant data sources, he is able to run his model simulation. Following this

framework, Parry simulates the addition of various policies and taxes and judges their impacts on overall efficiency. His numerical findings support the notion that urban freeways are over-utilized when drivers are not forced to account for marginal external costs.

Winston and Shirley (1998) come to a similar conclusion. They use a model to estimate the probability that commuters will choose one form of transportation over another. As expected, the authors find that higher out-of-pocket costs on a given mode of transportation discourage passengers from traveling on that mode. They also find that the longer the commute, the less of an impact costs have on the mode of transportation, and the more drivers tend to dislike carpooling. Additionally, they are able to use the total travel time per mile and cost per mile to estimate commuters' value of travel time. They find that the value of travel increases with distance traveled for all but the longest commutes. This type of framework could easily be applied to modeling the choice between driving on urban freeways and driving on arterial streets.

While Parry (2002) and Winston and Shirley (1998) focus on the individual driver's assessment of the costs and benefits of varying modes of travel, another study (Carey, Mansour, and Semmens 2000) concentrates on the overall value of a single mode of travel within Maricopa County, Arizona. They accomplish this by means of a corporate-style financial analysis that evaluates the Maricopa County Regional Area Road Fund (RARF) highway system by its overall profitability. This style of analysis differs from the traditional government style. In the government style, all sources of revenue are taken into account, including those sources that come in the form of subsidies from other branches of government and non-highway users. Not surprisingly, when the authors analyze the RARF highway system using a corporate-style analysis, which excludes revenue from subsidies and non-highway users, they find that the system is not profitable and actually operates at a net loss. They interpret this loss as an indicator that the revenue generated directly from highway users by current taxes is not sufficient to cover the cost of the system.

Modern accounting is not the only proposed means of assessing the overall value of a freeway system. Following Rowell, Buonincontri, and Semmens (1999), Carey, Mansour, and Semmens (2000) use the cost of owning and operating a vehicle as a proxy for highway value. They estimate that highway users' willingness to pay is higher than the current user-tax cost per mile that they actually do pay, which leads them to conclude that highways tend to be undervalued. Roadways are nearly useless without vehicles to be driven on them, and vehicles are nearly useless without roadways. Any two goods with this type of relationship are known as complements. Since roadways and vehicles are nearly perfect complements, the implication of this is that users value highways more than they are currently paying. If the current highway system is undervalued, then the public should be willing and able to pay for further expansion of the urban freeway system.

Model Framework

Much of the work cited in the literature review provides a foundation of theories that can be used to form hypotheses regarding the true impact of adding new freeway segments to an already existing urban street system. Any such hypotheses must be tested within the framework of a robust and accurate model that can be estimated using realistic assumptions and adequate data that is not overly difficult to obtain.

One of the primary and most important assertions in the literature is that freeways reduce the overall *cost* of travel. This cost of travel can be thought of as being broken into many constituent components. One component is the cost of fuel, which increases the longer a vehicle is stuck in traffic. Another component is the wear and tear exacted on a vehicle as the result of constant stop-and-go traffic. One of the more subtle costs, while at the same time one of the most important from an economic perspective, is the opportunity cost to a driver of spending longer amounts of time in traffic. In other words, each minute spent behind the wheel is one less minute that a driver could be using towards another desired activity. Simply put, the more time the driver spends in traffic, the more other opportunities he forfeits, hence the term opportunity cost. For example, the Greater Phoenix area is one of the nation's major metropolitan areas. It is relatively unique in that its low density demands that often great distances must be traveled in order to take advantage of what the region has to offer. This implies that the opportunity cost of a lower-capacity road system is higher than would otherwise be the case in a denser urban area.

All of these different forms of cost can be lumped together to form an overall composite cost, which, conveniently defined for the purposes of this paper, increases or decreases, based on the time a vehicle spends in traffic on a route between two given points, A and B. The more time spent in the vehicle, the higher the cost and vice versa. Consequently, in this paper, when we speak of the cost of travel, it is this overall or composite cost that is being referred to, i.e. a *total* cost that can be reduced by shortening the amount of time it takes for a driver to travel from A to B. What has been found in the literature is that a reduction in the cost of travel brings about a corresponding increase in per-capita traffic. If it is assumed that roadways and freeways obey the law of demand, or more specifically, if it is a safe assumption that people will use these modes of travel more when the cost of doing so decreases, then it also follows that any observed increase in overall traffic volume can be regarded as an indicator that the cost of taking a trip during peak hours is lower once a new freeway segment is opened. In the literature, this phenomenon is given the name of induced travel and, fortunately, it is something that can be empirically tested with proper data analysis. A question to be answered by any prospective model could then be the following: did the overall traffic within an urban geographic vicinity increase, with the addition of a new freeway segment, after accounting for increases in traffic due to other factors?

One such factor that can be identified beforehand is population growth. If it's assumed that an increase in population leads to an increase in the number of drivers within a particular geographic area, then it could be assumed that traffic increases as well; hence the assumption that population numbers and traffic volumes are positively correlated variables. If this is so, then any significant changes in population must be incorporated into a specified model. This theorem could be especially significant in a metropolitan area such as Greater Phoenix, where population growth has been positive and constant over the last several decades. Using data obtained from the Arizona Department of Administration, (ADOA 1970-2010) the steady growth in the Greater Phoenix area is depicted in Figure 1.

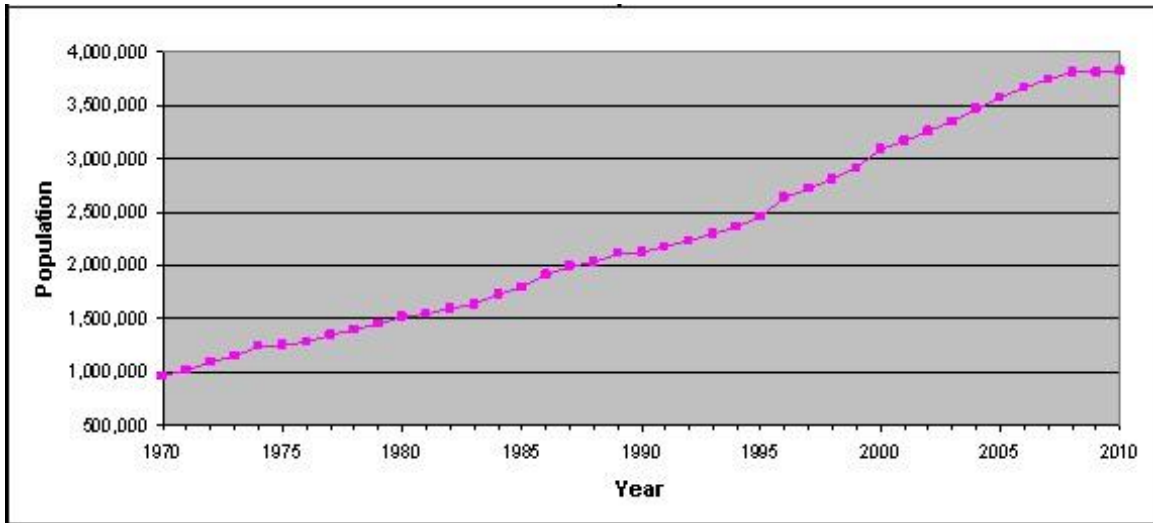


Figure 1. Greater Phoenix Population Trend

While it may be safe and reasonable to simply assume that a population increase certainly results in a higher number of drivers on the roads and freeways, an effective model should be able to quantify the actual degree of increased traffic that can be attributed to an increase in population. Once this effect is measured, it can be stripped out of the model's results to isolate the net increase in traffic due to induced travel from the construction of new urban freeway segments.

A concept related to induced travel, which is also introduced in the literature, is that of Downs's Law of Peak-hour Traffic Congestion, which states that any freeway capacity made available by trip-reduction programs or extra freeway space will soon be utilized by new trips. This results from latent demand, as people formerly discouraged from driving are attracted to the freeways given the new, lower cost of driving. The effect of induced travel causes the new capacity of freeways to be filled up with yet more drivers and vehicles until the cost of driving is about the same as it was before the addition of the new freeway. The only net difference is that more drivers are on the freeways and surface streets than before. In other words, the addition of new urban freeway segments does not significantly reduce congestion over time, but there is a higher overall traffic volume. In practice, new urban freeway segments *do* confer this benefit, and, instead of viewing the reoccurrence of high-volume congestion after the completion of new urban freeway segments as a negative condition that was supposed to have been eliminated, it should rather be viewed as an expected result of the new benefit of lower driving cost on urban freeways, thus fulfilling Downs's Law.

In summary, then:

- A driver typically has a latent demand to drive around more if his, or her, opportunity cost could be lowered by an uncongested street or freeway.
- Opening a new freeway segment lowers this person's cost and thus induces him, or her, to travel.
- Many such drivers fill up the new freeway segment, according to Downs's Law, until they balance against a restored cost.

Given these interrelated concepts, there are several key questions that can be answered by a properly specified model:

1. Does the permanence of long-term congestion in general mean that new urban freeway segments have little or no benefit?
2. Are there other effects conferred by the building of new urban freeway segments besides congestion?
3. What is the effect on arterial street traffic volume in the wake of building new urban freeway segments?

As with the process of building any model, we have formulated several hypotheses as to what the effects of adding new freeway segments might be. These are as follows:

1. Building new urban freeway segments has benefits outside of simply alleviating congestion, as we expect total traffic volume to increase due to induced travel, which, in and of itself, is a benefit to the public.
2. Total volume of arterial street traffic during peak hours will either remain constant as latent-demand driving fills the void left by drivers drawn to the new freeway or actually decrease if the added freeway capacity exceeds the latent demand.

In order to test these hypotheses, an experimental design was constructed according to the following assumptions and specifications:

1. If the theory of induced travel turns out to be true, then, when a new urban freeway segment is completed, we should see more total traffic within a defined geographical band than before the segment was built.
2. If we see that freeway traffic increases for every unit increase in arterial street traffic volume, we can show that not only are people substituting freeway driving for arterial-street driving, but also marginal drivers are now motivated to take an arterial-street trip that they wouldn't have otherwise taken. Such a result would simultaneously exemplify the theories of Downs's Law and induced travel.

To numerically analyze this experimental design, we will employ an analysis technique commonly used in economic analysis known as regression analysis. The next section describes this technique and how it is applied in this paper to develop and then estimate models of urban traffic.

The Model

Regression analysis is a common statistical technique used to determine the relationship between a set of variables and some response. It is widely used in econometrics to determine the relationship among variables; in the economy, in labor markets, in financial markets, etc. It is used in this paper to help determine if a relationship exists between the addition of new freeway segments and traffic volumes. This section will explain the concept of regression analysis and then illustrate its use by explaining how it was applied to construct and estimate the induced-travel model.

The goal of the analysis is to determine whether the construction of a freeway segment has an impact on total traffic volumes in the Greater Phoenix area. The hard part, however, is that we want to know, all else being equal, the relationship between total traffic and a new freeway segment. In order to do this, we need to control for potential confounding factors. Thus, we need to ask the question: what other factors could affect total traffic volumes in an area? One potential factor is the local population.

Figure 2 shows a scatter plot with the natural logarithm of total traffic depicted on the vertical axis and the natural logarithm of the population of the Greater Phoenix area along the horizontal axis.¹ The plot has two sets of points: one set representing traffic volumes at each population level where there are freeways present and one set where freeways are not present. The goal here is to estimate what the difference in total traffic is between areas that have freeway segments and areas that don't have freeway segments, controlling for changes in population. We do this by calculating a "line of best fit" through the data points, as suggested in the figure. This line may be written in the familiar slope-intercept form as

$$y = b_1x + b_0 \quad (\text{Eq. 1})$$

where:

- y is the natural logarithm of total traffic.
- x is the natural logarithm of population.
- b_1 is the line's slope, which is the change in y divided by the change in x .
- b_0 is the value of y where the line intercepts the vertical axis at the hypothetical place (off the graph) where the natural logarithm of population is zero.

To determine b_1 and b_0 with mathematical rigor, we may start by drawing the line that goes through the first traffic-volume measurement y_1 at a time of known population x_1 with a presently unknown slope and intercept. To account for the error between the known y_1 and its yet-undetermined equivalent calculated by $b_1x + b_0$, we introduce an error term ε , which, with rearrangement of the order of addition, leads to:

$$y_1 = b_0 + b_1x_1 + \varepsilon_1 \quad (\text{Eq. 2})$$

¹ Strictly, the quantities, of which these natural logarithms are taken, are scaled so as to make the numbers smaller than the raw quantities, but this does not affect our analysis, as we shall see.

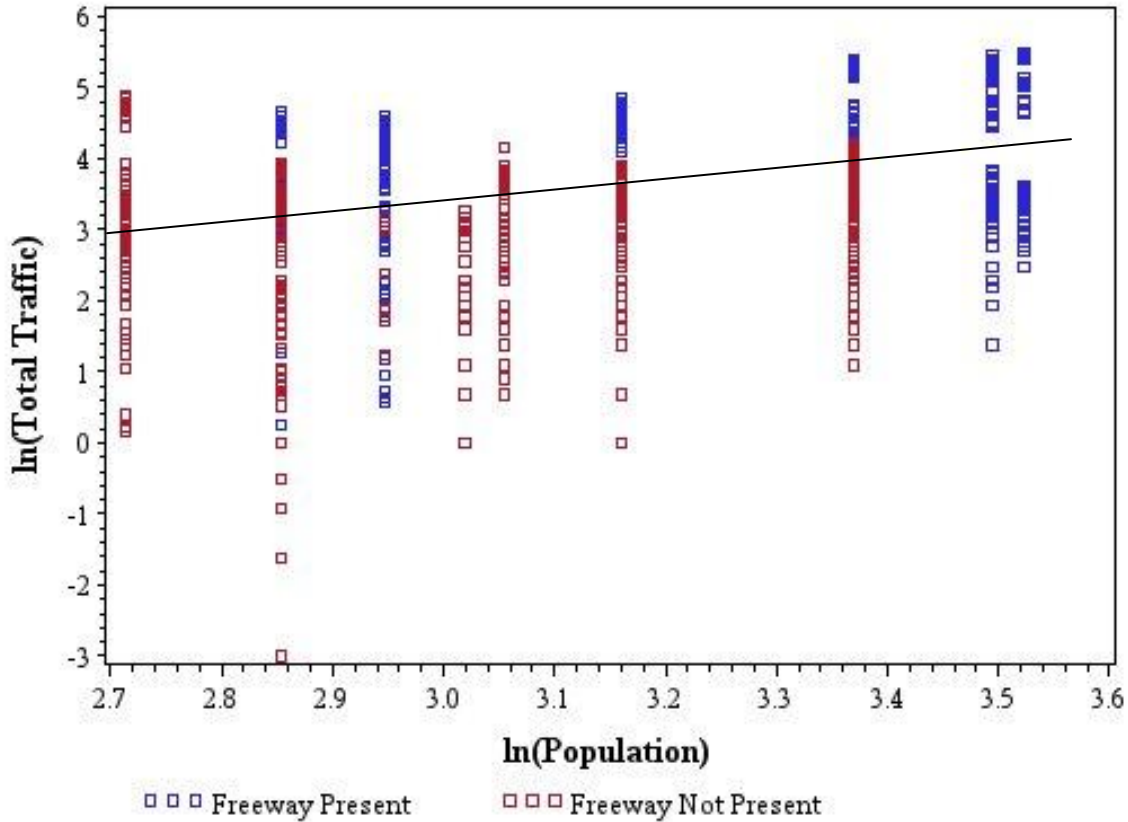


Figure 2. Typical Scatter Plot of Traffic Volume vs. Population with Approximate Best-Fit Line.

Then we may draw another line that goes through another measurement y_2 at the time of known population x_2 , which would have the equation:

$$y_2 = b_0 + b_1 x_2 + \varepsilon_2 \quad (\text{Eq. 3})$$

After drawing as many of these lines as there are traffic-volume measurements available, we may solve for their best-fit coefficients b_1 and b_0 so as to minimize the error terms taken as a group. We use a matrix equation of the form:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ 1 & x_4 \end{bmatrix} \times \begin{bmatrix} b_0 \\ b_1 \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \end{bmatrix} \quad (\text{Eq. 4})$$

or

$$Y = X\beta + E \quad (\text{Eq. 5})$$

where:

- Y is the *response variable*, a vector (one-column, or $n \times 1$ matrix) of the natural

logarithms of all the observed traffic volumes, where n (here, 4) is the number of observations.

- X is an $n \times k$ matrix, where k (here, 2) is the number of independent variables in β below. Its columns, for the case of Equation 4 are, respectively, unity multipliers for b_0 and the populations applicable to each observation. Such variables are often called covariates. They are also called confounding factors, if they represent changing conditions that might obscure desired results over a period of interest.
- β is the vector containing our b_0 and b_1 , the coefficients, where b_0 is the intercept of the line of best fit, and b_1 is the slope of the line of best fit. These coefficients determine the effects that the independent variables in X have on the dependent variables in Y .
- E is the error vector containing the residuals, which are the predicted observations minus the actual dependent observations.

Going back to the form of Equation 2, we may express y and x as the traffic and population quantities they represent, namely

$$\ln(TOTRAF) = b_0 + b_1 \ln(POP) + \varepsilon \quad (\text{Eq. 6})$$

where:

- $TOTRAF$ is the sum of traffic volumes on an arterial street parallel to the freeway plus the traffic volume on that freeway segment if it exists. $TOTRAF$ is exemplified by the vertical axis of the graph of Figure 2.
- POP is the population pertinent to a $TOTRAF$ observation, exemplified by the horizontal axis of the graph of Figure 2.

Our analysis, however, has more independent variables than just population. Fundamental to this study is the presence or absence of a freeway, which is a binary switch variable, with values of 0 or 1. Other variables may be the distance from the point of measurement to the freeway and the total stock of freeway mileage available in an area. All the variables cannot be shown simultaneously as in Figure 2, which is limited to only the two dimensions of traffic volume and population, but they may be mathematically accounted for in determining the coefficients of the best-fit conceptual line that would course through such a multi-dimensional graph. We may expand Equation 6 to include these other independent variables:

$$\ln(TOTRAF) = b_0 + b_1 AFTER + b_2 \ln(POP) + b_3 \ln(MILES) + b_4 \ln(TOTMILES) + \varepsilon \quad (\text{Eq. 7})$$

where the new variables are:

- $AFTER$, a binary switch variable (0 or 1) to denote that the freeway is not present or present.
- $MILES$, the distance, in miles, from the freeway segment to the arterial street.
- $TOTMILES$, the total stock, in miles, of urban freeway in a given year.
- b_k , coefficients as before, with some arbitrary renumbering of the subscripts.

Despite the fact that Equation 7 has four independent variables compared to the one in Equation 6, the system of simultaneous equations of this form may still be written in the form of Equation 5, namely

$$Y = X\beta + E \quad (\text{Eq. 5})$$

except that X will now have five columns instead of the two columns in Equation 4, and β will be a five-deep vector instead of two.

This is our model of the forces that result in the data of Figure 2, and it is the vehicle by which to obtain the vector β that describes the best-fit line that minimizes the distances between points on the line² and their respective actual data points. The specific structure of Equation 7, with its particular choice of covariates, is called a specification.

We obtain the best-fit β by using matrix calculus to minimize the sum of the squares of ε in Equation 5; that is, we minimize

$$E' \times E \quad (\text{Eq. 8})$$

Where E' is the transpose of E . But because

$$E = Y - X\beta \quad (\text{Eq. 5a})$$

We can substitute $Y - X\beta$ for ε in Equation 8 to get:

$$(Y - X\beta)' \times (Y - X\beta) \quad (\text{Eq. 9})$$

Then, using calculus, we find the coefficients b_k that minimize this expression. It can be shown that the solution vector is:

$$\beta_{optimal} = (X' \times X)^{-1} \times (X' \times Y) \quad (\text{Eq. 10})$$

where the -1 exponent means the matrix inversion of $(X' \times X)$.

A numerical example may be useful here. Leaving the last two covariates out of Equation 7, casting it in the matrix form of Equation 5, and assigning some test values to it, we have:

$$Y = X\beta + E \quad (\text{Eq. 5})$$

$$\begin{bmatrix} 2.56 \\ 1.25 \\ 2.94 \\ 2.73 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 2.5 \\ 1 & 0 & 2.6 \\ 1 & 1 & 2.71 \\ 1 & 1 & 2.3 \end{bmatrix} \times \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \end{bmatrix} \quad (\text{Eq. 11})$$

Here the Y matrix contains the natural logs of four observations of total traffic in its four rows; and the columns of the X matrix are, respectively, the intercept multiplier (unity), a binary indicator variable, where 1 indicates the presence of a freeway and 0 indicates otherwise, and the

² It is understood that the “line” is no longer readily visualizable in a single graph because it now courses through five dimensions instead of the two dimensions of Figure 2.

natural log of population. The β vector, which is now three deep to accommodate the three covariates in X , contains, from the top, the intercept, the freeway-or-not slope parameter, and the population slope parameter. Substituting into Equation 10 to find the optimal values for β :

$$\beta_{optimal} = \left(\begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 2.5 & 2.6 & 2.71 & 2.3 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 2.5 \\ 1 & 0 & 2.6 \\ 1 & 1 & 2.71 \\ 1 & 1 & 2.3 \end{bmatrix} \right)^{-1} \times \left(\begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 2.5 & 2.6 & 2.71 & 2.3 \end{bmatrix} \times \begin{bmatrix} 2.56 \\ 1.25 \\ 2.94 \\ 2.73 \end{bmatrix} \right)$$

$$= \begin{bmatrix} 73.603 & -1.790 & -28.668 \\ -1.790 & 1.023 & 0.506 \\ -28.668 & 0.506 & 11.242 \end{bmatrix} \times \begin{bmatrix} 9.480 \\ 5.670 \\ 23.896 \end{bmatrix} = \begin{bmatrix} 2.557 \\ 0.923 \\ -0.265 \end{bmatrix}$$

That is,

Associated Covariate	Symbol	Value
Unity (Intercept)	b_0	2.557
<i>AFTER</i>	b_1	0.923
$\ln(POP)$	b_2	-0.265

Now we obtain our best-fit $X\beta_{optimal}$, which will be our four raw observations in Y ($\ln(TOTRAF)$) adjusted for population:

$$X\beta_{optimal} = \begin{bmatrix} 1 & 0 & 2.5 \\ 1 & 0 & 2.6 \\ 1 & 1 & 2.71 \\ 1 & 1 & 2.3 \end{bmatrix} \times \begin{bmatrix} 2.557 \\ 0.923 \\ -0.265 \end{bmatrix} = \begin{bmatrix} 1.895 \\ 1.868 \\ 2.762 \\ 2.871 \end{bmatrix} \quad (\text{Eq. 12})$$

We may plot this result in Figure 3, also showing our original Y for comparison:

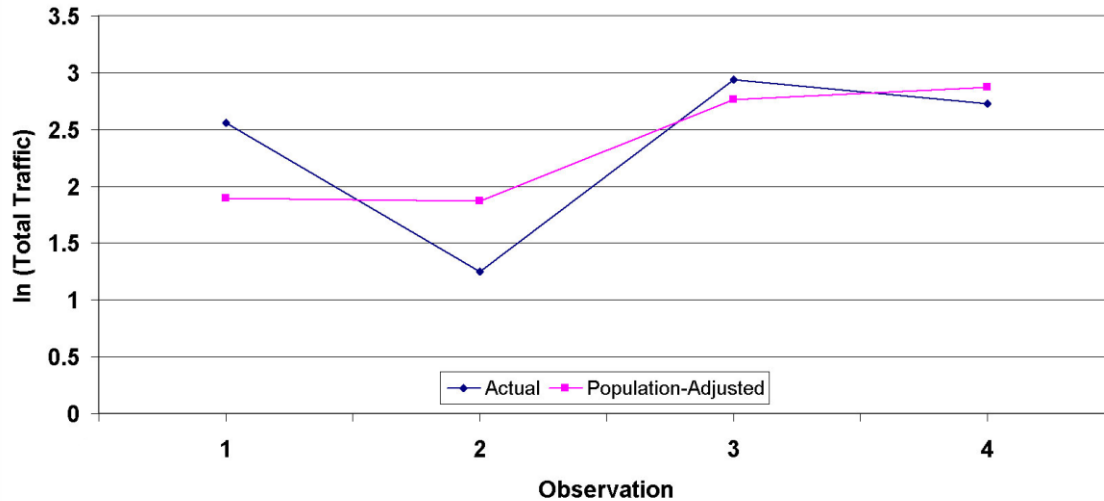


Figure 3. Best-Fit $X\beta_{optimal}$ (Population-Adjusted Y) for Sample Data of Equation 11.

It can be seen in the figure that a freeway (represented by the third and fourth observations) is associated with higher amounts of traffic. The increase in the natural log of total traffic, with population held constant, may be estimated by taking the difference between the means of the latter pair of observations and the first pair. That is,

$$\Delta \ln(TOTRAF) = \frac{2.762 + 2.871}{2} - \frac{1.895 + 1.868}{2} = 0.935 \quad (\text{Eq. 13})$$

$$\frac{TOTRAF_{AFTER}}{TOTRAF_{BEFORE}} = e^{0.935} = 2.547 \quad (\text{Eq. 14})$$

This means that *TOTRAF*, after the freeway opening, increases by an estimated factor of 1.547, or 155 percent, with population held constant.

However, it is unnecessary to draw Figure 3 and evaluate Equations 13 and 14 to reach this conclusion. When the covariates in *Y* are log-transformed as they are for *TOTRAF_n* in Equation 7, and some binary covariates in *X* are untransformed as they are for *AFTER_n*, then it can be shown that the change in *TOTRAF* caused by the change in *AFTER* from 0 to 1, with other covariates held constant, is obtained by simply applying exponentiation to *b₁*. That is,

$$\frac{TOTRAF_{AFTER}}{TOTRAF_{BEFORE}} = e^{0.923} = 2.517 \quad (\text{Eq. 15})$$

This means that *TOTRAF* after the freeway opening increases by a factor of 1.517, or 155 percent, with population held constant. This is the rigorously correct result, differing from our coarse estimate of Equation 14 by a relative 2 percent.

The ultimate goal of the model of Equation 7 is to describe and quantify the effects of new, urban freeway segments on overall traffic, specifically within the Greater Phoenix metropolitan area. As mentioned, there are two expected consequences from the development of new urban freeway segments:

1. A reduction in the cost of traveling, thus increasing the overall number of trips taken within the area—induced travel.
2. Preference for driving on freeways over driving on arterial streets—Downs’s Law of Peak-hour Traffic Congestion.

By confirming the theory of induced travel on the Greater Phoenix-area arterial streets and urban freeways, using Equations 11 through 15 with real observed data, we are halfway toward showing the existence of Downs’s Law. When a new urban freeway segment is added, we expect some of the traffic on paralleling arterial streets to shift to the new segment, decreasing traffic volumes on these arterial streets. This reduction will motivate motorists who were previously on the margin to take a trip they wouldn’t have otherwise taken if the freeway hadn’t been built. The theory of induced travel, however, predicts that the decreased traffic on arterial streets reduces the cost of driving on those streets, causing induced travel because of the latent demand, and thus increasing the total amount of traffic in the area. By studying traffic volumes before and after a

new freeway segment is constructed, we can determine if there is an overall increase in traffic. If so, induced travel is present.

As mentioned earlier, the model of Equation 7 (whose matrix form is that of Equation 5) estimates the effects of urban freeways while controlling for other factors that could potentially influence total traffic volumes. Its appropriateness and fit will be analyzed in the following section.

Utilizing this model framework, which is designed to use factors such as the existence of urban freeway segments, as well as other factors, to predict total traffic volumes, we can analyze the effect of new urban freeway segments on total traffic in an area immediately surrounding the segment. We can show the induced travel effect by demonstrating that total traffic has increased as captured by the binary variable *AFTER*. If the coefficient of *AFTER*, β_1 , is positive, then that is statistical evidence that total traffic increases after the completion of a new freeway segment, leading us to confirm the theory of induced travel. Additionally, given our specification of Equation 7 to estimate total traffic volume, with both the dependent variable and the non-binary covariates expressed as natural logarithms, we can interpret the coefficients β as percentage changes rather than absolute changes.

Case 1. Isolation of Population Change; Single Parallel Street

As we can see in Figure 4, by plotting yearly average total traffic per freeway segment in our sample on the same graph as yearly population, we see a strong correlation.

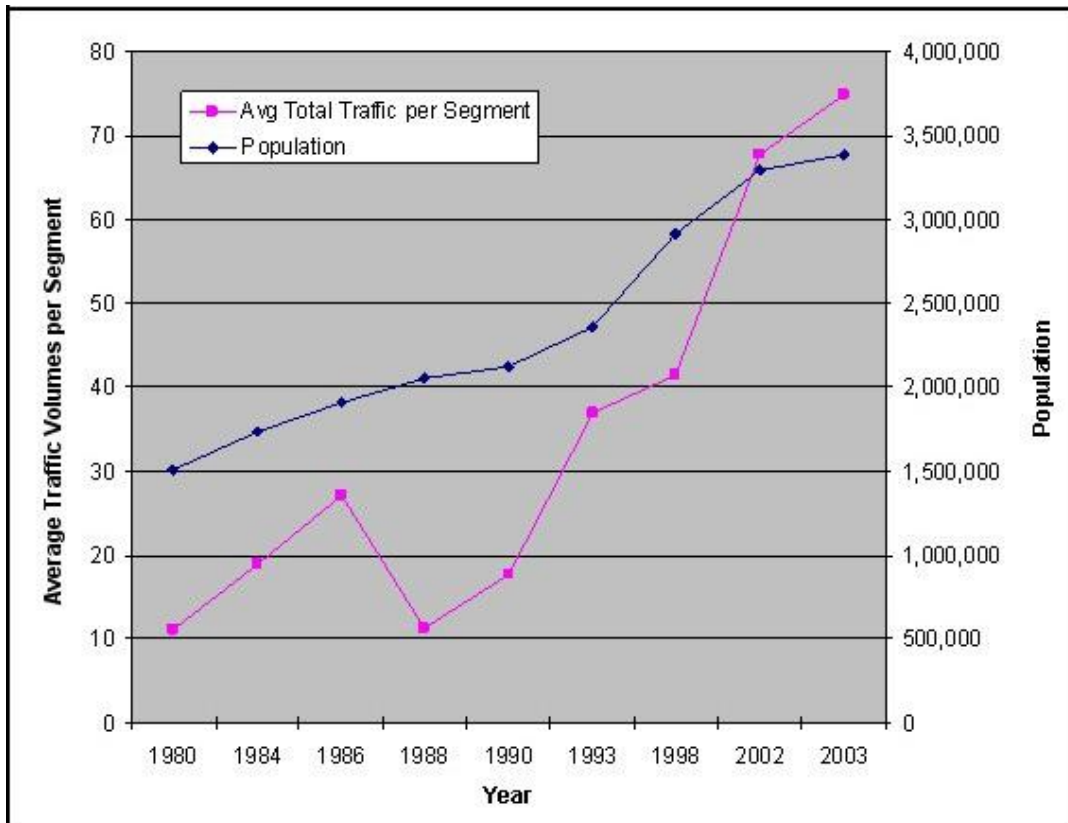


Figure 4. Greater Phoenix Traffic Volumes per Freeway Segment vs. Population.

Though the variables do not track perfectly, it is clear that population is a strong contributor to increases in traffic volumes within a given geographic band. By evaluating the model of Equation 7 with the $\ln(MILES)$ and $\ln(TOTMILES)$ covariates omitted, we can isolate the effects on traffic of a new freeway segment from changes in population, exactly as we did for the sample data of Equation 11. Restoring these covariates will also isolate the traffic effects from distance-to-freeway and freeway mileage stock, leading to determining how much they, too, have affected the traffic volumes. Using varying number of covariates will change the sizes of the resulting matrices but not the analysis method.

Case 2. Multiple Parallel Streets and Freeway

Case 1 measured the effects of a freeway segment on total traffic, relative to a single substitute arterial street in each observation. We can expand this analysis to a collection of nearby arterial street segments that run parallel to a freeway segment and are located within 3 miles of the freeway. For example, for a given segment of freeway that runs, say, east to west, we can look at the corresponding parallel arterial street segments that run 1 mile north, 2 miles north, and 3 miles north, respectively, of the freeway segment. We would then look at the three parallel arterial street segments that run, respectively, 1, 2, and 3 miles south of the freeway segment. The given freeway segment and all six of the corresponding parallel arterial street segments can be looked at as one composite traffic band that spans approximately 6 miles (3 miles on either side of the freeway segment). To show that total traffic volumes increase in the *entire* 6-mile band, we can create a new, total-traffic, dependent variable that sums across these parallel arterial streets in addition to the urban freeway, if available. To use this stratagem, we modify the specification of Equation 7 to become

$$\ln(TOTARTFWY) = b_0 + b_1 AFTER + b_2 \ln(POP) + b_3 \ln(TOTMILES) + \varepsilon \quad (\text{Eq. 16})$$

where:

- $TOTARTFWY$ is the sum of traffic volumes on multiple arterial streets parallel to the alignment of the freeway plus the traffic volume on that freeway segment, if it exists.
- b_0 is the value of $\ln(TOTARTFWY)$ where the line graphed as in Figure 2 intercepts the vertical axis at the hypothetical place where the other covariates or their natural logarithms, where applicable, are zero.
- b_1 through b_4 are the line's slope with respect to the associated covariate or its natural logarithm, where applicable.
- All other variables and constants are the same as in Equation 7.

Similarly, as in Case 1, we may perform regressions without $\ln(POP)$ and/or $\ln(TOTMILES)$ to check how much they affected the other results.

Case 3. Multiple Parallel Streets Only

As just discussed, the concept of induced travel and its resultant Downs's Law of Peak-hour Traffic Congestion predict that a reduction in cost of traveling associated with the construction of a new freeway segment motivates more people to travel. They predict further that freeways are a

more attractive alternative and hence should fill to capacity faster than arterial streets. If we are able to confirm the hypothesis of induced travel in Equation 7, then, to show that Downs's Law holds, we need to show that drivers are forsaking travel on surface streets for travel on freeway segments. If Downs's Law holds and total traffic increases, the bulk of that increase should be due to drivers shifting toward the freeway. As a result, if parallel arterial street traffic either decreases or remains constant while total traffic increases, and we adjust for potential covariates such as population growth, then we can be assured that the increase in traffic was due primarily to the construction of the new freeway segment. In order to prove this hypothesis, we again modify the specification of Equation 7 to become

$$\ln(TOTART) = b_0 + b_1 AFTER + b_2 \ln(POP) + b_3 \ln(TOTMILES) + \varepsilon \quad (\text{Eq. 17})$$

where:

- *TOTART* is the sum of traffic volumes on multiple arterial streets parallel to the alignment of the freeway, not including the traffic volume on that freeway, even if it exists
- b_0 is the value of $\ln(TOTART)$ where the line graphed as in Figure 2 intercepts the vertical axis at the hypothetical place where the other covariates or their natural logarithms, where applicable, are zero.
- b_1 through b_4 are the same as in Equation 16, and all other variables and constants are the same as in Equation 7.

If b_1 is negative or zero, then the increase in total traffic must be primarily due to drivers' preference for driving on the freeway; thus Downs's Law would hold.

It is important to note that, due to the nature of traffic volume data, the origins and destinations of individual drivers are unknown. Because of this fact, a person could originate from anywhere in the region and travel to anywhere in the region. Thus a region-wide population variable is a reasonable proxy to represent potential freeway demand.

Data and Estimation

As described earlier in the paper, hypotheses are useful only insofar as there are realistic and workable models that can be formed to test them. Although such a model was proposed in the preceding section, the process of building *any* model is inherently limited by the amount and quality of data that may be used in a model's estimation.

For use in our proposed model, such data was obtained using a series of traffic count maps over an interval of time and by compiling data related to population to isolate the effects of population growth. Nine traffic-count maps were obtained from the Maricopa Association of Governments (MAG), each of which indicated the average number of vehicles that utilized a given segment of arterial street or freeway. According to MAG, the traffic volumes shown on the maps are average weekday traffic, developed from 24-hour counts for each year. Traffic counts were seasonally adjusted in order to account for the effects of traffic count variation among different times of the year. The maps included the years 1980, 1984, 1986, 1988, 1990, 1993, 1998, 2002, and 2003.

For the purposes of this research, each map was divided into traffic bands based around existing or future freeway segments. Traffic counts on arterial streets were used on parallel streets aligned 3 miles or less from an existing or future freeway segment. A distance of 3 miles was chosen primarily due to the fact that data were consistently available for most freeway segments in the geographical band. Secondly, according to Downs (1992), due to the nature of habit persistence, drivers do not tend to shift their typical driving behavior to great degrees. Thus, it is only necessary to include those alternative parallel streets that would be likely substitutes for a new freeway segment.

In the maps, each unique segment of arterial street or freeway has been labeled with the actual traffic count number observed for that year. The segments on the maps were divided more or less according to the Phoenix grid network of streets, where one segment begins with one perpendicular street and ends with the next major perpendicular street. With the segments delineated in this manner, each arterial street and freeway segment has an average length of approximately 1 mile.

A dataset was compiled where each segment was given a name based on the perpendicular streets that defined each end of the segment. The only arterial street segments that were used for analysis were those that had a traffic count assigned to them and that were located within 3 miles of, and ran parallel to, an existing segment of freeway, or a segment of road or space that eventually became a segment of freeway.

Of all the segments used in the final analysis, Table 1 depicts the map year from which each segment was drawn, the total number of segments used from that map, and the population of the Greater Phoenix valley in each map's year. The segments in each year were randomly chosen from the new segments built in that year.

For a visual representation of the annual trends of arterial street and freeway traffic volumes, Figure 5 shows each count plotted over time. While the average daily traffic on arterial streets has stayed more or less constant, the average daily traffic on freeways used in the analysis has increased dramatically over time.

Table 1. Segments Sampled by Year.

Map Year	# Sampled Segments	Population
1980	63	1,509,175
1984	209	1,736,952
1986	159	1,905,504
1988	63	2,048,441
1990	138	2,122,101
1993	183	2,359,883
1998	367	2,909,040
2002	215	3,293,606
2003	98	3,388,768

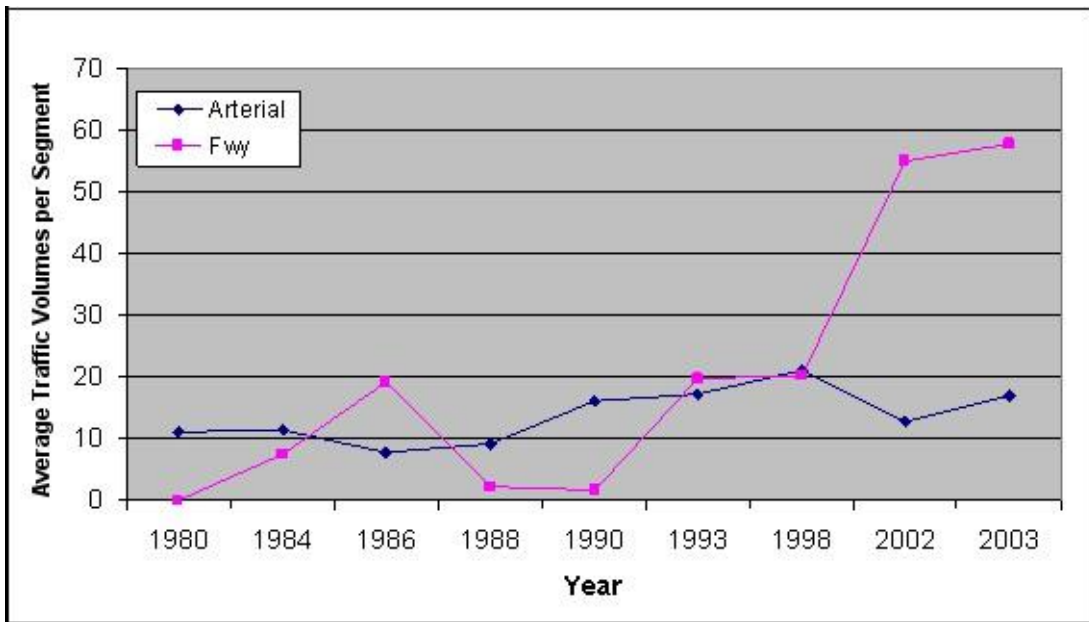


Figure 5. Average Arterial vs. Average Freeway Counts (in Thousands).

Figure 6, below, gives a more detailed representation of how traffic counts are marked between major perpendicular streets in the maps. This is true for freeway segments as well as arterial streets. In situations where a parallel street did not have a count, that portion of the street was omitted from the analysis for the years for which that count was missing. To calculate total traffic in a band, we add the counts of parallel streets between two perpendicular streets. For example, in the diagram below, the total daily arterial street traffic (*TOTART*) (in thousands) between the first perpendicular streets and within 3 miles of the freeway would be $35 + 49 + 52 + 50 + 40 + 39 = 265$. The total traffic counts (*TOTRAF*) are the daily traffic count on the freeway plus the count on a substitute arterial street. In the diagram below, the first three streets above the freeway would have daily counts of $52 + 80 = 132$, $49 + 80 = 129$ and $35 + 80 = 115$, respectively. In areas before the construction of the freeway, the total traffic is equal to the arterial street traffic.

30	31	31	30	} Parallel Arterial Streets
35	32	36	36	
49	48	50		
52	50	49	51	
80	86	89		} Urban Freeway
<hr/>				
50	58	56	59	} Parallel Arterial Streets
40	42	43	42	
39	39	38	38	
36	36	36	37	
} Perpendicular Streets that Delineate Bands				

Figure 6. Example of Daily Traffic Counts (in Thousands) along Bands of Arterial Streets Parallel to an Urban Freeway.

Estimating the Model

The results of the estimates resulting from the approach of the previous section as applied to Equations 7, 16, and 17 are presented in this section. The models are estimated using ordinary least squares. First we present the estimates of various specifications of both the induced travel model and the Downs's Law model, which were previously discussed. Finally, we analyze and interpret the results. The t-value is listed as a measure of the confidence with which the estimate can be taken. It is each coefficient's estimate divided by its standard error. The larger the absolute value of t, the less likely that the actual value of the b_k could be zero. The F value, which is the ratio of the mean regression sum of squares divided by the mean error sum of squares, tests the overall significance of the regression model by testing whether all of the b_k are equal to zero. This tests the full model against a model with no variables and with the estimate of the dependent variable being the mean of the values of the dependent variable. Its value will range from zero, showing that the independent variables are random with respect to the dependent variable, to an arbitrarily large number.

Estimate 1. Induced-Travel Model

Table 2. Induced Travel (1).

Induced Travel (1)		<i>Dependent Var: ln(TOTRAF)</i>					<i>F-Value</i> ³	<i>R</i> ²⁴
<i>Specification</i>	<i>b</i> ₀ (Intercept)	<i>b</i> ₁ (AFTER)	<i>b</i> ₂ ln(POP)	<i>b</i> ₃ ln(MILES)	<i>b</i> ₄ ln(TOTMILES)			
1	Estimate	2.88*	1.01*	N/A	N/A	N/A	183.46*	0.18
	t Value ⁵	60.49	13.54	N/A	N/A	N/A		
2	Estimate	-2.08*	0.89*	1.74*	N/A	-0.11	107.82*	0.28
	t Value	-4.01	12.40	3.91	N/A	-0.46		
3	Estimate	-1.69*	0.87*	1.53*	-0.12*	N/A	103.66*	0.28
	t Value	-3.64	11.99	10.32	-3.34	N/A		
4	Estimate	-1.96*	0.89*	1.55*	N/A	N/A	161.77*	0.28
	t Value	-4.33	12.50	10.73	N/A	N/A		

*Denotes estimate significant at the 95% confidence level.

³ A nonlinear regression and curve fitting website (Sherrod 2008) defines the F-value as the ratio of the mean regression sum of squares divided by the mean error sum of squares. It tests the overall significance of the full regression model by testing whether all of the b_k are equal to zero, thus comparing the model to a model with no variables and with the estimate of the dependent variable being the mean of the values of the dependent variable. Its value will range from zero, showing that the independent variables are random with respect to the dependent variable, to an arbitrarily large number.

⁴ A note about R^2 : In the quintessential graduate econometrics textbook, William Greene states, "In terms of the values one normally encounters in cross sections, an R^2 of 0.5 is relatively high. Coefficients of determination (which is an R^2) in cross sections of individual data as high as 0.2 are sometimes noteworthy. The point of this discussion is that whether a regression line provides a good fit to a body of data depends on the setting." (Greene 2002)

⁵ A nonlinear regression and curve fitting website (Sherrod 2008) defines the t-value as a measure of the confidence with which the estimate can be taken. It is the slope coefficient's estimate divided by its standard error. The larger the absolute value of t, the less likely that the actual value of the b_k could be zero.

All variations on the general model used to test the hypothesis of induced travel present robust results with regard to the primary variable of interest, b_1 . In the first variation, b_1 is highly significant with a positive value. This supports the hypothesis of induced travel. Subsequent regressions with different combinations of covariates (specifications), shown in rows 2 through 4 of Table 2, are done to confirm this, and all yield consistent results: The addition of an urban freeway segment can be shown to increase overall travel rather than simply shifting traffic from the arterial streets to nearby parallel freeways.

By adding the additional covariates representing potential confounding effects in rows 2 through 4 of Table 2, we attempted to discern the robustness of the effect of a new freeway segment on overall traffic. These covariates were the population (*POP*), the distance from the freeway segment to the arterial street (*MILES*), and the total miles in the freeway network (*TOTMILES*). The potential effect of population is discussed above and is included in the remaining model variations. In each model, the effect of *AFTER* on b_1 is significant, positive, and relatively stable, ranging from 0.87 to 1.01. This indicates that, even after we control for population growth, total freeway miles, and distance from the arterial street to the freeway, the addition of an urban freeway segment has a significant, positive effect on traffic volumes, which can be seen in all variations of the model. These results indicate that the construction of a new urban freeway segment results in a 138 percent to 175 percent increase in total traffic. This represents a large increase in regional mobility and is depicted in Figure 7.

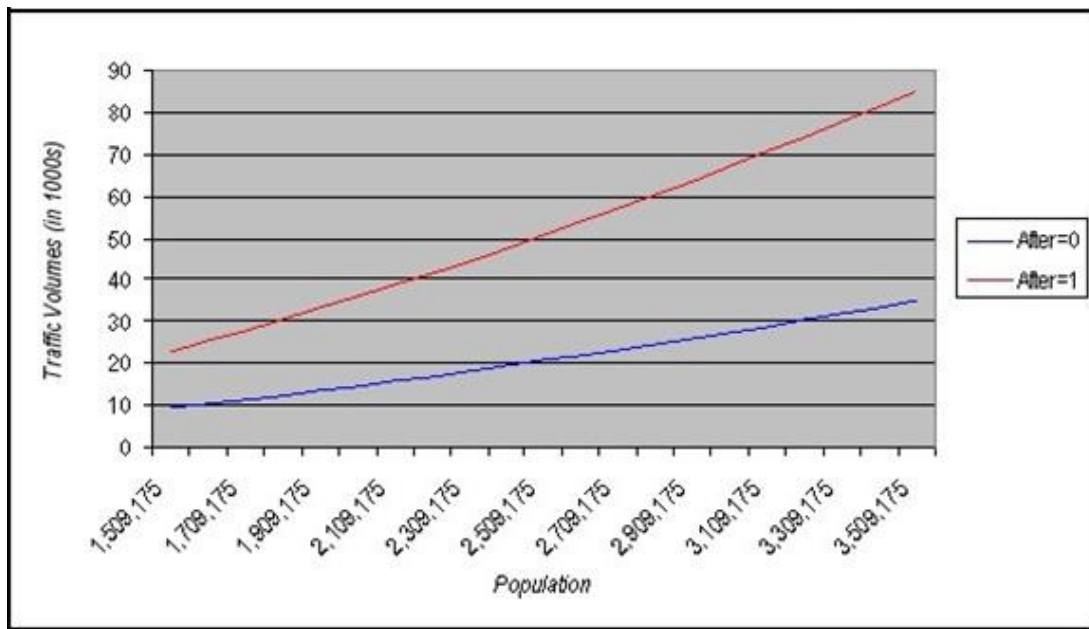


Figure 7. Predicted Traffic Volumes – Induced Travel (1).

Estimate 2. Induced-Travel Model with Inclusion of Freeway Count

To attempt to estimate the network effects of urban freeways, the variable *TOTMILES* was included. This variable measures the total stock, in miles, of urban freeway in a given year. If network effects are present, the effect of *TOTMILES* should be positive — the more miles of

urban freeway, the higher the total traffic volume we would expect. However, as seen in Table 3, the effect of the covariate *TOTMILES* is insignificant. This is likely due to the fact that total freeway miles and population are correlated to the extent that their individual effects can't be separated by regression analysis.

Table 3. Induced Travel (2).

Induced Travel (2) <i>Dependent Var: ln(TOTARTFWY)</i>		b_0	b_1	b_2	b_3	<i>F-Value</i>	R^2
<i>Specification</i>		<i>(Intercept)</i>	<i>(AFTER)</i>	<i>ln(POP)</i>	<i>ln(TOTMILES)</i>		
1	Estimate	4.35*	0.89*	N/A	N/A	43.75*	0.20
	t Value	60.35	6.61	N/A	N/A		
2	Estimate	1.59*	0.61*	N/A	0.64*	42.13*	0.32
	t Value	3.26	4.54	N/A	5.72		
3	Estimate	0.91	0.62*	0.69	0.31	28.34*	0.32
	t Value	1.03	4.61	0.92	0.81		
4	Estimate	0.46	0.64*	1.26*	N/A	42.27*	0.32
	t Value	0.68	4.88	5.75	N/A		

**Denotes estimate significant at the 95% confidence level.*

To confirm that total traffic has, in fact, increased, we estimate Equation 16. This is similar to Equation 7, except that the dependent variable $\ln(TOTARTFWY)$ includes freeway traffic counts, when available, rather than solely arterial street traffic counts. As evinced in Table 3, Equation 16 corroborates the estimations of Equation 7. In all four regressions, b_1 is significant and positive. When *AFTER* is the only covariate considered, the change in *TOTARTFWY* indicated by b_1 of the first specification in Table 3 is found in the manner of Equation 15, namely,

$$\frac{TOTARTFWY_{AFTER}}{TOTARTFWY_{BEFORE}} = e^{0.89} = 2.44 \quad (\text{Eq. 18})$$

This means that *TOTARTFWY* after the freeway opening increases by a factor of 1.44, or 144 percent, with population not held constant, across a 6-mile parallel band. When population is accounted for, as in the fourth specification, the construction of a new freeway still represents a 90 percent increase in total traffic volume. This result is depicted in Figure 8.

Estimate 3. Induced-Travel Model with Addition of Freeway Segment

As discussed above, in order to show Downs's Law, we need to show that the addition of freeway segments either have no effect or a negative effect on arterial street traffic volumes. In all four specifications presented in Table 4, the addition of a freeway segment has no impact on the sum of substitute arterial street traffic counts, as evidenced by the near-zero values of b_1 . In all of these outcomes, the results are clear: the addition of a freeway segment does not result in an increase in arterial street traffic volume, thus confirming Downs's Law of Peak-hour Traffic Congestion.

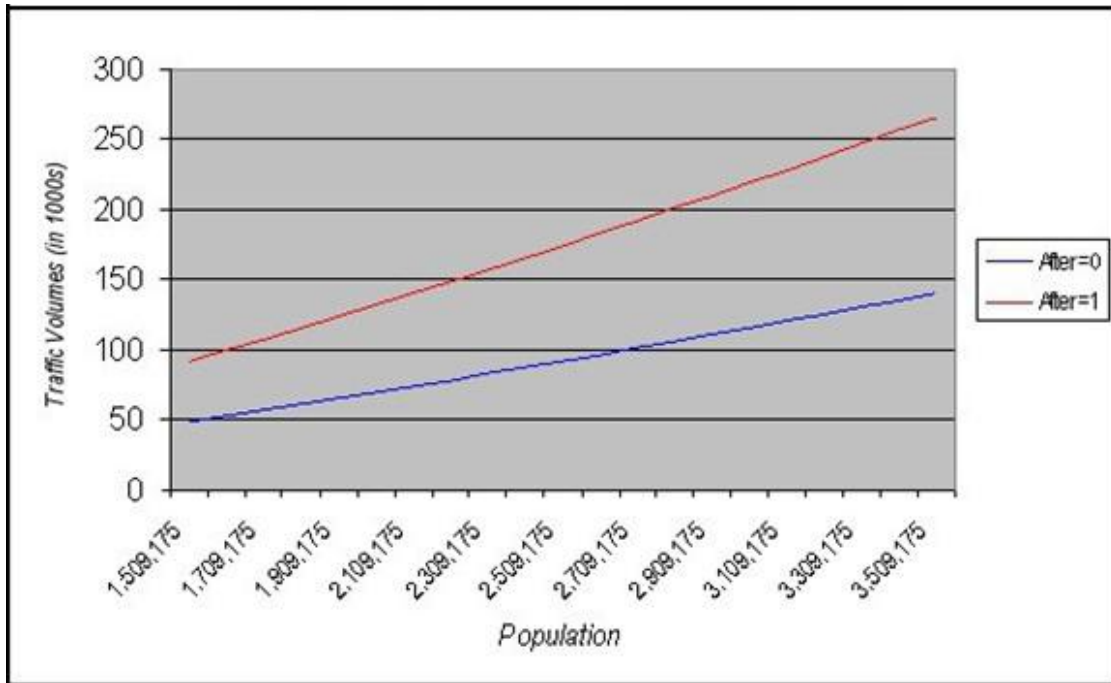


Figure 8. Predicted Traffic Volumes – Induced Travel (2).

Table 4. Downs’s Law (3)

Downs’s Law (3)		Dependent Var: $\ln(TOTART)$				F-Value	R^2
		b_0 (Intercept)	b_1 (AFTER)	b_2 $\ln(POP)$	b_3 $\ln(TOTMILES)$		
1	Estimate	4.30*	0.16	N/A	N/A	1.25	0.01
	t Value	55.14	1.12	N/A	N/A		
2	Estimate	1.50*	-0.12	N/A	0.65*	14.77*	0.14
	t Value	2.82	-0.85	N/A	5.30		
3	Estimate	2.06*	-0.13	-0.58	0.93*	9.99*	0.14
	t Value	2.15	-0.92	-0.71	2.24		
4	Estimate	0.70	-0.07	1.17*	N/A	12.21*	0.12
	t Value	0.93	-0.47	4.80	N/A		

*Denotes estimate significant at the 95% confidence level.

Valuation

The cost per vehicle-mile of trips taken is less than or equal to the value the drivers place on making the trip. Conversely, the cost per vehicle-mile of trips not taken is greater than the perceived value. If a number of vehicles per year do not make the trip because a freeway is not present, and if we know the overall cost per vehicle-mile that the drivers consequently do not spend, then this cost is at least just greater than the value that these drivers placed on taking the trip. In other words, this cost is the minimum possible value of the value that these drivers placed on taking the trip.

We can start to obtain this value by using the second model and Equation 16 to predict the total amount of traffic flowing in a given area with and without freeways. We do this by taking the traffic load as it is today, with the freeways that we have today, and then using the model to predict what the traffic would be today without freeways, but adjusted for the increase in population and other confounds. We then use the difference between the two traffic volumes to get an idea of what the value of today's freeways are, using the published statistics for the value of a trip.

As seen in the fourth specification in Table 3 and its associated discussion, estimation of Equation 16 predicts a 90 percent increase in traffic flow over bands of arterial streets when a freeway is placed as a central band (as in Figure 6). Thus, if we were to never have built the freeway in a typical 1- by 6-mile area in Figure 6, the population-adjusted average daily traffic flow, as predicted by our model, would not have reached the present-day 254,435 daily vehicles, but would have stayed at 134,162, representing 120,273 vehicles per day or 43,899,753 vehicles per year that would not have made the trip.

Using U.S. Department of Transportation (USDOT) statistics on personal consumption expenditures (USDOT 2010) and the Federal Highway Administration's Highway Statistics (FHWA 2008), we find that the estimated 2006 cost per vehicle-mile for automobiles was about 37 cents.⁶ At the time of this research, data for trucking, which was no more recent than 2001 (USDOT 2003), gives the estimated cost for trucks as \$2.25.⁷ Additionally, the same source shows that approximately 92.5 percent of traffic consists of autos and the remainder for trucks. Thus, the minimum value to these drivers of their trips, which is to say the annual benefit of a mile of freeway, can be calculated as:

$$\text{Benefit} = \left(0.925 \times 43,899,753 \frac{\text{veh}}{\text{yr}}\right) \times \frac{\$0.37}{\text{veh-mi}} + \left(0.075 \times 43,899,753 \frac{\text{veh}}{\text{yr}}\right) \times \frac{\$2.25}{\text{veh-mi}} = \$22,432,774 \text{ per mi per yr}$$

According to MAG, the average cost per lane-mile of a freeway segment is \$12,000,000 (Loudon, Connors, and Herzog 2004).⁸ On an average six-lane freeway, this amounts to

⁶ \$1,028 billion in expenditures divided by 2,784 billion vehicle-miles of travel.

⁷ \$467 billion in expenditures divided by 208 billion vehicle-miles of travel.

⁸ This paper estimated a cost of \$3.7 billion for adding 490 lane-miles to the Phoenix urban freeway system in 2003. Given a 50 percent increase in highway construction costs since then, a cost of \$12 million per lane-mile is estimated.

\$72,000,000. With a design life of 20 years, we have an average yearly cost of \$3.6 million. This amount is clearly far less than the economic benefit of over \$22.4 million. Thus, the annual mobility benefit of constructing a new freeway segment is approximately six times larger than the cost.

Conclusion

As stated at the beginning of this paper, many freeway users complain that new freeway segments fill up with traffic immediately after they are constructed. This phenomenon would seem to diminish the advantages of reduced costs and reduced driving time that would make freeways theoretically superior to arterial streets. According to previous literature, however, this phenomenon is to be expected and is not an indicator of the efficiency or inefficiency of having new freeways. Due to Downs's Law of Peak-hour Traffic Congestion, we expect newly completed freeways to experience peak-hour congestion simply because they do offer superior benefits to roadway users compared to the alternative arterial streets. Discerning drivers choose to enjoy these benefits. Another phenomenon cited in the literature review is that of induced travel, which states that, with the reduction in travel time gained by using freeway segments, more commuters can be expected to choose to travel on them than otherwise would. This, of course, will result in a higher flow of traffic between a given origin and a given destination.

When Downs's Law works synergistically with the phenomenon of induced travel, more vehicles can be accommodated in a given geographical area, thus increasing the total number of trips taken. This result adds to the overall value of our transportation system, since, after all, the value of that system is predicated on its ability to facilitate increased volumes of travel.

The process of valuating a freeway by an economic analysis is nicely validated by a section of the Federal Highway Administration's (FHWA) Procedural Guidelines for Highway Feasibility Studies, which is based, in turn, on guidance from the Office of Management and Budget. The Guidelines state, "Economic justification is typically a baseline consideration and the most important element in a feasibility study." The document proceeds to name a "benefit-cost analysis" and, particularly, "non-monetary but quantifiable considerations" as two "most important points to keep in mind during the study of economic justification" of a facility or strategy. It is this last item that this paper has sought to fulfill.

This paper is clearly founded on the conditions that drivers in an area of interest have unmet demand for mobility, are free to choose whether to drive or not and by what routes, and do not already have reasonably convenient, alternative roadways near the newly opened freeway. Surely these conditions affect the applicability of the principles of latent demand and induced travel and, accordingly, affect the monetary valuation that the methods of this paper would ascribe to each mile of new freeway, based on the cost to the driver of trips not taken because of freeways that were not constructed. Through our analysis of Maricopa County traffic count data, we have shown that Downs's Law, latent demand, and induced travel, previously validated in the references, are indeed present on Greater Phoenix freeways. Even when we account for changes in the local population, we are able to show a significant increase in traffic volume. At the margin, this increase in traffic volume accounts for a net benefit of over \$18 million per year for a given mile-long stretch of roadway. Over any reasonable design-life, this benefit will far exceed the \$72 million needed to construct that mile of freeway.

Of course, the reader is always free to temper the valuation of a particular new local freeway according to his estimation of the parameters governing the particular drivers who may proceed to congest it. The paper at least succeeds in providing a basis for the valuation. It also points the way to further study that could include testing the effects of further confounding factors on our

regression model, considering hourly variations in traffic, estimating the model at various stages of long-term traffic equilibration, and comparing estimates of the model with real-world traffic data in various locations.

Ultimately, any evaluation of the freeway system must take into consideration the explicit *and* implicit benefits of the system. We know that congestion is going to be present whether new freeways are constructed or not. Before freeway segments are constructed, the existing arterial streets are congested. After the completion of freeway segments, some drivers shift from arterial streets to the new freeway. This relief lessens traffic on the arterials, leading to more drivers taking trips they previously avoided (i.e. induced travel). Even though congestion is an inevitable condition, even on newly constructed freeway segments, freeways still offer a clear net benefit. The debate over building freeways to alleviate congestion is trumped by the overwhelming truth that, after freeways are constructed, more of the population can travel. If mobility is valued, the net benefit of new freeways suggests that they should be built where it is reasonably feasible to do so.

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