

VCI, A Regional Volume/Capacity Index Model of Urban Congestion

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ABSTRACT

This paper proposes a simple model of *regional* average congestion delay, as a closed-form, differentiable function of published regional transportation system volume and capacity. Three initially undefined parameters are calibrated by regression to best match the regional congestion delay estimates of TTI's "Mobility" analysis of 85 US urban regions. The model fits the TTI delay data quite well with goodness of fit parameter, $Ra^2 = 86\%$ and standard error of regional average congestion delay estimate, 0.046 minutes/mile.

The model is analytic, that is, a differentiable algebraic form as opposed to discrete data tables. This property makes possible simple closed form estimates, applicable to any urban area, of several region descriptive statistics of interest, derived with numeric examples, including:

- 1) Regional total and average congestion delay for a region not in the TTI ensemble;
- 2) Marginal congestion benefit of freeway lane-mile capacity addition; and benefit/cost;
- 3) Capacity addition necessary to improve the region to match congestion delay of the Median congested US city (Memphis);
- 4) "Marginal external cost" (delay) of congestion imposed on all other vehicles, per vehicle-mile of added volume;
- 5) The Volume-Capacity index "point of diminishing return" beyond which further capacity addition would cost more to build than it would return in congestion delay savings, and the potential net long-term savings of building to that point of "Least-Total-Cost"
- 6) The economic implications of a hypothetical national "Build-Our-Way-Out" program which would eliminate all "excess" urban congestion which is costing us more than would the additional capacity to eliminate it.

KEYWORDS

congestion, regional congestion, external cost-of-driving, diminishing return, "build-our-way-out", least-total-cost.

1. INTRODUCTION

Most transportation analysts and planners are familiar with the fact that congested speed or delay on any *short uniform segment* of roadway with no downstream bottleneck can be modeled as a simple power-law function of the segment Volume/Capacity ratio, where segment volume and segment capacity are expressed in vehicles per hour. This simple “BPR function”, dating from the Bureau of Public Roads era 50-60 years ago, with but minor modifications, is still today, at the heart of most of the traffic models that are key to urban traffic planning in most modern cities.

Less well known, is that it is possible to define a similar simple algebraic function of *Regional Volume* and *Regional Capacity*, V_r and C_r , vehicle-miles/day, (the “r” denoting “regional”) suitably defined in terms of regional transportation properties published annually by the US DOT for all US Urbanized areas. Such a model can provide a surprisingly accurate estimate of regional average or aggregate congestion for entire urbanized areas such as New Orleans or Los Angeles. The development, calibration, evaluation and use of that simple Regional Congestion model is the subject of this paper.

Since 1982, the Texas Transportation Institute [TTI] has — more-or-less annually — compiled from the HPMS database [HPMS 2003], the traffic volume and capacity data for every segment of every principal road for each of the 85 or so U.S. urban areas that constitute their representative city ensemble, and from them, compiled and published the regional congested volume, capacity, average speed, and travel-time delay.[TTI]

The TTI data uniquely has served a critical need in quantifying the steady decay of urban mobility over those two decades, providing a yardstick and explanation of our deteriorating urban mobility. While travel demand, (vehicle-miles per day) has grown 103%, our roads capacity (lane-miles) has grown only 44%. As a direct result, the average Volume/Capacity ratio grew by 1.4 times and estimated national average regional congested travel time delay (minutes per mile) by approximately 2.7 times.

Valuable as it has been, the TTI data has some significant shortcomings. The published results apply only to the 85 or so urban areas analyzed by TTI. Many outside that relatively small sample could benefit from the analysis. Even for those chosen TTI urban areas, there is no obvious way to calculate the incremental benefit and benefit/cost ratio of capacity improvements short of essentially reiterating the entire laborious TTI process with incremental changes in the volumes and capacities. The basic methodology has not been explained in the detail necessary to support independent replication, is subject to frequent minor methodological changes from year-to-year and may contain some unexplained, possibly subjective factors. For example, the regional delay due to traffic incidents is modeled as a regional “incident-to-recurrent-factor” times calculated regional recurrent delay, with the “factor”, ranging from 0.6 to 2.5, and derived by a methodology explained only as “developed by FHWA, based on the design characteristics and estimated volume patterns” of the region [TTI 2005, Appendix. B-12].

While, “4-step” travel models used by many of the larger agencies can address those problems, those analyses are expensive, time consuming, error prone, seldom understood by planning decision makers, and consequently widely mistrusted.

One feels there must be a simpler, more understandable way of putting those valuable TTI results to better use in the urban transportation planning process. This paper offers a way to do so. We start by postulating a physically reasonable parametric model of regional average

congestion delay as a function of a few published, readily available regional explanatory variables:

- **regional roads volume:** V_r , vehicle-miles per day, (DVMT), from HPMS [HPMS 2003] for Interstate, Freeway, and Principal Arterial class roads and
- **regional roads capacity:** C_r , a simple multiple of freeway, interstate and principal arterial lane-miles [HPMS 2003] , and
- **optionally, regional transit usage:** person-miles/day, available from the National Transit Database, [NTDB 2005])

We estimate or calibrate the model parameters by regression, to best match the TTI estimates of regional congestion delay for the 85 TTI urban areas ensemble. [TTI 2005]

The result is a simple algebraic formula that estimates regional congestion delay of any regional multimodal transportation system with a goodness of fit parameter (coefficient of multiple determination), R_a^2 of 86% (sometimes called 86% accuracy), and standard error of estimate of 0.05 minutes/mile, a usefully good fit.

We then illustrate the utility of the result in estimating the following descriptive, often discussed, but seldom evaluated, regional performance statistics:

1. Regional travel delay and ranking of a region not included in the TTI ensemble;
2. Expected value in terms of travel-time saving and long-term benefit/cost ratio of an incremental candidate freeway lane-mile expansion;
3. Marginal external cost of congestion imposed on other vehicles by the incremental vehicle-mile addition of regional traffic volume;
4. Amount and cost of additional capacity (freeway lane-miles) to improve any given congested region to a congestion level equal to that of the median congested US urban area (New Orleans);
5. Critical volume/capacity ratio, or point-of-diminishing-return, beyond which building more road capacity would cost more than it would return in time-savings (marginal benefit/cost ratio less than 1.00) and long-term savings of building road capacity up to that “least-total-cost” level.
6. Net Impact of a national “Build-Our-Way-Out” policy to eliminate all “excess” urban congestion that is costing us more than the cost of eliminating it by building sufficient additional freeway capacity.

2.THE VCI MODEL

2.1 PARAMETRIC MODEL

For this model, the dependent variable is the Regional Average Congestion Time Delay, TD, (hours per mile) for road travelers. Following TTI [TTI 2005] we define delay as travel time relative to 60 mph for interstates and freeways and relative to 35 mph for other principal arterial streets. This provides, arguably, the best single number, quantitative measure of regional

congestion. Multiplied by regional traffic volume, V_r and by Value-Of-Time, it gives the principal component of total regional cost of congestion.

Transit impacts travel time in two countervailing ways, 1) benefit to road users by volume of automobile traffic removed from the roads, and 2) detriment to transit users of significantly longer travel time. Preliminary exploration considered the effect of transit in reducing the road traffic volume V_r , (vehicle-miles/day) by an amount $K_t \times V_t$ (where V_t is the transit volume, person-miles/day removed from the roads, and K_t , an unconstrained parameter to be calibrated. We found the parameter K_t was ill-determined and had an insignificant effect on the overall goodness of fit, R_a^2 . Consequently, the transit term was dropped from the model.

We postulate the physically reasonable functional form of a parametric congestion delay model, resulting in:

- 1) a dimensionless regional Volume-to-Capacity Index, VCI;
- 2) the regional average specific congestion time delay; TD; hours/mile as function of VCI, and
- 3) the regional total vehicular delay, TTD, vehicle-hours/day.

In a nutshell, the postulated regional VCI model is this:

$V_r = DVMT$ $C_r = C_n (FLM + K_a ALM)$ $VCI = \frac{V_r}{C_r}$ <p style="text-align: center;">then,</p> $TD = K_d (VCI)^{K_e} \text{ hours/mile}$ $TTD = V_r TD \text{ vehicle-hours/day}$	1)
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where

$V_r = DVMT$, the regional average daily vehicle-miles traveled, vehicle-miles/day of the principal urban regional highway system comprising Interstates, Freeways, and Principal arterials, from HPMS [HPMS 2003]. Note that the *regional* volume and capacity properties V_r , and C_r , (veh-mi/day) while closely related are not to be confused with the *link* properties, V and C (veh/day) as commonly defined. V_r and C_r may, in fact, be viewed as the summation or integrals of link C over the entire length of the regional principal road network.

C_n is a normalizing constant defined initially as = 15,434 [veh-mi/day/ln-mi] so that VCI has tangible significance as “*relative to the US median congested urban area, Cincinnati*” (varies slightly from year to year); this makes the median VCI about 1.000,

FLM is Urban Regional Interstate and Freeway lane-miles, [ln-mi] FHWA functional categories 11, 12, from HPMS,. [HPMS]

ALM is Urban Regional Principal Arterial lane-miles, [ln-mi] functional category 14, from HPMS.

K_a , K_d and K_e are three initially undefined parameters to be determined by calibration, “estimating the model” in section 2.2 following.

TD , Congestion Time-Delay, is the regional average specific congestion Time-Delay, [vehicle-hours/vehicle-mile].

TTD is the regional *total* daily congestion time delay, [vehicle-hours/day] .

The three regional property or explanatory variables, V_r , FLM , and ALM are readily available, annually, for all defined US urbanized areas, from the “Highway Performance Monitoring System” database [HPMS 2003 and later].

The overall rationale for this particular model prototype is the result of a cut-and-try effort, over several years, guided by knowledge of what we do know about congestion, aimed to find the most *efficient* functional form, that is, that best fits the TTI delay estimate, with the smallest number of unknown parameters, specifically, maximization of R_a^2 , the coefficient of multiple determination, R^2 , adjusted for degrees of freedom.

The power law form of the delay function of VCI is reminiscent of the “BPR” function widely used in most four-step models for speed or delay of homogeneous (uniform) road segments, but was arrived at independently for this application by comparison with literally several thousand other simple functional form candidates.¹ In the end, the merit of the model will be measured by how well or poorly it manages to fit or predict the national TTI calibration data with this small number (3) of degrees of freedom.

2.2 MODEL PARAMETERS

To calibrate the three parameters, K_a , K_e , K_d , we need a database of the three real-world regional explanatory variables, (DVMT, FLM, and ALM) and TD (regional average specific congestion time delay, hr/mi) for a large number of representative urban areas. At present the only — and default best — known suitable source of such data is the Texas Transportation Institute (TTI)’s annual “Urban Mobility” project reports [TTI 2005].

2.2.1 TTI Data. TTI derives their regional average annual congestion delay, DEL (person-hours/year) estimate for each of 85 major urban regions by a laborious aggregation process, originally set forth by Lindley [Lindley 1986], extracting the roadway properties (Annual Average Daily Travel, AADT), segment length (typically less than a mile), number and properties of lanes, etc.) for each segment of each regional roadway from HPMS [2], calculating segment capacity by the “Highway Capacity Manual” [5] methods, estimating average speed and travel time for each such segment and finally summing segment volumes and delays over all (hundreds to thousands) of such segments for final estimates of total average regional volume and delay for each of the 85 analyzed urban areas. TD (veh-hr/veh-mi) is simply derived from TTI’s DEL (person-hours/year). Specifically,

$$TD = DEL / (AVO V_r DPY)$$

where $AVO = 1.25$ ps/veh,

$V_r = DVMT$; and

$DPY = 250$ congested days/yr all as per TTI [TTI 2005].

¹ Thanks to an excellent commercially available program NLReg© that attempts to fit a given table of data with several thousand different functional forms and return a ranked list of candidates.

While the overall TTI process is reasonable, there is cause to question some of the methodology details. Nevertheless, it remains the only, and default best, measure of overall national regional congestion of sufficient scope for the present purpose.

2.2.2 The Future — Traffic Sensors. Many of our larger urban regions are currently developing loop sensor networks, with magnetic proximity sensors buried in the pavement every half mile or so, in principal capable of providing more accurate measured values of vehicle count and speed on major highways. In California, such data are collected in real-time on most interstates and freeways statewide, and archived in the “PEMS” [PEMS] system that supports on-line data retrieval and analysis including regional aggregate delay calculations.

Unfortunately, as of today, most such data collection and archiving systems nationally are non-standardized, and appear almost universally to be plagued by reliability problems that limit their applicability to the present modeling effort. TTI is understood to be working toward replacing their dependence on HPMS data and present complex and ill-defined procedures based on HPMS data with such sensor system data. It is anticipated that within a few years it may be possible to replace the HPMS data and current TTI methodology for this purpose with more accurate actual sensor measurements.

In the meantime we will proceed to calibrate the model (or, “estimate the parameter set”) with the TTI / HPMS based data as a placeholder and to illustrate the potential of the VCI congestion model.

2.3 CALIBRATION RESULTS

Table 1 is the relevant TTI database from the (TTI 2005) based on 2003 HPMS data used for the non-linear regression. The resulting best fit (least-squared residuals) model constants are:

$$\begin{aligned} C_n &= 15,434 && [\text{veh-mi/day/ln-mi}] \text{ (by definition)} \\ K_a &= 0.368 && [\text{dimensionless}] \\ K_e &= 3.115 && [\text{dimensionless}] \\ K_d &= 0.00338 && [\text{hr/mile}] \text{ (=0.203 min/mi)} \end{aligned} \quad 2)$$

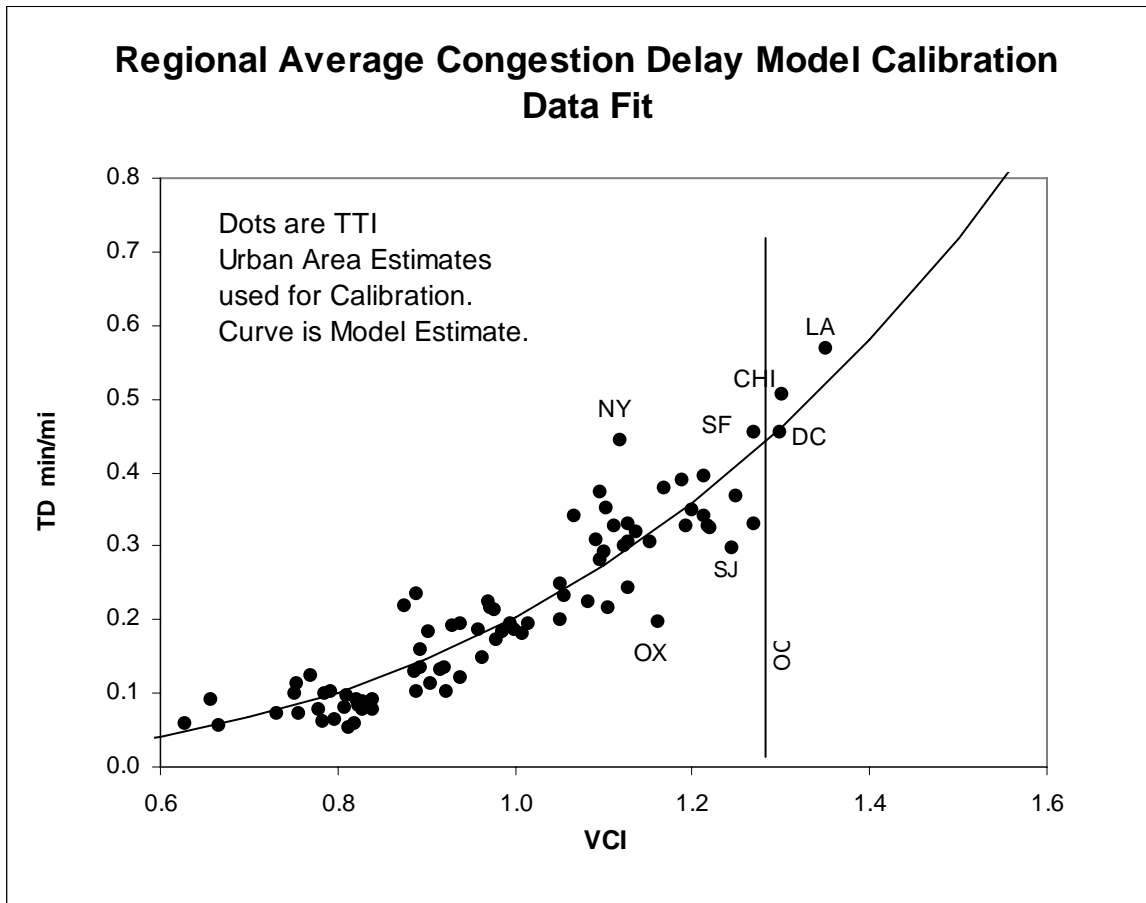


Figure 1. Calibration Fit

Figure 1 is a scatter plot of the 2003 TTI regional average congestion time delay data, TD, minutes per mile with the corresponding VCI Model estimate, the smooth curve. Here, each dot represents one of the 85 cities in the TTI ensemble and the curve is the VCI Model with the above calibrated fit parameters.

Other properties of the regression are:

Number of observations (urbanized areas)	85
Goodness of fit, R_a^2 adjusted for 3 degrees of freedom	86%
Standard Error of delay fit	0.046 min/mile = 2.8 Seconds/mile

All three fit parameters are statistically significant at the 98% or better confidence level, (all $|T| \geq 4$).

The significance of this is that:

given the regional explanatory statistics: Vr, FLM, and ALM, we can now estimate the regional average congestion delay, minutes per mile, as would be estimated by TTI, with generally insignificant error, as shown graphically in Figure 1 and statistically in the Standard Error of estimate, 0.04 minutes/mile and in the much more powerful form of a simple, analytic, differentiable function.

3. APPLICATIONS OF THE MODEL

We next consider several useful applications of the model, that are the principal motivation of this exercise. Most of these are made possible by the analytic, (i.e. differentiable) form of the model (as opposed to tables of numbers). A self-sufficient spreadsheet explaining, detailing, and source referencing all these example calculations is attached as Table 2 (p.19). Copying it for frequent reference as one proceeds through this next section may be helpful for best understanding. A glossary is included as section 5.

3.1. Power Law Implication

Perhaps the simplest significant implication of this model is the finding that *regional* congestion and its cost follow closely a simple power law function of the regional volume/capacity ratio, V/C, with power exponent, $Ke \approx 3.115$. This has an important implication with respect to the effectiveness of small capacity increases. From eq. 1,

$$\begin{aligned}
 TD &= Kd \left(\frac{Vr}{Cr} \right)^{Ke} \\
 \Delta TD &\approx \frac{\partial TD}{\partial Cr} \Delta Cr \\
 &\approx Ke \frac{-TD}{Cr} \Delta Cr \\
 \frac{\Delta TD}{TD} &\approx -Ke \frac{\Delta Cr}{Cr}
 \end{aligned}
 \tag{3)$$

In other words, a given percentage increase in roads capacity is expected to yield a Ke (≈ 3.115) times greater percentage reduction in congestion time delay; for example, a 2% capacity increase would be expected to yield a 6.2 % reduction in congestion. In this context, $-Ke$ may be seen as the “elasticity” of congestion delay with respect to regional capacity.

3.2 Congestion Delay Estimates for non-TTI Regions

Orange County (CA) is officially part of the Los Angeles Urbanized Area. As such it might be expected to share the dubious distinction of worst congestion in the nation but it is not treated separately in the TTI rankings, and is operated under a separate transportation agency, OCTA.

With the VCI Model we can estimate Orange County independently. Fortunately, the HPMS roads data include both Urbanized Area and County fields so data can be extracted either as part of the Los Angeles urbanized area, or separately as a county. Using 2003 HPMS data we find VCI and regional average specific congestion delay, TD min/mile for the two cases

LA: (VCI = 1.343, TD = 0.509 min/mi)

OC: (VCI = 1.286, TD = 0.445 min/mi).

The calculation of these results is explained in detail in Table 2.

Orange County is thus just slightly better off in terms of Volume/Capacity Ratio (VCI) and average Congestion Time Delay (TD) than Los Angeles and would rank at about the sixth percentile from worst nationally within the 85 TTI regional rankings in Table 1. For the Orange County example the estimated total aggregate congestion travel time delay, TTD is 397,000 vehicle-hours per day or 99 million vehicle-hours/year, (Table 2).

Even if there were no growth, and congestion got no worse, but the system is no better than it is now, the estimated Present Value (PV) of the 30-year lifetime congestion time delay cost would be \$37.8 Billion 2003\$ for Orange County and 169 Billion 2003\$ for Los Angeles UA (Table 2).

3.3. Marginal Congestion Benefit of Capacity Addition

From a strictly economic viewpoint, the primary benefit of adding freeway lane-miles is the reduction of Total Travel Time Delay, TTD [veh-hr/day] and its associated cost, $VOT \times TTD$. Other lesser savings, energy, pollution, accidents, and psychological impacts are ignored for the present.

For relatively small freeway lane-mile increments, ΔFLM , the resulting increment of total daily regional travel-time delay, ΔTTD , [veh-hr/day], is proportional to ΔFLM with coefficient the partial derivative of TTD with respect to FLM. Since the model gives TTD as a differentiable function of FLM, this is given directly by:

$$\begin{aligned} \Delta TTD &= \frac{\partial TTD}{\partial FLM} \Delta FLM \\ &= - \frac{K_e TTD}{(FLM + K_a ALM)} \Delta FLM \quad \text{veh - hrs / day} \\ &= 459 \Delta FLM, \text{ for Orange County today} \end{aligned} \tag{4}$$

The corresponding Present Value Benefit of this annual delay reduction, is

$$PVB = -CCC TTD \tag{5}$$

where we define

$$CCC = PVf VOT DPY = 95381 \text{ \$/ (veh-hr/day)}.$$

$PVf = PVf(N, I)$ = "Present Value factor", (years), the Present Value of an N year unit annuity, at real interest rate, I (accounting for interest and inflation). Under the capitalization assumptions in Table 2, $PVf = 19.6$ years.

$$DPY = \text{Congested Days Per Year} = 250 \text{ per TTI usage.}$$

VOT (Value Of Time) assumption, following TTI, is a composite of 95% personal travel at \$13.40/hr and 5% commercial at \$71.05/hr, for a composite \$19.47/hr as per Table 2.

For the Orange County example, the annual time savings per added freeway lane-mile evaluates to 114,750 [veh-hr/yr/fwyr ln-mi], annually, for the lifetime of the system, yielding a Present Value Benefit of \$43.8 [million 2003\$ per fwyr-ln-mi].

This can now be compared to the *cost* of building an average freeway lane-mile, recently averaging 12.5 [million 2003\$ per ln-mi] (source: Caltrans District 12), for a benefit/cost ratio (B/C) of 3.5:1 on the average, for Orange County.

3.4. The External Cost of Driving

On a congested roadway, the presence of each vehicle on the road contributes incrementally to the total congestion delay and thereby to the total cost of delay of the trip for all other vehicles. Some economists argue that in order to avoid “tragedies of the commons” and maximize societal economic efficiency, a toll should be imposed such that each vehicle’s own marginal trip cost, that is, (marginal cost of driving + cost of own delay plus toll) is equal to or greater than the (total incremental cost of *external delay* its presence imposes on *all* other vehicles). This would discourage low value trips worth less to the driver than the costs his trip imposes on society, and thereby maximize the total net *societal benefit* from the limited roadway capacity. This has been stated as an argument for toll road pricing.

The condition for “efficient toll” then is:

$$\begin{aligned} \text{“efficient toll”} &\geq \text{total cost of external delay imposed on others} \\ &\quad - \text{cost of own delay} \\ &\quad - \text{own marginal cost of driving (fuel etc).} \end{aligned} \quad 6)$$

Because any incremental added volume will generally cause diversions of traffic in time and place, the marginal trip may impact hundreds or thousands of other drivers in varying degrees at other times and places. For this reason one might expect that the *total* external delay to all other drivers cost could be very high and dominate the right side of this inequality. However, there have been few if any valid estimates of it and the issue is illusory. These very traffic diversions in time and place make a direct approach to the problem practically incalculable. In practice it would seem the best that could conceivably be done (or be of any practical use) is to deal with *expectations*, e.g., the expected impact of an “average” marginal addition of one vehicle trip /day, distributed in place in proportion to the existing volume. The VCI model, by dealing with the *total* cost of congestion, and being in the form of a differentiable function conveniently provides exactly that result.

Each vehicle-mile traveled by the marginal vehicle is a unit (1 veh-mi/day) increment of volume, V_r . The marginal *total* (over all vehicles) aggregate delay increment, ΔTTD , veh-hrs/day, caused by that unit volume increment is then given directly by the partial derivative of Total Travel Delay, TTD with respect to V_r , i.e., differentiating equation 1):

$$\begin{aligned} \Delta TTD &= \frac{\partial TTD}{\partial V_r} \Delta V_r \text{ (veh - mi / day)} \\ &= (1 + K_e) CTD \Delta V_r \text{ (veh - hrs / day)} \end{aligned} \quad 7)$$

The “1” inside the parenthesis here may be identified as that part of the aggregate delay suffered by the marginal vehicle *itself*, i.e., the Marginal *Internal* Delay, ΔMID . The rest, i.e., “ $K_e TD$ ”, is the total (over all drivers, times, and places) *external* delay, ΔMED , imposed on others:

$$\Delta MED = K_e TD \Delta V_r = 3.11 TD \Delta V_r$$

Thus the efficient toll condition reduces to

$$\text{Efficient toll} \geq \text{VOT (Ke-1) TD} - \text{COD}$$

where VOT (Ke-1) TD = \$0.305 /veh-mi for the near-worst-case Orange County example (Table 2 row 40)

COD = Cost-Of-Driving, fuel etc. recently estimated by AAA [Ref AAA] at \$0.52 / veh-mi

so that the efficient toll criterion finally boils down to

$$\text{Efficient toll} \geq = - \$0.21 / \text{veh-mi}$$

So even without any toll, the average driver's internal cost of driving *already* exceeds the external congestion cost he imposes on others, and the toll necessary for "optimal economic efficiency" is *less than zero*. In short, the economic efficiency issue is, on the average, irrelevant to "optimal tolling".

Since TTD is the Total Time Delay summed over all time and place, the above external cost calculation inherently includes, as it must, the regional impact on all drivers at all places and times in that same day. With respect to the place and time of occurrence of the marginal trip itself, this calculation implicitly assumes the marginal unit of volume is likewise distributed in time and place in proportion to the regional traffic volume, V_r , itself. In other words, it is a unit increment of *expected* total volume. Peak hour, or, worst place trips would be more expensive, off-peak trips less expensive. Thus, the above discussion does not preclude that there may be times and places where tolling or congestion pricing is supported by economic efficiency arguments, but they would appear to be exceptions. Bridges and narrow canyons which preclude the implicitly assumed free diversions are probable such exceptions.

3.5. The "Point of Least-Total-Cost"

In subsection 3.2 above we calculated the average benefit/cost ratio, (B/C), for added freeway lane-miles for Orange County and found it in the neighborhood of 3.5:1. Clearly, however, if we were to build more and more system capacity, reducing VCI and delay indefinitely, there must be a point of diminishing return, beyond which, it would be *less costly to suffer the remaining congestion than build the road capacity to further reduce it*. That could be called the point of Diminishing Returns or Least-Total-Cost, (LTC).

Counting only personal and commercial time delay savings as the largest element of cost (ignoring accidents, insurance, noise, emissions, psychological trauma etc. (which, however, generally vary hand-in-hand with time delay) the total generalized regional cost of travel, TGC, may be expressed as the sum of the cost to build the system expansion plus the cost of change in travel time delay.

$$\text{TGC} = (\text{Cost to build}) + (\Delta \text{ Cost of Delay})$$

Considered as a function of freeway lane-miles, FLM, (generally the most cost effective controllable independent variable), the total generalized cost, TGC can be expressed

$$\text{TGC} = \text{CFLM FLM} + \text{CCC } \Delta \text{TTD} \tag{8}$$

where CFLM is the average cost of building a freeway lane-mile, and for clarity we have lumped several constants not involved with FLM into one:

$$\text{CCC} = \text{PVf DPY VOT} \quad [\$ / (\text{v-hr} / \text{day})].$$

In order to add or compare one-time and recurring costs, we have expressed both cost components in terms of Present Value, PVf being the present value of a unit lifetime annuity (see Table 2).

Since the cost-to-build is monotonic increasing with FLM and cost-of-delay is monotonic decreasing, there is one and only one minimum of TC, which is the point of Least Total Cost, (LTC).

This point, being an extremum, must satisfy

$$\begin{aligned}
 0 &= \left. \frac{\partial(\text{TC})}{\partial \text{FLM}} \right|_{\text{LTC}} = \text{CFLM} + \text{CCC} \left. \frac{\partial \text{TTD}}{\partial \text{FLM}} \right|_{\text{LTC}} \\
 &= \text{CFLM} - \frac{\text{CCC } V_c \text{ Kd } K_e \text{ VCI}_{\text{LTC}}^{K_e}}{(\text{FLM}_{\text{LC}} + K_a \text{ ALM})} \\
 &= \text{CFLM} - \text{CCC } K_d \text{ K}_e \text{ C}_n \text{ VCI}_{\text{LTC}}^{K_e+1}
 \end{aligned}$$

Solving for the critical VCI_{LTC} ,

$$\text{VCI}_{\text{LTC}} = \left(\frac{\text{CFLM}}{\text{CCC } K_d \text{ K}_e \text{ C}_n} \right)^{1/(K_e+1)} \quad 9)$$

Notice that this is not dependent on any of the regional properties, it is a universal constant, the same for all regions. For the assumed freeway lane-mile cost, $\text{CFLM} = \$12.5$ million/lane-mile; that evaluates to $\text{VCI}_{\text{LC}} = 0.949$. By interesting but sheer coincidence, this is near the median point of the distribution of the 85 TTI urban areas ensemble in Table 1, $\text{VCI} = 1.000$, characterized by regions like Cincinnati, and Raleigh-Durham.

We will refer to congestion in excess of that at the point of Least-Total-Cost or 0.18 minutes per mile, as unnecessary or “*excess* delay”. Table 2 derives in detail the implications of such a “build-to-least-cost” program for Orange County and for Los Angeles. The Orange County results are, summarized here.

At present Orange County Congestion levels, even ignoring growth, the lifetime total present value of congestion delay would be \$37.8 billion. We estimate that for Orange County to build to point of L would require:

Building:	958 more lane-miles of freeway;
at a building cost of	\$12.0 billion, but
returning gross travel time savings PV of	\$23.2 billion,
for a net total Present Value benefit of	\$11.2 billion.

All dollar figures are present-value, based on assumed real interest (actual interest minus inflation) of 3% p.a. and expressed in 2003\$. Detailed calculations for Orange County and Los Angeles are shown in Table 2.

3.6. A National “Build-Our-Way-Out” Program

Arguably, as a national policy, we should build all the capacity that can more than pay for itself in congestion cost savings. In other words, we can and should “build our way out” of all “excess” congestion.

What would be the implications of such a national “Build-Our Way Out” policy? What would be the total gross national cost and net benefit?

In the 2006 HPMS data, 419 U.S. Urban Areas (cities) provide the necessary data. One-hundred four (104) of these cities (in 2006 data) had VCI exceeding VCI_{LC} (=0.949) and *excess* delay, totaling 1.2 Billion veh-hrs per year, valued at \$24 billion per year, or a lifetime present value (PV) of \$464 Billion. We estimate that to “Build Our Way Out” of that excess congestion would require:

Building:	22,000 new lane-miles of freeway
at a gross present value cost of:	\$276 billion, but,
returning gross travel time savings PV of:	\$464 Billion
for a Net Total Present Value Benefit of:	\$188 Billion (2003\$).

The overall result may be viewed as a return of $(464/276) = 1.7$ times on investment.

Of course, this rough finding considers only the one, economic, dimension of feasibility. Further, the economic benefits claimed are partly personal and subjective values, not legal tender that can be used to pay the road builder. In our view, however, the central message of these calculations strongly supports the fundamental economic feasibility of some kind of tolling mechanism to convert those personal values to monetary terms, and build-our-way-out of significant urban congestion, to the significant benefit of all.

The full 419 city calculation spreadsheet is on-line at <http://www.urbantransport.org/VCI.Tbl5.pdf> [Ref 10].

4. CONCLUDING REMARKS

The VCI model makes possible simple, reasonably sound estimates of the regional total congestion and economic impacts or benefits of regional capacity or volume additions. It assumes, implicitly, that regions of comparable regional volume/capacity ratio are comparably effective in how they distribute their road building efforts. But that assumption is tested and well supported by the comparison in Figure 1.

As presently calibrated to the TTI Mobility delay estimates, the model duplicates them with a generally negligible standard error of estimate (rms residual error) of 2.7 seconds per mile. The resulting delay estimates, are insignificantly different from the TTI delay estimates. But, of course, neither are they any *better* than that calibration data. As such the specific estimate values and any policy implications herein must be used with care and qualification. The model should be recalibrated (parameters re-estimated) when more reliable loop sensor data becomes widely available.

The ability to produce the essential results of the TTI congestion delay analysis in the form of a simple differentiable (analytic) function, (rather than data table) enables a number of enlightening, simple, closed-form, system descriptors such as marginal cost/benefit estimates of capacity additions, external cost of congestion, point of diminishing return in capacity building, and minimal total cost of (congestion + capacity building) for any urban region. Applied to the total national urban transportation inventory, the example results strongly suggest that there is no fundamental economic reason why we can not “build our way out” of *excess* congestion,

corresponding very nearly to that of the median TTI ranked US urbanized area, and at a significant cost total benefit.

The VCI model is easily calculated from readily available government statistics (HPMS) and is recommended for use by local transportation agencies as a simple, consistent, and more informative, annual congestion management audit in the ongoing battle against regional congestion.

5. GLOSSARY

assumed values in curly braces: { xxx }

AADT: Annual Average Daily Traffic, 365 day year average daily count of Number of vehicles or persons passing a given point on a transportation channel, available HPMS

ALM: Principal Arterial Lane Mile

AVO: Average Vehicle Occupancy

COD: Cost-Of-Driving including depreciation, maintenance, fuel and supplies, but excluding the cost of congestion delay. Recently estimated by [AAA 2006] as \$0.52/veh-mi.

Cr: Regional Capacity = C_n (FLM + K_a ALM) veh-mile/day

CFLM: Cost of Freeway Lane-Mile: Average total cost to design, buy ROW, build, and open a freeway lane-mile. Assumed { \$12.5 million per lane-mile }. Source: Caltrans District 12 (Orange County).

CCC: = $PV_f \times DPY \times VOT$ = Present Value cost of one veh-hr per congested day over the lifetime of a typical roads project { = \$95,380 }

Cn: { 15,434 } [veh-mi/day/ln-mi]. Normalization factor. With this normalization, the VCI congestion index is “relative to the US median congested city, New Orleans”.

TD: Congested time delay, vehicle-hours per vehicle-mile.

DVMT: Regional veh-mi per day.

DPY: Congested days per year, { 250 days/year } in TTI data.

FLM: Regional Interstate and freeway lane-miles, [ln-mi], per HPMS [2].

LTC: Least Total Cost, Equivalent to point of diminishing return, where cost of building further capacity is exactly balanced by savings in congestion cost. With the above model parameters, this occurs at $VCI = 0.949$.

MED: Marginal External Delay. The additional delay (hrs/mile) imposed on all other vehicles by due to the addition of one more vehicle mile/day of regional total travel volume.

MID: Marginal Internal Delay. The additional delay suffered by a vehicle traveling one additional vehicle-mile/day.

KD: Regional average congestion Time-Delay, [hour/mile] $TD \triangleq K_d (VCI)^{K_e}$.

Ka, Kd and Ke: parameters in the travel time delay model, calibrated by regression to best match the TTI congestion delay findings.

$K_a = 0.368$ [dimensionless]

$K_e = 3.115$ [dimensionless]

$K_d = 0.230$ [minutes/mile] = 0.00384 [hr/mile].

TC: Total generalized cost of a roads project = (cost to build) minus (savings in cost of congestion delay)

TD: Regional Average Congestion Time Delay, vehicle-hours/vehicle-mile.

TTD: Regional total (aggregate) time delay [vehicle hours/day] = $V_r TD$.

PVf: Present Value factor of Annuity, the present value of a unit annuity of lifetime, N years with real interest rate i . For the example we assume {lifetime $N=30$, Real Interest rate $i=3\%$, then, $PV_f = 19.6$ yrs}.

UA: Urbanized Area, Census designation for contiguous metropolitan density areas.

Vr: *Regional* DVMT, veh-mi/day. Regional interstate, freeway, and principal arterial highway volume, [vehicle-miles per day] per HPMS [HPMS 2003]. This differs from highway capacity, V vehicles/day.

VCI: Regional Volume/Capacity Index, = Vr/Cr [dimensionless].

VOT: Dollar Value of In-Vehicle Travel Time [dollars/vehicle-hour]. For the examples, following TTI, we assume an average mix of private and commercial traffic, {\$19.5 per vehicle-hour. See table 2}.

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Table 3.a. CALIBRATION DATA

	TTI 2005-03 Data					VCI Calc		
	Fwy In-mi	Pri Art In-mi	Annual Volume	Cong Delay	Annual Delay	VCI	Del*	
URBANIZED AREAS	FLM In-mi	ALM In-mi	DVMT k v- mi/d	DEL min/mi	AD M v- hr/yr	VCI -	DEL FIT min/mi	
Chicago IL-IN	2665	5730.0	95755	0.507	202.3	1.300	0.521	
Los Angeles-Long Beach-Santa Ana CA	5843	11504.0	208941	0.573	499.0	1.343	0.577	
Washington DC-VA-MD	2040	2790	61420	0.455	116.4	1.298	0.518	
San Francisco-Oakland CA	2420	2320	64170	0.456	121.9	1.270	0.485	
New York-Newark NY-NJ-CT	7170	7970	174490	0.445	323.6	1.119	0.327	
San Jose CA	895	1460	28040	0.330	38.5	1.268	0.483	
Atlanta GA	2285	1390	53890	0.369	82.9	1.249	0.460	
Sacramento CA	710	1335	23080	0.299	28.7	1.245	0.455	
Portland OR-WA	715	950	19580	0.327	26.7	1.192	0.397	
Tampa-St. Petersburg FL	675	2500	29935	0.329	41.1	1.216	0.423	
San Diego CA	1860	1930	48395	0.324	65.4	1.220	0.428	
Las Vegas NV	485	495	12485	0.342	17.8	1.212	0.419	
Houston TX	2460	2900	65955	0.395	108.5	1.212	0.418	
Miami FL	1925	5500	72375	0.391	117.8	1.187	0.393	
Detroit MI	1910	4450	65685	0.350	95.7	1.200	0.406	
Denver-Aurora CO	1140	1820	32635	0.380	51.6	1.168	0.374	
Seattle WA	1745	1990	43400	0.321	58.0	1.135	0.342	
Boston MA-NH-RI	2370	2860	58665	0.328	80.2	1.111	0.319	
Oxnard-Ventura CA	355	540	9925	0.198	8.2	1.161	0.367	
Riverside-San Bernardino CA	910	2315	31300	0.308	40.1	1.151	0.357	
Sarasota-Bradenton FL	65	535	4555	0.243	4.6	1.127	0.334	
Baltimore MD	1530	1495	36175	0.331	49.9	1.127	0.334	
Orlando FL	780	1710	24435	0.300	30.5	1.123	0.331	
Minneapolis-St. Paul MN	1590	1325	36110	0.306	46.0	1.126	0.333	
Tucson AZ	245	775	9000	0.294	11.0	1.100	0.310	
Phoenix AZ	1325	3060	41705	0.353	61.3	1.102	0.312	
Philadelphia PA-NJ-DE-MD	2300	4165	63055	0.342	89.8	1.066	0.281	
Charlotte NC-SC	485	515	11405	0.281	13.4	1.096	0.306	
Indianapolis IN	730	1020	18830	0.218	17.1	1.104	0.313	
Austin TX	585	740	14440	0.308	18.6	1.091	0.302	
Dallas-Fort Worth-Arlington TX	3105	4050	77680	0.375	121.5	1.095	0.306	
Salt Lake City UT	530	500	11585	0.250	12.1	1.051	0.269	
Bridgeport-Stamford CT-NY	600	390	12425	0.225	11.6	1.083	0.295	
Louisville KY-IN	720	770	16350	0.234	15.9	1.056	0.273	
St. Louis MO-IL	1785	1570	38280	0.200	31.9	1.050	0.268	
Honolulu HI	415	265	7785	0.184	6.0	0.984	0.219	
Cape Coral FL	45	350	2735	0.190	2.2	1.020	0.245	
Virginia Beach VA	940	1170	21475	0.194	17.4	1.015	0.241	
Jacksonville FL	735	1135	17935	0.180	13.5	1.008	0.236	
Charleston-North Charleston SC	255	420	6280	0.195	5.1	0.993	0.226	
Columbus OH	955	740	18915	0.188	14.8	0.999	0.229	
San Antonio TX	1075	920	21285	0.215	19.0	0.976	0.213	
Memphis TN-MS-AR	MEDIAN	555	1180	14815	0.226	14.0	0.970	0.210

(cont)

Table 3.b. Cal. Data Cont

	TTI 2005-03 Data					VCI Calc	
	Fwy In-mi	Pri Art In-mi	Annual Volume	Cong Delay	Annual Delay	VCI	Del*
URBANIZED AREAS	FLM In-mi	ALM In-mi	DVMT k v-mi/d	DEL min/mi	AD M v-hr/yr	VCI -	DEL FIT min/mi
New Orleans LA	425	955.0	11425	0.182	8.7	1.000	0.183
Raleigh-Durham NC	610	615.0	12620	0.175	9.2	0.999	0.182
Cincinnati OH-KY-IN	1160	1200	24035	0.218	21.8	0.996	0.180
Milwaukee WI	700	1470	17960	0.195	14.6	0.976	0.170
Birmingham AL	675	450	12490	0.149	7.8	0.975	0.169
Nashville-Davidson TN	955	950	19295	0.188	15.1	0.974	0.169
New Haven CT	520	315	9215	0.122	4.7	0.957	0.161
Eugene OR	110	125	2220	0.103	1.0	0.957	0.161
Omaha NE-IA	300	695	7975	0.192	6.4	0.955	0.160
Fresno CA	265	435	6000	0.134	3.3	0.943	0.154
Grand Rapids MI	370	570	8225	0.137	4.7	0.941	0.153
Salem OR	100	290	2885	0.114	1.4	0.938	0.151
El Paso TX-NM	280	765	7740	0.161	5.2	0.930	0.147
Albuquerque NM	330	990	9655	0.184	7.4	0.929	0.147
Pensacola FL-AL	110	575	4400	0.130	2.4	0.919	0.143
Allentown-Bethlehem PA-NJ	395	490	7930	0.136	4.5	0.911	0.139
Providence RI-MA	900	1040	17600	0.236	17.3	0.909	0.138
Hartford CT	790	595	13845	0.103	5.9	0.907	0.137
Colorado Springs CO	290	440	6095	0.219	5.6	0.893	0.131
Spokane WA	140	545	4330	0.083	1.5	0.862	0.118
Dayton OH	550	745	10660	0.080	3.6	0.859	0.117
Cleveland OH	1375	1220	23280	0.088	8.6	0.855	0.116
Oklahoma City OK	785	1040	15100	0.092	5.8	0.854	0.115
Beaumont TX	135	205	2690	0.079	0.9	0.846	0.112
Akron OH	435	480	7740	0.091	2.9	0.837	0.109
Boulder CO	65	100	1270	0.082	0.4	0.833	0.107
Toledo OH-MI	330	550	6655	0.098	2.7	0.830	0.106
Columbia SC	390	345	6525	0.060	1.6	0.829	0.106
Little Rock AR	420	290	6605	0.055	1.5	0.823	0.104
Brownsville TX	45	135	1145	0.064	0.3	0.823	0.103
Springfield MA-CT	445	530	7860	0.064	2.1	0.815	0.101
Pittsburgh PA	1250	1700	22285	0.125	11.6	0.804	0.097
Kansas City MO-KS	1770	930	25780	0.103	11.1	0.800	0.095
Richmond VA	985	900	15950	0.100	6.6	0.799	0.095
Albany-Schenectady NY	550	570	9130	0.080	3.0	0.798	0.094
Buffalo NY	640	1035	11850	0.113	5.6	0.775	0.087
Rochester NY	500	195	6660	0.073	2.0	0.770	0.085
Tulsa OK	700	535	10400	0.100	4.3	0.762	0.082
Bakersfield CA	195	600	4690	0.073	1.4	0.760	0.082
Laredo TX	75	265	1745	0.092	0.7	0.690	0.062
Corpus Christi TX	300	285	4160	0.057	1.0	0.681	0.059
Anchorage AK	195	100	2240	0.059	0.6	0.642	0.050

End Table 1

TABLE 2. Applications
2003 Data

Concise Calculations Summary
3/26/2009

TTI Assumptions Adopted	Dimensions	Name	Value		Source
Value of passenger time	\$/ps-hr	VOTp	\$ 13.40		TTI
AvgVehicleOccupancy	ps/veh	AVO	1.25		TTI
Value of Coml veh time	\$/veh-hr	VOTc	71.05		TTI
Fraction of veh commercial	-	pC	5%		TTI
Wtd avg Value of Vehicle Time	\$/veh-hr	VOT	\$ 19.47		=pC*VOTc+(1-pC)*VOTp*AVO
Congested Days per Year	d/yr	DPY	250		TTI
Financial Assumptions					
Avg Cost of a Freeway In-mi	\$/ln-mi	CFLM	\$ 12,500,000		OCTA
Lifetime	yr	N	30		
Actual Interest p.a.	/yr	Ia	7%		FTA
Inflation p.a.	Inflation	Inf	4%		
Real Interest (adj for inflation)	Real Interest	Ir	3%		= actual interest rate - inflation rate
Present Value factor 30 yr annuity adj for Infl.	yr	PVf	19.60		=(1-(1+Ir)^-N)/Ir
VCI Defined Parameters					
Normalizing factor	veh-mi/d/ln-mi	Cn	15,434		cf: Sect 2.3
Arterial Relative Effectiveness Parameter	--	Ka	0.368		"
Congestion Delay Parameter	hrs/mile	Kd	0.00338		"
Exponent Parameter	--	Ke	3.12		"
Input Data for Orange County\$ LA UZA			Orange Cnty	LA UZA	
Freeway Lane Miles	ln-mi	FLM	1,529	5,843	HPMS 2003
Primary Arterial Lane Miles	ln-mi	ALM	3,163	11,504	HPMS 2003
Total Volume, Fwy + PriArt	veh-mi/day	V	53,461,694	208,941,000	=Vr
Internal Congestion Cost of Driving	\$/mile	ICD	\$ 0.14	\$ 0.17	=VOT * TD
Calculated Results (1)					
Volume-Capacity Index	dimensionless	VCI	1.286	1.343	=V/(Cn*(FLM+Ka*ALM))
Time Delay per Mile	hr/mile	CTD	0.00742	0.00849	=Kd*(VCI)*Ke
Total Time Delay per day	veh-hr/day	TTd	396,519	1,774,831	=Vr*CTD
Total Time Delay per yr	veh-hr/yr	TTY	99,129,834	443,707,862	=TTd*DPY
Annual Cost of Congestion Delay	billion 2003\$/yr	ACC	\$ 1.93	\$ 8.64	=TDy*VOT/1e9
Present Value Cost of Congestn Delay (1)	billion 2003 \$	PVACC	\$ 37.8	\$ 169.3	=PVf*ACC
Marginal Benefit of Freeway Lane-Mile Build (1)					
Marginal annual benefit / flm built	veh-hr/dy/flm	MBy	459	549	=Ke*TTd/(FLM +Ka*ALM)
PV Delay Saving / flm built (1)	\$/flm	PVB	43,761,108	52,348,752	=PVf*DPY*VOT*MBy
Marginal Benefit/Cost	--	BoC	3.5	4.2	=PVB/CFLM
External Congestion Cost of Driving					
External Congestion Cost of Driving	\$/veh-mi)	ECD	\$ 0.305	\$ 0.350	=VOT*(Ke-1)*CTD
Point of Least Total Cost (Diminishing Return) (1)					
PV Cost of Cong.@ Status Quo (1)	2003 \$billion	PVCCsq	\$ 37.820	\$ 169.3	=PVf*ACC
VCI @ Point of Least Total Cost (LC)	----	VClc	0.949	0.949	=(CFLM/(PVf*VOT*DPY*Kd*Pe*Cn))^(1/(Pe+1))
Add'l Fwy Lane-Miles to Build to LC	ln-mi	DFLM	958	4,194	=V/(Cn*VClc)-(FLM+Ka*ALM)
Cost of Build to LC	billion 2003\$	GCB	\$ 12.0	\$ 52.42	=DFLM*CFLM/1000000000
PV Cost of Cong @LC	billion 2003\$	PVCClc	\$ 14.6	\$ 57.25	=PVf*DPY*VOT*V*Kd*VClc*Ke/1000000000
Net Benefit	billion 2003\$	NSpdr	\$ 11.2	59.62	=PVCCsq-PVCClc-GCB

(1) Assumes volume status quo; no growth