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Highway Capacity Reduction and Fuel Consumption

by Eric Toder[*]

I. INTRODUCTION

PUBLIC concern about the adequacy of future energy supplies has led to an interest in the energy-consumption consequences of many public policies. In particular, much attention has been focused on the role of the automobile as a major user of energy, and on ways to reduce energy consumption by improving automobile fuel efficiency and limiting total automobile travel. Raising the price of automobile travel by limiting growth of the supply of highways is one potential method of reducing automobile travel which is available as a policy option both to state and local highway departments, and to Federal policy-makers designing possible modifications in existing highway subsidy programs.

The principal conclusion of this paper is that fairly substantial changes in urban highway capacity will not have a big impact on the amount of gasoline consumed in urban automobile travel. Evidence presented below suggests that lowering highway capacity will, on balance, increase the amount of fuel consumed in urban automobile travel because the percentage increase in fuel consumption per VMT from the resulting increase in peak-period congestion exceeds the percentage reduction in VMT's. The increase in urban highway fuel consumption from a 20 percent reduction in urban highway capacity is estimated to be at most 2 percent.

Estimation of the effect on fuel consumption of a reduction in urban highway capacity requires knowledge of:

- The shape of the highway supply curve, which relates travel time on a given highway to the volume of automobile traffic;
- The shape of the highway travel demand curve, which shows the effect of increased travel times on desired highway use at different initial levels of travel time;
- The division of reduced peak-hour highway travel in response to an increase in peak travel time between (1) traffic diverted to other times of day and (2) traffic either totally suppressed or diverted to other modes;
- The initial congestion conditions, relating highway speed and operating conditions to design speed on different types of urban highways in the peak period;
- The effect on automobile fuel efficiency of reducing actual highway speed relative to design speed through increased congestion.

Methods used for deriving these parameters and a detailed discussion of how they are combined to estimate the effect on automobile fuel consumption of highway capacity reduction are discussed in the remainder of this paper. Section II outlines the theoretical framework used in the analysis. In Section III the empirical implications of previous research on estimating highway speed/volume curves and research on the fuel consumption effects of altering the pattern of traffic flow, are reviewed. Estimates of the effects of changes in travel time on desired peak and non-peak traffic volume, applying to the analysis findings on travel behavior developed in previous research in transportation demand modelling, are presented, along with estimates of the effects of reduced highway capacity on fuel consumption when peak-period automobile travel demand is totally inelastic. In Section IV, a method of combining the supply and demand parameters to obtain point estimates of the net impact on fuel consumption of highway capacity reduction is outlined, along with sample computations for highway capacity reductions of 20 and 10 percent. Section V reviews the principal findings and briefly discusses policy implications.

II. THE EFFECTS OF REDUCED CAPACITY ON FUEL CONSUMPTION: THEORETICAL ANALYSIS

Total urban highway fuel consumption may be expressed as the product of vehicle miles traveled (VMT's) and aver-

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age fuel consumption per mile. Vehicle miles traveled, in turn, may be expressed as the product of number of vehicle trips and average trip length. An increase in travel time per mile resulting from increased highway congestion is likely to reduce both the number of desired trips and the average trip length in the peak.[1] Number of trips will decline as individual drivers switch to other modes, postpone trips to off-peak hours, or eliminate some trips completely in response to increased time costs. Average trip length is expected to decline in the long-run as individuals (i) make shopping trips closer to home, and (ii) change location of residences and places of employment, reducing trip length to counteract the increase in total travel time brought about by the reduction in average speed.

Figure 1 depicts the equilibrium determination of the rate of peak-hour traffic flow and the average travel time for a single highway of fixed length.

In Figure 1, the horizontal axis measures traffic flow in number of vehicles per unit time passing a fixed point (or distance interval) on the highway, while the vertical axis measures the time required to travel from one end of the stretch of highway to the other for any given average speed. The curve D_1D_1 gives the desired peak period traffic flow as a function of travel time; as travel time falls (i.e., average speed increases) for a given distance, the demand for travel and volume of traffic required to accommodate it increases. The curves S_1 and S_2 represent the technological tradeoff between traffic volume and travel time for a given distance for two levels of capacity; S_1 represents the base case, while S_2 represents the time-volume tradeoff for an assumed capacity reduction.

DETERMINATION OF EQUILIBRIUM TRAFFIC VOLUME AND TRAVEL TIME

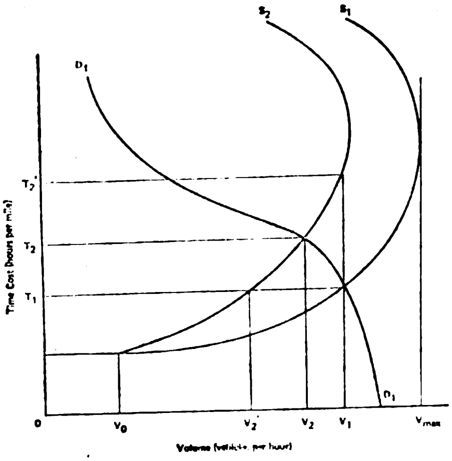

FIGURE 1

Equilibrium[2] volume and travel time is determined by the intersection of the supply and demand curves; reduction in highway capacity lowers traffic volume from V_1 to V_2 and raises average travel time from T_1 to T_2. If demand for the highway in the peak period is totally elastic, traffic volume in the peak hour falls from V_1 to V'_2 and travel time remains the same. If demand is totally inelastic within the relevant range, then travel time increases from T_1 to T'_2. The maximum increase in congestion from a reduction in highway capacity will occur if peak-hour highway demand is totally insensitive to increases in travel time.

The shape of the supply curve is derived from qualitative results from previous speed-volume studies by highway engineers.[3] The flat portion of the curve near the origin depicts a point where the road is almost totally uncongested; additional vehicles do not interfere with each other and reduce the speed of the traffic flow. Moving to the right along the supply curves, additions in traffic lead to a progressively greater deterioration in average highway speed. The point V_{max} where the supply curve is vertical, represents the maximum possible traffic flow on the highway for capacity represented by S_1; beyond V_{max} increases in traffic density (i.e., automobiles per lane mile) lead to a reduction in the traffic flow per unit time because of delays and queues in the movement of traffic. The point V_{max} represents what highway engineers denote as the "design capacity" of the roadway.[4]

The shape of the demand curve depicted in Figure 1 is consistent with the type of demand curve estimated in logit analysis models of transportation demand.[5] The curve has the usual downward slope, but is more elastic near some normal range of highway performance; for very poor performance very few people wish to use the highway in peak-hours[6] while for very high performance, practically all potential users are already using the highway and little additional use will be induced by further improvement in travel times.

Figure 1 shows that the elasticities of supply and demand in the neighborhood of any initial point on either curve depends both on the estimated param-

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eters of the curves and on the initial point chosen.

Estimates of the parameters of the supply and demand functions in Figure 1 and of the initial equilibrium point can be used to compute the reduction in number of vehicle trips and the increase in travel time corresponding to a given reduction in the capacity of the highway. The estimated increase in travel time can be transformed into an estimated increase in fuel consumption per mile using previous research on the relationship between different patterns of highway driving and fuel consumption combined with an assumption about how the average speed reduction implied by the increase in travel time is realized. The product of number of vehicle trips of a fixed distance and fuel consumption per trip then yields the fuel consumption on a highway.

If average trip length is reduced because of a reduction in capacity of the entire highway system, then peak hour VMT's will fall by a greater percentage than the fall in number of peak-hour trips; however, fuel consumption per mile will probably rise because (i) for shorter trips, especially work trips, a greater proportion of the trip probably occurs within a congested region,[7] and (ii) trip distance per cold start is smaller.[8]

Ideally, we would like to know the speed-traffic volume relationship for an entire highway network. As such estimates are not available, the best approximation is to use a weighted average of speed-volume relationships on typical urban highways. In practice, the effects of a given highway capacity change will depend on the change in the composition, as well as the total amount of the highway stock.

Estimates of the change in fuel consumption from a reduction in urban peak period highway travel also require estimates of the extent to which reduced peak hour automobile travel is (i) suppressed or shifted to other modes, or (ii) shifted to other times of the day. Reduction in vehicle miles traveled will be smaller than depicted in Figure 1 to the extent that traffic is shifted to other times of the day, but fuel consumption per mile of the increased non-peak traffic will be lower than fuel consumption per mile in the congested peak conditions.

III. HIGHWAY DEMAND AND SUPPLY CURVES AND THE EFFECTS OF INCREASED CONGESTION ON FUEL EFFICIENCY

This section reviews the available sources of information on highway demand and supply curves and on the effects of a deterioration of traffic conditions on automobile fuel efficiency and presents some empirical estimates of the effects of highway capacity reduction on fuel consumption per mile when peak-period highway demand is inelastic. The estimates of fuel efficiency loss are sensitive to assumptions about how a given slowdown in average speed actually affects the pattern of traffic flow; for different plausible assumptions the fuel efficiency loss differs by a factor of approximately 2.5. The upper bound estimate of the fuel efficiency loss for a highway capacity reduction of 20 percent is under 5 percent. The estimated loss declines more than proportionately with the decline in the assumed highway capacity reduction.

The travel time elasticity of demand for urban highway travel was derived by applying the results of previous research in disaggregate demand modelling.[9] Estimates of the parameters of logit models of work trip mode choice, shopping trip mode choice, shopping trip time of day choice, and trip frequency are combined with national averages of the values of variables used in the estimating equations, and data on the proportions of different types of auto trips in urban areas to obtain estimates of the effect of increasing peak-period auto travel time on the number of peak period auto trips.[10] These estimates, along with estimates of the breakdown of reduced peak-period trips into trips diverted to other modes, trips diverted to off-peak periods, and trips suppressed are presented in Table 1.

Table 1 shows that a 20 percent increase in peak period auto travel time will lead to a reduction in peak auto trips of 9.4 percent, of which .9 percent will be diverted to other modes, 6.0 percent will be diverted to off-peak periods, and 2.5 percent will be suppressed. Within the relevant range, the travel demand curve is quite inelastic, especially inasmuch as most peak auto trips are merely diverted to other modes when peak travel time is increased.

The supply curve for automobile volume on a highway relates varying volume levels to operating conditions. Highway engineers have estimated the relationship of speed to volume for expressways and freeways in numerous empirical studies.[11] The relationship is typically depicted by a curve relating average speed on a highway to traffic volume. By computing time per unit distance as the reciprocal of average speed, we can transform a speed-volume curve into a relationship between volume and travel time similar to the supply curves pictured in Figure 1.

The Highway Capacity Manual evaluates operating conditions on highways by defining categories of service level. The level of service is a qualitative measure combining factors such as maximum speed, travel time, interruptions and operating costs. Level of service A represents a free flow of traffic, corresponding to the horizontal sections of the supply curves in Figure 1. Level of Service C, defined as a steady flow with choice of speed restricted, is the design target for most highways at peak hour use. At level D, the traffic flow approaches instability and interruptions downstream cause rapid declines in speed. Level E is the range of maximum flow, corresponding to the point V_{max} in Figure 1 where the supply curve is vertical. At level F, demand exceeds the capacity of the roadway, causing stop and go conditions in which the throughput of the roadway declines with an increase in demand. We have not found an empirical study which quantifies the exact speed-volume relationship for the range of level F.

The shape of the highway supply curve is sensitive to the design features of each individual roadway. The most salient features that need to be considered are the number of service lanes and the design speed of the road.[12] Unfortunately, sufficient empirical work has not been done to model the flow of traffic on roadways with signalized intersections. Thus, we cannot estimate congestion effects on urban arterials.[13]

Sample computations of the percentage increase in gasoline consumption on urban highways resulting from elimination of federal aid to urban highways, assuming that the demand curve for peak period travel is totally insensitive to travel time, for alternative percentage reductions in urban highway capacity are shown below.

The estimated percentage increase in fuel consumption for a given reduction in highway capacity depends in part on the initial conditions of traffic flow. For highways which are initially more (less) congested, a given percentage increase in traffic volume leads to a greater (smaller) percentage increase in fuel consumption per vehicle. Estimates of the distribution of peak-period highway conditions in representative large urban areas and "small" urban areas were developed from conversations with traffic engineers. For large urban areas, we used estimates for Boston that most traffic in the peak is at level E conditions. We assumed that Boston, the eighth largest metropolitan area in the nation, is representative of the 16 largest SMSA's. The 16 largest SMSA's account for approximately 27 percent of home to work automobile trips in all urban areas.[14] For the remaining SMSA's, we assumed that 5 percent of traffic is at level E conditions, 45 percent at level D conditions, and 50 percent at level C conditions. The percentage increase in peak-period fuel consumption is computed by taking a weighted average of the fuel consumption increase in the large and small urban areas, using the weights of 27 percent home to work auto trips for large urban areas, and 73 percent for the small urban areas. The percentage increase in peak-period fuel consumption for all urban areas is then multiplied by between 0.32 and .34 to obtain a range of percentage increases in total automobile fuel consumption for alternate assumptions about the effect of a decline in average speed on the pattern of traffic flow.[15]

The following steps were used to compute the peak-period fuel consumption change for the small urban areas:

1) The projected capacity reduction was translated into a reduction in potential VMT's under the same driving

EFFECT OF INCREASING PEAK PERIOD AUTO TRAVEL TIMES ON THE NUMBER OF PEAK PERIOD AUTO TRIPS

Effect of An Increase in Auto Travel Times of	Percent of Auto Trips Diverted to Other Modes	Percent of Auto Trips Diverted to Off Peak Periods	Percent of Auto Trips Suppressed	Total Percent Reduction of Auto Trips[1]	Arc Elasticity[2]
20 Percent	0.9	6.0	2.5	9.4	.47
40 Percent	2.6	11.2	5.0	18.8	.47

[1] Assumed mode diversion, time of day diversion, and trip suppression effects are additive. That is, different persons are predicted to switch to transit, to switch to offpeak periods, and to not take trips.

[2] Defined as $\frac{\text{Percent Change in Number of Auto Trips}}{\text{Percent Change in Travel Times}}$

Source: Charles River Associates, *Energy Impact of Federal Capital Grants Programs for Transportation.*

TABLE 1

conditions for each category of roads. As noted above, for every 100 peak-period VMT's in small urban areas, it was assumed that five were driven under level E conditions (group I of roads), 45 under level D conditions (group II of roads), and 50 under level C conditions (group III of roads). For a 10 percent capacity reduction, group I roads could now accommodate 4.5 VMT's at level E conditions, group II 40.5 VMT's at level D conditions, and group III 45 VMT's at level C conditions. The entire system, with the capacity reduction, can handle 90 VMT's at the same driving conditions for which it previously accommodated 100 VMT's in the same time period. If demand is inelastic, VMT's per unit time in the peak period would remain at 100. As level E roads are at maximum capacity, VMT's on level E roads must fall to 4.5: the remaining 95.5 must be distributed across group II and group III roads. We assumed the extra .5 VMT's would go to group II roads; otherwise initial VMT's per hour on group II roads and group III roads would remain the same. Thus, the volume to capacity ratio would rise by 12.35 percent on group II roads (45.5/40.5) and by 11.11 percent on group III roads (50/45).

2) Using the speed volume curves from the Highway Capacity Manual, we estimated the change in speed from the given increases in congestion on the different groups of roads. We used speed-volume curves for 4-lane divided highways; these were viewed as "typical" roads in urban areas.

3) We then estimated average delay by the formula:

$$\Delta T = \frac{1}{S_2} - \frac{1}{S_1} \qquad (3.6)$$

where

S_1 = initial speed in miles per hour

S_2 = speed after volume change in miles per hour, and

ΔT = increased time to travel one mile.

The terms "$1/S_1$" and "$1/S_2$" represent the time necessary to travel one mile before and after the speed changes, respectively.

4) The next step performed was to compute the increased fuel consumption per mile corresponding to the estimated increase in travel time.

An increase in driving time for a given distance can occur with many different changes in driving patterns. If it is accomplished through a lowering of a steady-state speed, the effect will be to increase fuel efficiency for all speeds above 35 mph. Generally, however increased congestion on urban highways manifests itself in more erratic movement of vehicles; average speed over a given stretch of distance falls much more than maximum speed because drivers are continually accelerating and decelerating as permitted by traffic patterns. Claffey has presented empirical estimates of the effects of speed change cycles on fuel consumption; these estimates show that the greater the speed changes from the same initial speed, the greater the excess gasoline consumption, and the greater the initial speed the greater the excess gasoline consumption for equal speed reductions.[16] We have not seen any research, however, which estimates the typical pattern of average speed reduction (i.e., stop and go, lower constant speed, acceleration and deceleration between speed within a 10 percent range) which may be expected when congestion increases on different types of highways.

In computing the fuel efficiency loss from slower average speeds caused by congestion, we initially assumed that the entire time loss was caused by additional idling time. Vehicles are assumed to enter the roadway, wait in a queue, and then drive the entire distance at the initial steady state speed; increased fuel consumption occurs while the auto is idling. Claffey has estimated that the typical automobile consumes 0.6 gallons per hour while idling, or 0.01 gallons per minute.[17] Attributing the time loss to idling time provides a lower estimate to additional fuel consumption; if we assume two full stops and then return to an initial 40 mph speed as the cause of the average time delay, the extra fuel consumption increases by a factor of 2.5.

5) The percentage change in gas consumption over initial conditions caused by the slowdown is then computed as the ratio of the increased gasoline consumed while idling (where idling time is the difference between initial and final time per mile) to the gas consumption per mile at the steady state initial speed.

The procedure for computing the peak-period fuel consumption change in the large urban areas is similar, with the exception of step (1.). For the large urban areas, it is assumed that driving conditions are initially at level E in the most congested hour of the peak period. Thus, a reduction in highway capacity necessarily means that VMT's must fall in the peak hour. We assume that VMT's in the peak hour fall in proportion to the reduction in capacity, and are diverted to the second hour of the peak, raising congestion for that period of time.[18] Data on the distribution of traffic in the three afternoon peak hours in Boston are used to estimate the resulting increased congestion in the second most congested hour, and, for a 20 percent capacity reduction, in the third most congested hour as well. These estimates are then applied to the highway speed volume curves from the **Highway Capacity Manual** to compute the average time delay, and the resulting increase in fuel consumption per mile, using the same method used in computing increased fuel consumption in the small urban areas.

Table 2 summarizes the results of the calculations. The columns labeled weighted average show that, with inelastic peak period automobile travel demand, fuel consumption would increase between 1.57 and 3.925 percent for a 20 percent reduction in highway capacity, and between 0.08 percent and 0.2 percent for a 2 percent reduction in highway capacity.[19] The percentage increase in fuel consumption, for equal reductions in highway capacity, is greater in large urban areas than in small urban areas. It can be readily seen that the fuel consumption increase rises more than proportionately with the increase in traffic congestion.

IV. ESTIMATING NET EFFECT OF HIGHWAY CAPACITY REDUCTION ON FUEL CONSUMPTION

The net effect of a reduction in highway capacity on fuel consumption is computed below by 1) applying our previously obtained parameters on initial congestion and on the shape of highway supply and demand curves described in Section II to derive the equilibrium change in peak-hour VMT's, off-peak VMT's, and peak hour travel time from a reduction in highway capacity, and 2) computing a fuel-efficiency weighted average of relative VMT's driven in the new equilibrium conditions.

The functional forms for the highway demand and supply curves are complex; however, in the neighborhood of a given initial equilibrium point the curves may be approximated by constant elasticity equations. If so, the supply and demand equations are:

Demand: $\log Q = \log a - b \log P$ (1)

Supply: $\log Q = \log c + d \log P$ (2)

where Q = number of trips, P is average travel time, and a, b, c, and d are constants. The constant "d" represents the elasticity of volume with respect to travel time along the time-volume curve depicted in Figure 1, while "$-b$" represents the elasticity of desired peak period trips with respect to a change in travel time. All trips are assumed to be of the same length, so that the percentage change in VMT's is equal to the percentage change in the number of trips.

Solving Equations (1) and (2) simultaneously, we can represent the percentage change in VMT's and travel

ESTIMATED INCREASE IN FUEL CONSUMPTION PER VMT FOR ALTERNATIVE REDUCTIONS IN HIGHWAY CAPACITY

	Percentage Increase in Fuel Consumption			
	Capacity Reduction			
	20 Percent	10 Percent	5 Percent	2 Percent
Large Urban Areas I	2.53	.64	.29	.15
Large Urban Areas II	7.16	1.84	.83	.42
Small Urban Areas I	1.36	.53	.25	.07
Small Urban Areas II	3.61	1.40	.66	.17
Weighted Average I	1.68	.56	.26	.09
Weighted Average II	4.57	1.52	.71	.24

Comment

For the rows labeled "I," additional fuel consumption is computed assuming the entire time delay consists of idling time before entering the highway. For the rows labeled "II," the fuel consumption increase is 2.5 times greater, corresponding to the factor by which the fuel consumption change increases when a time delay is caused by two full stops and return to initial speed from 40 mph rather than by idling before reaching cruising speed.

SOURCE: Computational methods explained in detail in the text. Empirical estimates of speed volume curves and fuel consumption losses from traffic delays obtained from Highway Research Board Special Report 87, *Highway Capacity Manual* (Washington, D.C., 1965) and from P. J. Claffey, *Running Cost of Motor Vehicles as Affected by Road and Traffic*, NCHRP, Report III (Washington, D.C., Highway Research Board, 1971).

Weighted Average = .27 large urban areas + .73 small urban areas.

TABLE 2

time, respectively, in equilibrium, with respect to a given percentage change in highway capacity by the expressions:

$$\frac{d \log Q}{d \log C} = \frac{b}{b + d} \qquad (3)$$

$$\frac{d \log P}{d \log C} = \frac{1}{b + d} \qquad (4)$$

From Table 1 above, the value of b is approximately 0.47. We can estimate the typical value of d for roads in small urban areas by estimating the elasticity of a highway time-volume curve in the neighborhood of the border between level C and level D conditions. The elasticity of highway volume with respect to travel time, is approximately 2.22 in that range. Thus, applying Equations (1) and (2), $(d\log P/d\log C) = -.372$, and $(d\log Q/d\log C) = .175$.

Table 3 presents a sample computation of the effect on fuel consumption of a 20 percent reduction in highway capacity. It is initially assumed that 100 VMT's are driven in the entire day, of which 30 percent are in the peak period. Using the computed value of $(d\log P/d\log C)$ of $-.372$, we find that a 20 percent reduction in capacity leads to a 7.4 percent increase in peak travel time. The fuel consumption multipliers give bounds on the estimates of relative fuel consumption per VMT when travel time per mile is 7.43 percent higher than current conditions, derived by the method discussed in Section III above. From Table 1, a 1 percent increase in peak travel time leads to a 0.47 percent reduction in peak auto trips, which can be partitioned into a switch of 0.30 percent of peak auto trips to the off-peak, and a total suppression (including shifts to other modes) of 0.17 percent of peak auto trips. The resulting new level of peak, non-peak and total trips that would result from a 7.4 percent increase in peak travel time is shown in Column 2 of Table 3.

We then apply the fuel-consumption multipliers to new peak VMT's to obtain estimates of relative fuel consumption in peak-period driving. Relative fuel consumption in non-peak driving is equal to the sum of previous VMT's and new VMT's multiplied by the relative improvement in fuel consumption per VMT for traffic diverted from the peak to off-peak periods. The improvement in fuel consumption for diverted traffic is computed by assuming that all non-peak driving is at level C conditions; thus, we are using bounded estimates of the improvement in fuel efficiency for drivers switching from level D to level C conditions, weighted by the fraction of peak drivers initially at level D.

The total relative change in fuel consumption is the sum of fuel consumption weighted VMT's in peak and off-peak auto travel. Columns (3) and (4) of Table 3 show that a 20 percent highway capacity reduction is estimated to lead to an increase in fuel consumption of between 0.5684 percent and 1.6568 percent.[20]

Table 4 combines computations of the relative fuel consumption change, computed in a manner similar to the computations of Chapter 3, for small and large urban areas, for 10 percent and 20 percent capacity reductions, to obtain bounded estimates of the expected impacts of highway capacity reduction on total urban highway fuel consumption. The lower bound computations assume all additional travel time is spent idling; the upper bound estimates assume two complete stop and go cycles

SAMPLE COMPUTATION: EFFECT OF 20 PERCENT HIGHWAY CAPACITY REDUCTION IN "TYPICAL" SMALL URBAN AREA

	Initial VMT's	VMT's With Lower Capacity	Stop and Go Relative Fuel Consumption	Idling Relative Fuel Consumption
Peak	30.00	28.9524	31.1036	29.9329
Non-Peak	70.00	70.6687	70.5532	70.6355
Total	100.00	99.6621	101.6568	100.5684
Peak Travel Time	1.000	1.0743		
Fuel Consumption Multiplier, Stop and Go		1.0842		
Fuel Consumption Multiplier, Idling		1.0338		

NON-PEAK Fuel Consumption (Stop and Go) = 70 + (.6687/1.2088)

NON-PEAK Fuel Consumption (Idle) = 70 + (.6687/1.0522)

TABLE 3

per mile from the non-congested average speed. The estimates in Table 4 indicate that highway capacity reduction will lead to a very small increase in fuel consumption per VMT.

It is important to note two factors not considered in the present analysis which may affect the results. First, the highway travel demand model used did not consider the possible impacts of changes in highway capacity supply on residential location; changes in location could lead to big changes in average trip lengths.[21] If, as is expected, smaller highway capacity leads people to move closer to workplaces, trip lengths will fall and relative fuel consumption with the smaller highway capacity will be lower than our estimate. Second, we have not estimated the increased energy consumption from increased transit use by motorists induced to shift modes. Thus, the estimated increase in automobile fuel consumption from reducing highway capacity understates the total increase in energy consumption in the transportation sector.

V. CONCLUSIONS

This paper has outlined a methodology for estimating the effects of reduced urban highway capacity on automobile fuel consumption, using a supply-demand framework to calibrate equilibrium changes in highway traffic volume and peak-hour congestion conditions. Using the best available evidence from previous research on the shapes of highway supply and demand curves, current levels of congestion prevailing in major urban areas, and the effects of congestion-induced increases in highway travel time on fuel consumption, we estimated that a reduction in urban highway capacity would, on balance, slightly increase fuel consumption on urban highways.

The findings suggest that attempting to save fuel by restricting highway capacity, far from contributing significantly to fuel savings, may actually be counterproductive and increase energy consumption. In any case, the likely magnitude of the effect of potential policy-induced changes in urban highway capacity on fuel consumption is so small that other considerations, such as the balance between site acquisition and construction costs, on the one hand, and the discounted value of improved travel time to users, on the other hand, would seem to be more relevant to making decisions about constructing new highways.

SUMMARY OF RELATIVE FUEL CONSUMPTION EFFECTS OF HIGHWAY CAPACITY CHANGES

	Highway Capacity Reduction			
	10 Percent		20 Percent	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Small Urban Areas	100.2388	100.8431	100.5684	101.6568
Large Urban Areas	100.2133	100.8441	100.6194	102.5301
Weighted Average[1]	100.2319	100.8434	100.5822	101.8926

[1] Weights are .27 for large urban areas and .73 for small urban areas.

TABLE 4

FOOTNOTES

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1 Reduction in highway capacity is likely to affect driving conditions substantially principally in peak-periods. Excess capacity is generally prevalent in the off-peak.

2 In equilibrium, the desired traffic flow at the given travel time is equal to the actual flow made possible by highway conditions at that speed.

3 Some engineering estimates of speed-volume relationships for different types of urban highways are shown in Highway Research Board Special Report 87, Highway Capacity Manual, (Washington, D.C., 1965).

4 It should be noted that the "socially optimum" use of the roadway is at a point to the left of V_{max}. For a fuller discussion of this point, see Charles River Associates, "Energy Impact of Federal Capital Grants Programs for Transportation," draft final report submitted to Federal Energy Administration, March 1976, Chapter 3.

5 See, for example, Charles River Associates, "Disaggregated Behavioral Model of Urban Travel Demand," submitted to the Federal Highway Administration, U.S. Department of Transportation, March 1972.

6 The level of performance at which demand becomes very elastic depends on the quality of alternative modes and socioeconomic characteristics of potential users.

7 This statement assumes that residences are typically more widely dispersed than places of employment.

8 As cold starts consume a significant amount of fuel, better average fuel economy is achieved by spreading the fixed fuel cost of each cold start over a longer trip length.

9 See Charles River Associates, "Disaggregated Behavioral Model of Urban Travel Demand," op. cit.

10 For a full discussion of the derivation of the travel demand estimates presented here, see Charles River Associates, Energy Impact of Federal Capital Grants Program for Transportation, op. cit.

11 Speed-volume relationships for different types of highways derived from such engineering studies are presented in the Highway Capacity Manual, op. cit.

12 Design speed gives the maximum safe speed for a roadway taking account of sight of distances, curves, and grades of a given section of road.

13 Research currently under progress by Don Dewees at the University of Toronto is developing estimates of speed-volume relationships for a network or urban streets.

14 This estimate was derived from data in the U.S. Census of Transportation. We are implicitly assuming that the distribution of peak-period auto trips across types of cities is the same as the distribution of home to work auto trips.

15 Data from several urban areas suggest that peak-period travel accounts for approximately 30 percent of daily VMT's. See Charles River Associates, *Energy Impact of Federal Capital Grant Programs for Transportation*, Appendix E. The 32 percent and 34 percent figures are obtained by applying estimates of fuel consumption per mile in peak driving conditions relative to non-peak driving conditions to the assumption on distribution of VMT's.

16 P. J. Claffey, *Running Cost of Motor Vehicles as Affected by Road and Traffic Design*, NCHRP, Report III (Washington, D.C., Highway Research Board, 1971).

17 See Claffey, op. cit.

18 It is possible that VMT's could fall more than in proportion to capacity in the peak hour if people are willing to accept even slower travel times than are characterized by level E. In effect, attempted use of the highway system beyond its capacity causes level F conditions to develop, leading to a reduction in the actual rate of VMT's per hour, though density on the highways is increasing. If that happens, an x percent reduction in capacity will lead to a more than x percent shift of peak hour traffic to the second hour of the peak period, with the extra traffic in the second hour consisting of vehicles attempting to travel in the first hour but delayed by the increased congestion. If level F conditions develop, or increase, because of a reduction in highway capacity, the increase in fuel consumption per VMT will be greater than the increase estimated by the method described in this section.

19 The fuel consumption increase is computed by multiplying the peak-period percentage increase in fuel consumption by estimates of the fraction of urban highway fuel consumption in the peak. We assume that reduction in highway capacity does not significantly affect congestion conditions in off-peak periods.

20 The method computation presented in Table 3 is not fully consistent because it does not adjust for the fact that initial fuel consumption in the peak is slightly greater than 30 percent because fuel consumption per mile is greater during the peak period than for non-peak traffic. A revised computation weighting peak and non-peak VMT and fuel-efficiency changes by initial fuel-consumption weighted VMT in the peak and off-peak raises the estimated percentage fuel consumption increase from a 20 percent reduction in highway capacity in small urban areas from between .5684 percent and 1.6568 percent to between .5869 percent and 2.1559 percent.

21 For estimates of the maximum potential savings from a reduction in highway capacity which account for the maximum reasonable change in trip length, see Charles River Associates, "Economic Impact of Federal Capital Grants Programs for Transportation," op. cit. CRA's bounded estimate shows that the maximum potential reduction in urban highway fuel consumption from eliminating the entire Federal-Aid to Highways Program (FAHP) until 1990 is 1.3 percent.