CHAPTER **6**

CASE STUDIES II: ESTIMATION OF COMMUTING COSTS

This chapter summarizes case study analysis findings concerning impacts of congestion on labor market access—specifically, the impacts on commuting costs and resulting changes in business operating costs. Other business costs relating to the delivery of business products and services were covered in the preceding chapter.

The analysis results indicate how congestion increases the direct costs of workers and causes firms to substitute among workers located closer in and farther out to adjust to changes in accessibility to specialized labor markets.

For this study, the research team analyzed commuting patterns and calibrated model elasticities for Chicago using very detailed U.S. census data. Those elasticities were then applied to a corresponding Philadelphia data set to test their transferability to an urban area with similar characteristics.

KEY FACTORS: COMMUTING TRIP PATTERNS

As noted above, the research team first analyzed the pattern of commuting trips in the Chicago metropolitan area and the extent to which this systematically varied by industry category and by occupation group. This analysis revealed more distinct differences by occupation, with businesses hiring workers from longer distances in the more specialized and highly trained occupations. The differences were less pronounced among industries, for many of the office-related occupations represented all industries. Figure 6.1 indicates how average commuting trip lengths varied by occupation.

Figure 6.2 indicates how the overall spatial pattern of the workforce and different industries differs by subregion within a metropolitan area. It shows that relative levels of demand for workers in the finance and insurance industries are greatest in the central business district and diminish with distance from that area. Those systematic differences are then used in the model calibration process (including calculation of worker demand elasticities) discussed in the section *Model Calibration*.

MODELING COMMUTING COSTS

There are four aspects to the direct value of commuting costs. Those aspects are defined below, along with basic assumptions about their estimated value.

- The direct expense associated with commuting delay includes the value of vehicle operating expenses associated with commuting. For this study, the direct travel cost, including car depreciation and gasoline cost, is assumed to be 16.67 cents per minute. This is consistent with various combinations of speed and cost of travel [for instance, it is consistent with an average commuting speed of 28.6 mph (45.8 km/h) at 35 cents per mile (56 cents per km)].
- The user time value of commuting delay is based on the wage rate in accordance with the literature on the implied value of time (described earlier). For this study, however, the value of commuting time is based on the applicable wage rate for each occupation group.
- The business cost of commuting delay is based on the opportunity cost of worker compensation for excess delay. Based on the literature review concerning business wage compensation costs for additional commuting time, this is conservatively assumed for this study to be 50 percent of the wage rate value of commuting delay.
- The additional business cost of commuting travel time variability was based on the standard deviation of commuting time, which was multiplied by 1.3 times the full average wage rate in accordance with the literature review.

The corresponding values for each occupation group are presented in Table 6.1.

There are additional elements of the total business cost of congestion delay associated with commuting delay. They relate to production functions, such as how businesses adjust their production processes in response to changes in worker market access. They are discussed below.

MODEL CALIBRATION

Interpretation of Business Response to Workforce Commuting Costs

The economic model summarized in Chapter 4 yields coefficients reflecting the elasticity of business substitution among workers. This reflects the extent to which firms hire workers who have specialized skills. In general, the more the workers are not specialized, the more firms can substitute

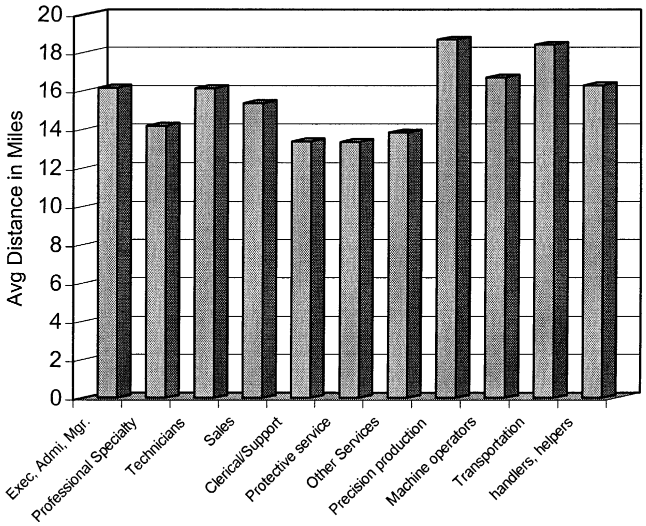


Figure 6.1. Commuting trip length by occupation in the Chicago area.

closer workers when costs of obtaining workers from farther away increase, as occurs with increased congestion. These elasticities were calculated separately by industry and by occupation.

The modeling analysis showed substantially more variation in the business valuation of commuting time by occupation group (a range of ±70 percent) than by industry group (with a range of ±17 percent). The reason for the lower variation among industries is that each industry has some mix of broad-skill and specialized skill jobs. The overall differences in valuation of commuting time among these various kinds of employees thus tends to hover around the mean for every industry.

The more striking differences are among occupations in which the more specialized skill occupations showed a lower degree of substitutability among workers, indicating that businesses sought such workers from a broader geographic area and were thus willing to pay the associated higher (commuting cost) compensation required to attract such workers. These differences lead to the conclusion that it is more useful to analyze commuting costs by occupation and then use industry-occupation tables (produced by the U.S. Bureau of the Census) to assign those costs to individual industries.

TABLE 6.1 Unit cost factors for commuting delay

Occupation	Average hourly wage
Precision production and crafts	$16.20
Transport and material moving	$15.08
Executive, administrative, managerial	$21.90
Technicians	$17.40
Machine operators	$12.25
Protective services	$9.79
Helpers and laborers	$11.03
Sales occupations	$15.65
Professional occupations	$22.39
Clerical occupations	$12.64
Private household occupations	$ 4.57

TABLE 6.2 Elasticity of labor substitution coefficients (production function)

Occupation category	Elasticity of substitution	Standard deviation
Precision production, craft, and repair	11.27	0.017
Transportation and material moving	11.35	0.028
Executive, administrative, and managerial	12.25	0.016
Technician and related support	12.83	0.031
Machine operators, assemblers, and inspectors	13.04	0.024
Protective services	13.21	0.043
Handlers, cleaners, helpers, and laborers	13.75	0.031
Sales	13.05	0.018
Professional specialty	14.57	0.018
Administrative support	14.66	0.016
Private household services	16.02	0.14
Services (excluding household and protective)	16.49	0.024

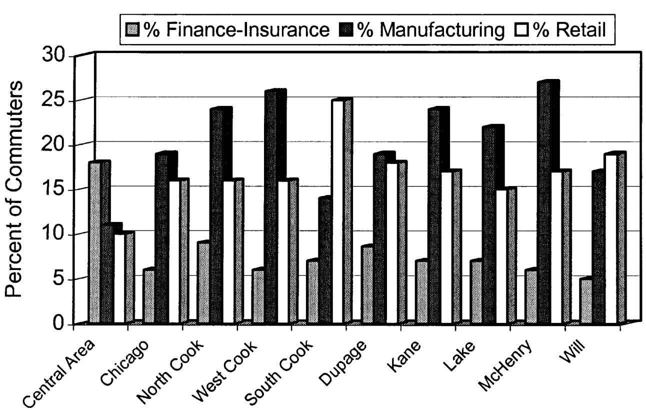


Figure 6.2. Location pattern of jobs by industry in the Chicago area.

Value of Estimated Elasticities

The key findings of differences by occupation are presented in Table 6.2. It is notable that all these coefficient estimates have a very high degree of statistical accuracy and significance, as reflected by the very low standard deviations associated with each of them. Although explanations for all the differences among occupations are not immediately obvious, there are some general trends.

Interpretation of Results

In general, these coefficients indicate that:

- The lowest degree of substitution (coefficient under 12.30) occurs for the three categories: executives and managers, precision production occupations, and transportation and material moving occupations. For these occupations, the model coefficients indicate that businesses seek a broader area to attract those with the appropriate specialized skills and pay a commuting cost premium as required to reach that labor market.
- The highest degree of substitution (coefficient over 14.60) occurs for the three categories: service occupations, private household (e.g., maid) occupations, and clerical occupations. For these occupations, the model coefficients indicate that businesses are more concerned with lower cost than with finding unique skills and tend to hire more local workers rather than pay the additional commuting cost premium associated with longer commutes.

Goodness of Fit

These coefficients were then applied as a test of the goodness of fit of the elasticity equations in terms of forecast versus actual trip lengths for all trips, stratified by occupation. The result was an R^2 value, representing the portion of variance explained by the model, which was 0.91 for Chicago. Following this result, the elasticity coefficients derived from the Chicago model were applied to the available commuting data for Philadelphia as a test of the transferability of this model. The resulting R^2 value (0.80) indicates an acceptable fit. The result also indicates that these parameters may be transferable to other urban areas. Figure 6.3 compares model forecasts of commuting trip volumes with actual trip volumes for various trip length classes.

Although the estimated coefficients may be of academic interest, they do not directly explain the actual costs of congestion. To illustrate their application, the team applied the production function model with these coefficients to forecast how businesses would bear costs of particular congestion scenarios. This is shown in the following sections.

MODEL RESULTS: TESTING ALTERNATIVE SCENARIOS

Definition of Scenarios and Impact Indicators

Scenarios

Once the production function model was estimated, its coefficients were reapplied to forecast how alternative congestion scenarios would affect business patterns in the Chicago and Philadelphia regions. These results show how businesses seek to change hiring patterns (and hence worker commuting patterns) to minimize the negative impact of an increase in congestion or maximize the positive impact of a decrease in congestion. Two scenarios were tested for both Chicago and Philadelphia: a regionwide congestion decrease scenario and a localized area congestion scenario.

For each scenario, impact indicators were calculated reflecting how businesses' costs and trip patterns would change under fixed production functions, in which employee occupational requirements are fixed, and flexible production functions, which allow businesses to respond with some substitution of workers, to minimize business operating costs.

Impact Indicators

For each scenario, impact indicators were calculated reflecting how business costs and trip patterns would change compared with existing conditions. These indicators were as follows:

- Change in total vehicle miles associated with adjustment in trips and trip lengths, due to a change in worker commuting costs, with flexible production;
- Change in labor cost associated with reductions in travel times and improved labor productivity, with flexible production;
- Change in total cost with worker adjustment (flexible production functions), which reflects the above adjustments in trips, trip lengths, and associated mileage, as they respond to changes in congestion with some substitution of workers; and
- Change in total cost with no worker adjustment (fixed inputs, reflecting no change from base case trip patterns) due to a change in worker costs.

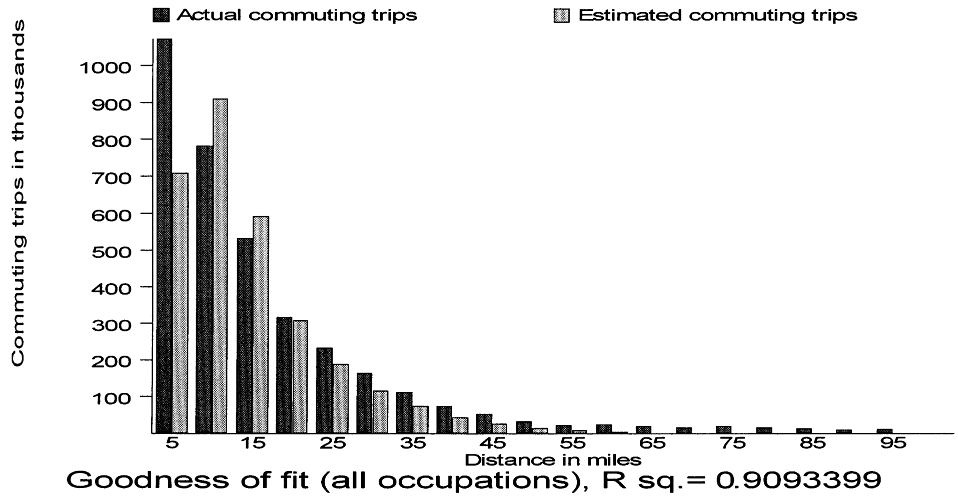
The scenario impacts were estimated separately by industry and by occupation for each of the traffic analysis zones in the Chicago and Philadelphia metropolitan areas. Therefore, the model results can indicate the impacts of congestion on the economy of the region, counties, the city, and individual neighborhoods as well as on individual sectors of the economy and portions of the population.

Illustration of Calculation

The elasticities affect business costs of commuting in the following ways, illustrated by this example of a congestion decrease:

- The decrease in travel times leads to a reduction in total user travel cost. Valuing time savings at half from the perspective of business cost, it represents a smaller value of reduction in the business operating cost (for preexisting employees).
- Applying the elasticity of substitution (described in Chapter 5 in the section *Model Calibration*), businesses

(A) Chicago



(B) Philadelphia

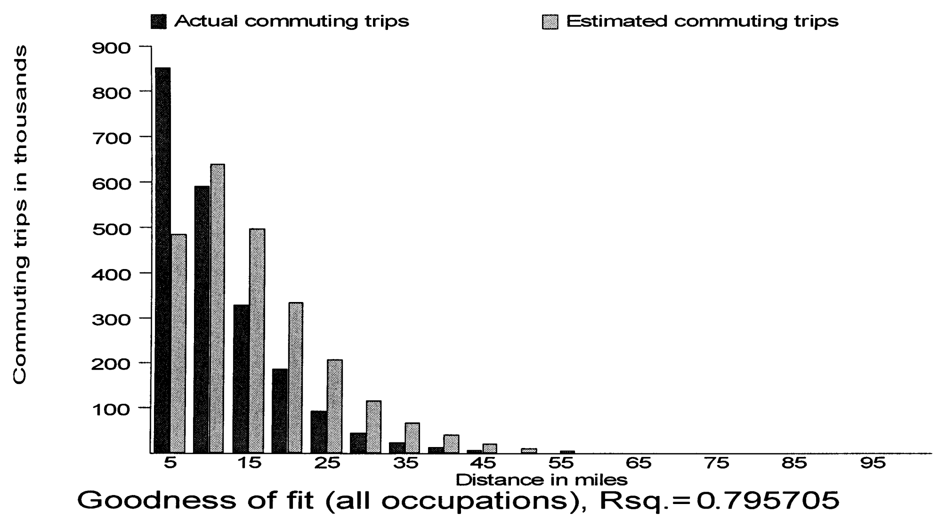


Figure 6.3. Estimated versus actual commuting trip distances.

will take advantage of the lower commuting cost to seek new workers from a wider area. The result will be greater business productivity but also an induced increase in total miles traveled because of the changes in the composition of labor.

- The net impact (reflecting both of the above factors) will be a net reduction in the portion of total labor cost associated with commuting. This is the result of two factors:
  1. Savings in a share of the commuting cost for pre-existing and new employees, and
  2. Additional savings due to an increase in labor productivity that results from having a larger labor market to choose from, which is only partially offset by a cost increase to compensate for the added length of average commutes.

Scenario 1: Regionwide Congestion Reduction

Scenario Definition

The first scenario is a simplistic reduction in regionwide congestion, which reduces travel time for all trips in Chicago and Philadelphia by 10 percent.

Cost Impact

Table 6.3 presents results of the flexible production function model. The reduction in congestion leads to an increase in business productivity and a corresponding reduction in labor cost. This difference is more than would be expected if

TABLE 6.3 Scenario: 10 percent reduction in vehicular travel time for entire metro region

Chicago region	Current conditions	10 percent reduction in commuting time: No worker adjustment switch	10 percent reduction in commuting time: With worker adjustment
VMT/day	35,757,446	35,757,446	36,383,438
(% change)	—		(+1.751%)
Total cost of labor/day	$382,341,672	$380,740,700	$380,724,828
(% change)	—	(−0.419%)	(−0.423%)
Commuting cost element of labor cost	$47,012,761	$45,411,789	$46,190,285
(% change)	—	(−3.405%)	(−1.749%)
Components of % change in cost of labor			
Due to better labor productivity	—	0.00%	−0.234%
Due to reduced travel times	—	−0.419%	−0.423%
Due to longer trips	—	0.00%	+0.245%
Total	—	−0.419%	−0.423%

Philadelphia region	Current conditions	10 percent reduction in commuting time: No worker adjustment	10 percent reduction in commuting time: With worker adjustment
VMT/day	29,888,795	29,888,795	30,222,247
(% change)			1.1156%
Total cost of labor/day	$300,231,474	299,307,723	299,302,605
(% change)		−0.3077%	−0.3094%
Commuting cost element of labor cost	$41,825,892		
(% change)		40,902,141	41,235,147
Components of % change in cost of labor			
Due to better labor productivity	—	0.0000%	−0.1314%
Due to reduced travel times	—	−0.3077%	−0.3483%
Due to longer trips	—	0.0000%	0.1740%
Total	—	−0.3077%	−0.3094%

Note: VMT = vehicle miles traveled.

there had been no change in employees. The additional productivity savings comes from the ability of businesses to use workers from a broader area. The value of the savings in labor cost is equivalent to $350 million/year ($1.6 million/day) for the Chicago region and $200 million/year ($0.9 million/day) for the Philadelphia region.

Figure 6.4 presents the breakdown by location of the impacts of a 10 percent regionwide travel time decrease (from congestion reduction) for the Chicago region. It indicates that the highest percentage savings in labor costs accrue to the outer suburbs, and the least savings accrue to the central business district and the rest of the city. The inner suburbs also show a lesser savings than the outer areas. This finding indicates that the costs of regionwide travel accrue greatest to the longer-distance trips, which are associated with outlying areas.

Occupational Differences

Figure 6.5 presents the same chart with the results broken down by occupation. The results generally indicate that the greatest percentage cost savings are for those occupations that require unique skills and require a wide labor market area, particularly executive occupations, precision skill occupations, and specialized material moving occupations. These are the same groups that had the lowest coefficients of substitution. On the other hand, the results also indicate that the smallest percentage cost savings are for those occupations in which worker substitution is easiest, particularly clerical occupations, private household occupations (e.g., maid), and general service occupations.

Overall Findings

Key findings from the 10 percent congestion reduction scenario for Chicago and Philadelphia are as follows:

- Vehicle miles traveled with worker adjustment increases by <2 percent as firms seeking specialized labor draw on a larger labor pool.
- The total cost of labor charges because of increased labor productivity and decreased travel times. In each city, the cost decrease due to labor productivity is less than half the value of the decrease due to reduced travel times.

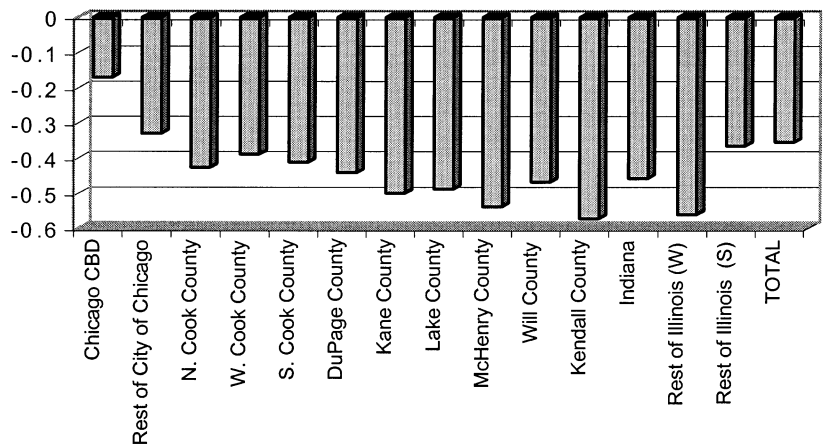


Figure 6.4. Percent change in total labor cost by location, resulting from 10 percent regionwide decrease in commuting time (Chicago region).

- There is a net decrease in labor costs. The costs of increased trip lengths are more than offset by the productivity gains and congestion reductions.
- The decrease in travel cost outweighs the additional cost incurred from purchasing inputs farther away. Labor cost decreases by 0.4 percent in Chicago and by 0.3 percent in Philadelphia.
- The gain to firms when labor substitution is allowed is slightly higher than when travel time gains are the only benefits realized by firms. The percentage decrease in costs when labor substitution is included is 0.42 percent, as opposed to 0.41 percent when travel time benefits only are considered for the Chicago scenario. These results are consistent with those for Philadelphia, for which the corresponding figures for cost reductions are 0.0308 and 0.0306 percent, respectively.

Scenario 2: Localized Commuter Congestion Decrease

Scenario Assumption

The second scenario assumes that a localized area congestion bottleneck has been eliminated so that travel times

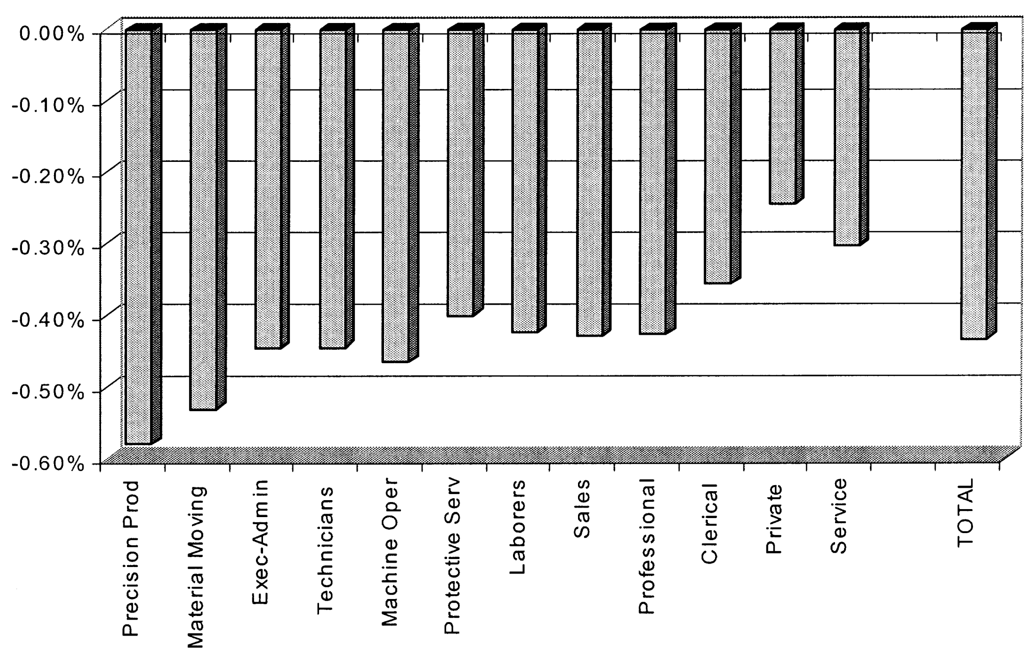


Figure 6.5. Percent change in total labor cost by occupation, resulting from 10 percent regionwide decrease in commuting time (Chicago region).

decrease 50 percent but only for suburban residents along one corridor. In this case, two suburban suburbs were chosen: Lake County, north of Chicago, and Chester County for Philadelphia.

Total Cost Impact

Table 6.4 indicates that, when the model allows for worker adjustment (flexible production function), the decrease in congestion leads to an increase in business productivity, which decreases business costs of labor more than would have been the case if the same people had been employed. That is because businesses use the opportunity of substituting workers from a much larger potential pool than previously had been the case. The value of the savings in labor cost from this scenario is equivalent to $100 million/year for the Chicago region and $7 million/year for the Philadelphia region (where a smaller impact local zone was selected).

Figure 6.6 presents a breakdown of the impacts of 50 percent travel time decreases only for Lake County. Not surprisingly, it indicates that the greatest percentage change in labor costs accrues to businesses in Lake County. However, note that that cost impacts are shown to also occur for businesses in adjacent areas of McHenry, Kane, and northern Cook Counties in the Chicago scenario.

OVERALL IMPLICATIONS

The analysis results in this chapter indicate that firms with greater dependence on less-specialized or more common occupations (such as clerical workers) tend to be hurt relatively less by congestion (and benefit relatively less from congestion reduction) than those with requirements for more specialized occupations (such as executives or precision production occupations), because the former tend to more easily adjust to congestion by finding suitable workers within a closer distance.

The case studies also indicate how congestion impacts can differ depending on the nature of the congestion scenario. For instance, when congestion reduction was assumed to be evenly distributed regionwide, the economic benefit was still largest for those businesses located on the periphery of the metropolitan area. That is because there tend to be longer travel distances for workers traveling to those businesses, and hence they are most highly affected by increases or

TABLE 6.4 Scenario: 50 percent decrease in vehicular travel time only for one subarea

Chicago region impacts (congestion change only on Lake County commuters)

		50 percent change for Lake County	
	Current conditions	**No worker adjustment**	**With worker adjustment**
VMT	35,757,446	35,757,446	35,981,137
(% change)	—		0.6256%
Total cost of labor	$382,341,672	381,898,954	381,874,445
(% change)	—	–0.1158%	–0.1222%
Commuting cost element of labor cost	47,012,761	46,570,042	46,774,786
(% change)		–0.9417%	–0.5062%
Components of % change in cost of labor			
Due to better labor productivity	—	0.0000%	–0.0657%
Due to reduced travel times	—	–0.1158%	–0.1383%
Due to shorter trips	—	0.0000%	0.0851%
Total	—	–0.1158%	–0.1222%

Philadelphia region impacts (congestion change only on Chester commuters)

		50 percent change for Chester County	
	Current conditions	**No worker adjustment**	**With worker adjustment**
VMT	29,888,795	29,888,795	29,902,586
(% change)			(0.046%)
Total cost of labor	300,231,474	300,202,616	300,201,549
(% change)		–0.0096%	–0.0100%
Commuting cost element of labor cost	41,825,852	41,797,033	41,808,421
(% change)		–0.069%	–0.0418%
Components of % change in cost of labor			
Due to better labor productivity	0.0%	0.0000%	–0.0052%
Due to reduced travel times		–0.0096%	–0.0122%
Due to shorter trips		0.0000%	0.0071%
Total		–0.0096%	–0.0103%

Note: VMT = vehicle miles traveled.

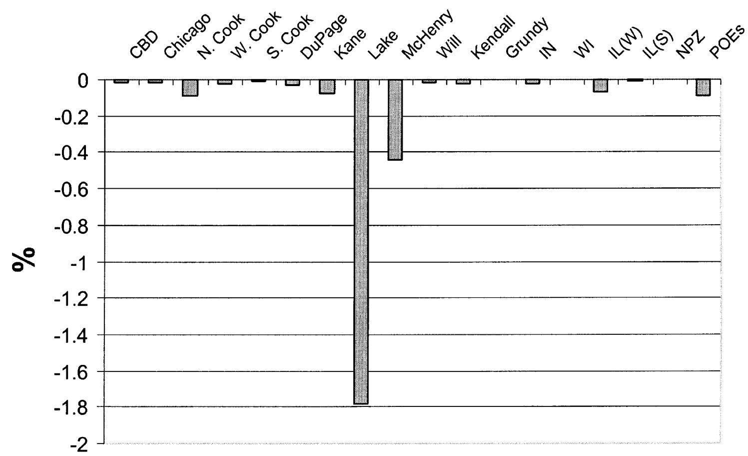


Figure 6.6. Percent change in total labor cost by location, resulting from 50 percent commuting cost decrease in Lake County only.

decreases in congestion costs. In contrast, when the congestion reduction was assumed to be centered around an area with many skilled and educated workers, the economic benefit was more broadly distributed among locations throughout the metropolitan area. It was also greatest for the types of businesses that employ executives and precision-skilled workers.

Like the freight delivery scenarios discussed in Chapter 5, these commuting scenarios show how congestion impacts can vary among types of businesses and their locations within a metropolitan area. They also demonstrate that the economic impacts of congestion are experienced not only in the congested areas but also in other areas that are economically linked to it by product delivery patterns.

CHAPTER **7**

SKETCH PLANNING TOOL FOR ASSESSING ECONOMIC IMPACTS OF CONGESTION

OVERVIEW

The analysis process used to assess congestion impacts in Chapters 5 and 6 made use of data available for the Chicago and Philadelphia metropolitan areas. That methodology can be extended for application to any other metropolitan area in which the necessary data can be obtained. Currently, the set of metropolitan areas that have available information on interzonal truck movements is limited, but more areas may be able to obtain or derive such information in the future.

In anticipation of such future applications, the analysis process used in this study (to assess the business impacts of congestion) has been developed into a planning software tool referred to as the congestion decision support system (CDSS). It expresses the economic impacts of congestion to businesses as monetary costs that producers of goods and services bear as a consequence of changes in travel times (arising from changes in transportation supply or demand).

The software has several notable features. CDSS provides a convenient user interface that allows users to develop model inputs (including travel demand inputs), model parameters, and program configuration files. A database for secure storage of key inputs and parameters has been developed as well. Users develop model inputs and perform analyses through a familiar MS Windows interface and can develop and test small data sets quickly.

RELATIONSHIP TO OTHER ANALYSIS TOOLS

Basically, CDSS provides a means of estimating the economic impacts of alternative scenarios for future congestion growth or reduction in a way that goes beyond mere changes in average travel time, cost, and safety. Specifically, it provides economic impact estimates that (*a*) broaden the coverage of delay costs to also include variability, perishability, and production scheduling costs; (*b*) distinguish different values of delay by industry and occupation category; and (*c*) incorporate a business response function in which vehicle miles traveled can change in response to changes in congestion levels. Current tools for benefit-cost analysis do not cover such a broad range of congestion-related impacts.

However, CDSS is an impact assessment tool and not a benefit-cost accounting system (such as MicroBenCost or the AASHTO Red Book). CDSS does not address either the costs of alternative actions to address congestion or the effectiveness of alternative actions to address congestion. Both of those additional items are needed to calculate any benefit-cost ratios or return-on-investment rates for transportation spending to address congestion. However, once additional research on those topics is completed, CDSS can provide a foundation for conducting assessments of spending and investment alternatives.

SUMMARY OF INPUTS AND OUTPUTS

Table 7.1 summarizes the CDSS input requirements, and Table 7.2 summarizes the CDSS output product. A detailed documentation, along with the computer program, is available from the National Cooperative Highway Research Program (specify NCHRP Project 2-21).

TABLE 7.1 Required inputs for CDSS

Commuter market	Commercial market
Travel demand inputs	
• Population by residential zone for each occupation • Employment by destination zone for each occupation	• Truck trips by origin-destination zone by industry (mining, agriculture, manufacturing) • Service-related trips by origin-destination zone • Conversion of tons of commodities to truck trips (optional)
Transportation performance inputs	
• Base case average daily travel times (minutes) by origin-destination zone • Improvement case average daily travel times by origin-destination zone • Distance (miles) by origin-destination zone • Percentage of travel occurring on freeway system (optional) • Average daily on the freeway system in the base case (optional) • Average daily on the freeway system in the improvement case (optional)	• Base case average daily travel times (minutes) by origin-destination zone • Improvement case average daily travel times by origin-destination zone • Distance (miles) by origin-destination zone • Percentage of travel occurring on freeway system (optional) • Average daily on the freeway system in the base case (optional) • Average daily on the freeway system in the improvement case (optional)
Model parameters	
• Average daily wage • Elasticity of substitution by occupation • Average mode share for drive-alone, transit, carpool, and other modes	• Average hourly cost of truck usage • Average value of shipment • Reliability costs ($\$/min^2$) • Elasticity of substitution by industry
System parameters	
• Number of zones • Number of districts • Name, location of input files • Name, location of output files • Reliability option • District option	• Number of zones • Number of districts • Name, location of input files • Name, location of output files • Reliability option • District option

TABLE 7.2 Outputs from CDSS

(All output data are stratified by industry and/or occupation)

- Total miles, old trips: Total daily vehicle miles of travel in the base case
- Total miles, new trips: Total daily vehicle miles of travel in the improvement case
- Total hours, old trips: Total daily person hours of travel in the base case
- Total hours, new trips: Total daily person hours of travel in the improvement case
- Input use, new trips: Transportation portion of industry production costs in the improvement case
- Input use, old trips: Transportation portion of industry production costs in the improvement case
- Input cost, old trips, new time: Transportation portion of industry production costs, with no induced demand effect, in the improvement case
- Input cost, new trips, new time: Transportation portion of industry production costs, with induced demand effect, in the improvement case

CHAPTER **8**

CONCLUSIONS

CONTRIBUTION OF THIS STUDY

The intent of this research effort was to extend the traditional transportation impact framework by examining how congestion affects producers of economic goods and services in terms of business costs and productivity. It also showed how various types of businesses differ in their sensitivity to congestion. This sensitivity to traffic congestion is attributable to a particular industry sector's reliance on skilled labor or specialized inputs and a large transportation-based market area to obtain those inputs. Congestion effectively contracts the market area for inputs, bidding up their costs, thus increasing production costs. Industries can compensate for congestion and reduce costs by location choices and other strategies.

This study is of particular interest for three reasons:

1. More complete measurement. The most important aspect of this study is that it provides a measure of the real monetary cost of congestion to local or regional economies, which is more complete than the accounting of vehicle operating expense and traveler time cost. This includes incorporation of additional business cost and productivity factors associated with travel time variability, worker time availability, freight inventory/logistics, and just-in-time production processes. The economic analysis further demonstrates how congestion effectively shrinks business market areas and reduces (eliminates) the scale economies (agglomeration benefits) of operating in large urban areas.
2. Link to productivity studies. This study also builds on the recent work by Krugman (1979, 1995) and Fugita (1985), who have provided a microeconomic framework that explains agglomeration economies based on access to differentiated inputs. Their framework provides a basis for statistical estimation of business production functions, which yield elasticities of substitution among differentiated labor and material inputs. This information indicates the differing ability of various types of businesses to adjust to the higher costs of travel and the effect of those cost changes on business output. This form of analysis is complementary to, but distinctly different from, the work of Nadiri (1996), which estimated elasticities among aggregate-level highway investment and other capital investment in the determination of national productivity. The key difference is that, whereas Nadiri's work examined the link between highway investment and aggregate productivity, this study examined the link between travel time changes and the productivity of specialized inputs based on microeconomic theory.*
3. Application for policy testing. The end product is the demonstration of a general approach that can be applied for broad analysis of the economic costs of congestion around the country. The model results indicate that a congestion alleviation strategy that explicitly considers impacts to firms in terms of their costs of doing business can provide a fuller picture of the trade-offs among alternative investments than a traditional comparison based on user costs (and, occasionally, also external costs).

RESEARCH FINDINGS

Statistical Relationships

The research team conducted extensive data assembly and statistical model analysis for the Chicago and Philadelphia metropolitan areas. The analysis models were developed to examine the degree of sensitivity of various types of business activity to the costs of transporting products and costs of worker commuting. The actual estimation and application of these parameters are the subject of considerable discussion in this report. In general, however, the calibrated models for Chicago and Philadelphia yielded consistent results:

- Industry differences in congestion costs. The results for both areas showed that industries with broader worker requirements and higher levels of truck shipping absorb higher costs associated with congestion. They also benefit most from congestion reduction.
- Industry sensitivity to congestion costs. However, the production function models also showed that firms with lower-skilled labor requirements or nonspecialized (commodity) input requirements tend to be hurt relatively less

* The Nadiri work indicated the apparent return on highway investment, although it did not distinguish how changes in congestion levels or other aspects of transportation conditions affect those results. In contrast, this study did focus specifically on the economic effects of changes in transportation conditions. To estimate the rate of return on highway investment to reduce congestion, it is necessary to also have estimates of the cost of strategies to reduce congestion and the relative impact of such strategies on transportation conditions.

by congestion (and benefit relatively less from congestion reduction) than those with requirements for highly skilled labor or highly specialized material inputs.
- Effect on travel demand. The models confirmed that reduction in traffic congestion costs can lead to demand for additional travel. (In one scenario, an assumed 10 percent reduction in commuting travel times in the Chicago area resulted in a 1.7 percent increase in vehicle miles traveled. Roughly 40 percent of that increase was due to new trips, and 60 percent was due to longer trips.)
- Economies of scale. The models also illustrated how traffic congestion has the effect of nullifying some of the agglomeration benefits of operating businesses in larger urban areas. The labor cost model, for instance, indicated that doubling the effective labor market size leads to an average 6.5 percent increase in business productivity.
- Overall magnitude of congestion costs. The analysis showed that the economic cost savings from reducing congestion, which includes higher productivity due to wider labor and delivery markets, is greater than the direct traveler cost savings alone. However, the analysis also showed that some of this cost savings is offset by the added cost of longer trips resulting from reduced congestion.

Impacts of Congestion Scenarios

The actual economic impacts of traffic congestion can differ by metropolitan area, depending on its economic profile and business location pattern. Nevertheless, the two case study areas described here indicate how congestion impacts can differ depending on the nature of the congestion scenario. Although it was beyond the scope of this study to define or investigate the effectiveness of any particular transportation policies or strategies, some hypothetical scenarios were created to illustrate how they differentially affect business activity and costs.

Four types of scenarios were investigated: metropolitan-wide congestion reduction, congestion reduction focused on the central business district (CBD) only, congestion reduction focused on an older working class and industrial area, and congestion reduction focused on a white collar commuter area. The results were as follows:

- Truck delivery delays in the CBD. The economic impacts were dramatically different depending on where the congestion occurred. When congestion reduction centered on the CBD of both cities, the economic benefit was largely concentrated on those businesses located in the CBD. That is because many of those CBD businesses are service oriented, relying on incoming deliveries of supplies but with relatively modest movements of outgoing truck deliveries to other parts of the metropolitan area.
- Truck delivery delays in industrial zone. In contrast, when congestion reduction centered around an older industrial area in both cities, the economic benefits were widely distributed among industries and business locations throughout the metropolitan area. That is because the directly affected businesses had a high level of outgoing truck shipments serving broad industries and locations from the CBD to outlying fringe areas.
- Regionwide worker commuting delays. The economic impacts associated with worker access were also dramatically different depending on where the congestion occurred. When congestion reduction was evenly distributed regionwide, the economic benefit was still largest for those businesses located on the periphery of the metropolitan area. That is because there tend to be longer travel distances for workers and incoming deliveries coming into those businesses, and hence they are most highly affected by increases or decreases in congestion costs.
- Commuting delays for outlying residential areas. In contrast, when congestion reduction centered around an area with many skilled and educated workers, the economic benefit was broadly distributed among locations throughout the metropolitan area. It was also greatest for businesses that employed executives and precision-skilled workers.

The actual estimated costs of congestion depend on the specific scenario. For the test scenarios used for this study, annual changes in business costs associated with product and service deliveries were as high as $980 million/year in the Chicago region and $240 million/year in the Philadelphia region for the hypothetical scenario in which there is a regionwide average 2.5 percent reduction in average truck travel cost. For alternative scenarios in which there is a more concentrated 6.3 percent reduction in travel cost only in the CBD, the annual change in business cost for product and service deliveries was estimated to be $272 million/year in Chicago and $100 million/year in Philadelphia. The annual savings in commuting costs ranged as high as $350 million/year in Chicago and $200 million/year in Philadelphia for the hypothetical scenario in which there is a regionwide 10 percent reduction in average commuting time and cost.

DIRECTIONS FOR FUTURE RESEARCH

The findings from this study indicate six key directions for future research.

1. Examination of congestion impacts for additional classes of trips. This study focused on the measurement of congestion impacts on business product and workforce-related costs. It did not cover the value of congestion delay for personal travel or for shopping trips. In both cases, this was due to a lack of available interzonal data on trip patterns and trip lengths. Future research should attempt to acquire and analyze data on those classes of trips and how congestion affects them.

2. Estimating impacts of specific transportation policies and strategies. This study examined the impacts of simplified, hypothetical scenarios concerning reductions or increases in congestion. It did not examine relative costs and benefits of alternative transportation projects and policies to mitigate congestion. To address those issues in the future, methods developed from this study have to be applied in combination with separate analyses of the impact of potential transportation investments (and policies) on reduction of congestion delays.
3. Development of improved data on truck movements within metropolitan areas. Future improvements in congestion cost estimation also have to await improvement in availability of data on business-related travel patterns. Although metropolitan planning organizations have highly detailed origin-destination data on commuting patterns by industry and occupation (from census journey-to-work data), typically there are scant data on truck movements. This includes a lack of data on truck origin-destination zonal patterns, coverage of truck trips with outside origins or destinations, and industry/commodity breakdown for products being carried. Much of the existing metropolitan data on truck movements miss delivery of business products and services via car, van, and light delivery vehicles. Often they are also synthesized on the basis of partial information. In the future, such data can be improved through detailed breakdowns of the commodity flow survey (as specially obtained for this study) and better survey coverage of noncommodity business travel.
4. Model calibration and verification for additional metropolitan areas. This study involved substantial effort working with metropolitan planning organizations to obtain and derive interzonal data on trip patterns for specific trip purposes, industries, and occupations. Now that the methodology has been demonstrated to be feasible, further testing is needed to establish the level of consistency in statistical relationships (model elasticities) among a broader range of metropolitan area sizes and locations.
5. Analysis of long-term economic adjustment to congestion. This study focuses on developing estimates of the cost changes incurred by business when congestion is increased or decreased—given patterns of business location, scheduling, and operating technologies. In fact, businesses can in the longer run adjust operations and locations in response to congestion increases or decreases. In addition, changes in regionwide congestion levels can affect the cost competitiveness of doing business in a region and hence its longer-term economic growth. There is a need for further research to examine actual business behavior and to apply methods for estimating the magnitude of potential future impacts on regional economic growth associated with congestion changes.
6. Additional research on the service sector. This study treated producers of services as a single industry and considered a particular class of modeled trip, work-to-work trips, as a suitable surrogate. However, there is considerable variation within the service sector in terms of the reliance of various types of service-oriented businesses on transportation for their inputs and to deliver their services. A useful extension of this study would be to develop a more detailed understanding of the service industry through carefully designed surveys. Such an effort could yield quantitative information useful for model estimation as well as qualitative information on the relationship between congestion and the service industry, benefiting planners and decision makers.

APPENDIX A

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APPENDIX B

PRODUCTION FUNCTION MODEL SPECIFICATION

This appendix presents further details on the purpose, logic, and formulation of the technical approach that was used to estimate elasticities of substitution among capital and labor inputs and the impact of congestion on total business costs.

BACKGROUND

Purpose of the Economic Model

This study used a microeconomic framework to examine the link between urban travel delay (attributable to congestion), business operating costs, and business productivity. It built on the microeconomic concept of business production functions, which yield elasticities of substitution among differentiated labor and material inputs. This formulation was used to estimate the differing costs of congestion delay among types of business and their ability to substitute among labor and capital inputs to minimize those costs.

Difference from Aggregate Studies

This form of analysis is complementary to, but distinctly different from, the macroeconomic production function work of Nadiri and others, which estimated elasticities among aggregate-level highway investment and other capital investment in determination of national productivity. The key difference is that, whereas Nadiri's work examined the link between highway investment and aggregate productivity, this study examined the link between travel time changes and the productivity of specialized inputs based on microeconomic theory.

The Nadiri line of research has yielded estimates of the apparent return on highway investment, although it has not distinguished how changes in congestion levels or other aspects of transportation conditions affect those results. In contrast, this study did focus specifically on the economic effects of changes in transportation conditions. To estimate the rate of return on highway investment to reduce congestion, though, it is necessary to also have estimates of the cost of strategies to reduce congestion and the relative impact of such strategies on transportation conditions.

GENERAL APPROACH: LOGIC OF THE ECONOMIC MODEL

Overview of the Production Function Analysis and Its Interpretation

An important basis for the business cost analysis was the finding from the Phase I literature review that transportation costs are a significant component of total business cost. For freight, this includes not only the direct cost of vehicle operations and driver time (which comprise the traditional measure of user benefit and are reflected in the U.S. transportation satellite accounts) but also costs associated with logistics/stocking, scheduling/perishability, and just-in-time processing. For commuting, the literature review indicated empirical evidence that employers in competitive urban labor markets do end up carrying much of the burden associated with higher commuting costs.

However, it is known that businesses do not have to just absorb all the added costs of worker commuting or freight shipping caused by congestion. Instead, they have some ability to adjust to those cost changes. Thus, the introduction of realistic production functions can help to better calculate the true cost effects of congestion on business. The production function recognizes that one supply material is not a perfect substitute for another supply of the same commodity class any more than one employee is a perfect substitute for another in the same occupation class. Therefore, employers can enhance productivity by selecting the appropriate materials and employees for each job. The larger the market the employer has to draw on, the easier this task is. Because increasing congestion tends to increase the cost of shipping products and hiring employees and limits the effective size of the market for them, changes in the costs affect not only the cost of production but also the number and distance of freight delivery or commuting trips.

The business cost of materials and employees thus incorporates two components: (*a*) the cost of the product or worker in the absence of any shipping or commuting time, and (*b*) the additional compensation required to ship products or attract workers from any given zone to travel to a job in another given zone. For each industry and occupation, businesses may have a different elasticity of substitution among market opportunities for supplies and workers. This elasticity reflects how sensitive businesses are to changes in their costs. Products with specialized qualities and jobs with specialized skills tend to have a lower elasticity of substitution, which indicates that businesses seek them from a wide geographic area and are more willing to compensate for the higher costs of obtaining them. On the other hand, products with more common qualities and jobs with more common skills tend to have a higher elasticity of substitution, which indicates that businesses get them from wherever is convenient nearby and are less willing to pay additional costs to obtain them from farther away.

Explanation of the Theoretical Justification for the Model

A central aspect of the economic model is that we can calculate congestion costs by first estimating how industry type and location affect the elasticity of substitution among different labor and material (input) categories.

We first note that a major reason why economic activity can locate and thrive within urban areas—in competition with rural areas where labor and land inputs costs are often lower—is because the concentration of labor and material inputs in urban areas provides businesses with access to the inputs that meet their specific needs. The reason an urban area is necessary for this advantage arises from the choice of heterogeneous labor and material inputs that are uniquely available in areas that are more densely populated.

We can distinguish between two different types of differentiation. Vertical differentiation is associated with differences in quality. In this case, purchasers are willing to pay a higher price for the input that has the higher quality. Horizontal differentiation occurs when some purchasers choose one input while others choose a competing input even if it is offered at the same price or wage rate.

Of particular interest here is the extent of horizontal differentiation. In the case of labor markets, a person seeking employment has a wage below which he or she is not willing to be hired. This wage is called the reservation wage. A rational person seeking employment will adjust his or her reservation wage to reflect the time and other costs associated with commuting to that job. Thus, the reservation wage for a job across the street is lower for an individual than his or her reservation wage at a more inaccessible location. The parallel holds for supplies or materials, in which there is a basic price for products produced or services provided at the source and an incremental price for delivering the products or services to customers.

Businesses seeking materials or employees in a market with horizontal differentiation will thus be confronted with choices having different specialized characteristics and different reservation wages or base costs. If the differentiation is pronounced, we expect to observe some employees commuting long distances and some products being shipped long distances, even though there are nominally some closer suppliers and workers in the same product or occupation categories. On the other hand, if the extent of differentiation is small or almost nonexistent, then almost all businesses will obtain supplies or hire workers from the nearest supplier or labor pool.

The degree to which horizontal differentiation occurs can be quantified as an elasticity of technical substitution. This elasticity reflects how important the horizontal differentiation is in a particular market. It reflects how a given percentage difference in product cost or worker wage affects a business's choice of suppliers or employees. The size and location of firms and trip distances contains key information about the importance of supplier/worker differentiation and access to variety for different types of businesses, and this is reflected in the value of the elasticity of substitution.

High Elasticity of Technical Substitution

If the product market or worker pool is completely homogeneous (within a given product type or worker occupation category), then this elasticity of substitution is very high. In that case, suppliers or workers located outside the immediate area (whose costs are higher than those located closer) would not be hired. If, for example, congestion increased the delivered cost or reservation wage from a particular location by 1 percent, we would expect to see almost all the materials and workers from that area to be replaced by closer-in choices.

Low Elasticity of Technical Substitution

If, on the other hand, there is a very high degree of differentiation or specialization of materials (within a given commodity type) and employees (within a given occupation category), then the elasticity of substitution would be very low. In that case, an increase in cost for products or workers coming in from outside the immediate area would have relatively little impact on their use.

This preference on the part of businesses stems from the effect on productivity of having material inputs and employees that closely match the ideal set of characteristics that maximize output given a certain expenditure. The cornerstone of this analysis model is the fact that the elasticity of substitution for some types of material inputs and some occupation groups is higher than for others. This is true whether goods or services are being produced. The relationship is here represented with a constant elasticity of substitution production function for differentiated inputs (within each product type or worker occupation), which are combined assuming Cobb-Douglas substitutability (among product types or worker occupations).

Calculation of Accessibility Costs from Elasticities

By observing the product shipping patterns for each type of commodity or service, and the worker commuting patterns for each occupation, and knowing their shipping/commuting travel costs as a percentage of their total cost, we are able to estimate the elasticity of substitution for materials and labor. These elasticity estimates are important for calculating private firms' total productivity and costs because any increase in material shipping and labor costs will increase their costs. This means that the firm needs to pay a higher cost to retain their current suppliers or workforce or else substitute with other suppliers and workers who do not have the special characteristics they desire. If the elasticity of substitution is high, firms can easily replace distant suppliers or labor with nearby suppliers or labor at little loss of productivity or increase in costs. However, if elasticities of substitution are low, then the productivity and cost effects may be very large.

Importance of Access to Variety

With the presence of shipping cost, suppliers simply impose the cost on firms by asking a higher price to cover that cost. If products in each industry are homogeneous, then firms tend to buy products from suppliers located as close as possible, to minimize the product cost. On the other hand, if products are differentiated, then firms face a trade-off between the benefit of reducing shipping cost (by buying from suppliers close by) and the benefit of a productivity gain (from reaching out for a larger product variety).

Statistical details of the cost model specifications follow.

PRODUCTION FUNCTION FOR FREIGHT/SERVICE DELIVERY

Delivery Travel Model Specification

Consider a metropolitan area with N zones and n industries. The available supply of product of industry l in each zone is stt_i^l for zone $i = 1, 2, \ldots, N$ and industry $l = 1, 2, \ldots, n$. The demand for product l in zone i is dtt_i^l for $i = 1, 2, \ldots, N$. The shipping-free value of shipment is Trk_val^l. Letting cc_{ij}^l be the shipping cost from zone i to zone j for an average shipment of industry l (expressed as a percentage of shipping-free value of shipment), we can write total value of a shipment as

$$Trk\_val_{ij}^l = Trk\_val^l (1 + cc_{ij}^l) \tag{B.1}$$

It is assumed that firms in each zone produce output with the following constant elasticity of production function:

$$z_i^l = \left[\sum_{j=1}^{N} \left(\frac{tt_{ji}^l}{stt_j^l} \right)^{\frac{\sigma^l - 1}{\sigma^l}} stt_j^l \right]^{\frac{\sigma^l}{\sigma^l - 1}} \tag{B.2}$$

where z_i^l is the output level in zone i from product inputs in industry l. tt_{ji}^l is the number of truck trips from zone j to zone i in industry l. Note that the output level is higher when the supply in origin zone j, stt_i^l, is larger even if the same amount of inputs are used from that origin zone. This reflects the advantage the firm has from having access to a larger variety of inputs.

The assumption about firms' behavior is the following. First, firms produce at an output level fixed at the observed output level that can be calculated from Equation B.2 using the observed number of truck trips and the supply distribution in space. Second, firms minimize their cost with that fixed output level as the constraint and take the shipping-augmented truck value in Equation B.1 as given. Formally, the optimization problem in each zone for occupation l is

$$\min_{\{tt_{ji}^l\}} \sum_{j=1}^{N} tt_{ji}^l \cdot Trk\_val^l \cdot (1 + cc_{ji}^l) \tag{B.3}$$

$$s.t. \left[\sum_{j=1}^{N} \left(\frac{tt_{ji}^l}{stt_j^l} \right)^{\frac{\sigma^l - 1}{\sigma^l}} stt_j^l \right]^{\frac{\sigma^l}{\sigma^l - 1}} = z_i^l \tag{B.4}$$

The optimal set of truck trips derived from the above cost-minimization problem is

$$ett_{ji}^l = \frac{stt_j^l (Trk\_val_{ji}^l)^{-\sigma^l}}{\left[\sum_{k=1}^{N} stt_k^l (Trk\_val_{ki}^l)^{1-\sigma^l} \right]^{\frac{\sigma^l}{\sigma^l - 1}}} z_i^l \tag{B.5}$$

The estimated elasticity of substitution σ^l is the one at which the above theoretical trips match the observed actual trips the best in the sense that the likelihood to observe the actual trips is the maximum under the model assumptions. To estimate the elasticity of substitution by the maximum likelihood method, we need to make an additional assumption about the underlying stochastic process that generates the actual trips with the mean given in Equation B.5. This is done by assuming that the number of truck trips follows a Poisson distribution. To illustrate why this is the case, considering the decision of supplier in origin zone i regarding whether he or she will supply a firm in zone j, we can define the outcome of the decision as a Bernoulli variable

$$y = \begin{cases} 1 & if \quad Yes \\ 0 & if \quad No \end{cases} \tag{B.6}$$

The total number of shipments from i to j, tt_{ji}^l, then, is the summation of stt_i^l independent variables defined in Equation B.6. When the probability for supplier to ship products from i to j is small because of a large number of possible destination zones, and the total supply from origin zone i, stt_i^l, is large, the summation variable follows the Poisson distribution (Greene 1997).

With Poisson distribution, the likelihood function L can be written as

$$L = \prod_{i=1}^{N} \prod_{j=1}^{N} \left[\frac{e^{-ett_{ij}^l} (ett_{ij}^l)^{ct_{ij}^l}}{tt_{ij}^l!} \right] \tag{B.7}$$

and the log-likelihood function is

$$\log L = \sum_{i=1}^{N} \sum_{j=1}^{N} \left[-ett_{ij}^l + tt_{ij}^l \log(ett_{ij}^l) - \log(tt_{ij}^l!) \right] \tag{B.8}$$

If $\hat{\sigma}^l$ is the maximum likelihood estimator, then the standard deviation for the estimator can be calculated as

$$\Delta_{\hat{\sigma}^l} = \left\{ -\left[\frac{\partial^2 \log L}{(\partial \sigma^l)^2} \right] \right\}^{-\frac{1}{2}}_{\sigma^l = \hat{\sigma}^l} \quad \text{(B.9)}$$

Estimation of Shipping Costs

As we can see from the model specification, estimation of the economic shipping cost cc_{ij}^l is crucial to estimation of elasticity of substitution. For a given truck trip pattern, a higher shipping cost means that the variety effect must be more important to offset the shipping cost. Therefore, overestimation of shipping cost results in underestimation of the elasticity of substitution.

Two important costs are involved when a product is shipped by truck—namely, direct shipping cost and time variability cost. Direct costs include the depreciation of vehicles, cost of fuel, and maintenance and tire costs. On the other hand, time variability costs capture the cost or disutility of changes in travel time variability. Industries particularly sensitive to travel time variability are those in which there is a potential loss of value due to perishability of the shipment—for example, agricultural commodities—as well as just-in-time industries.

Formally, we can write the shipping cost as a percentage of the value as follows:

$$cc_{ij}^{l,1} = \frac{1.1 \cdot \left[Dir\_Cost_{ij}^l + JIT\_FAC^l \cdot PHR\_REL^l \cdot \frac{\sqrt{\text{var}_{ij}}}{60} \right]}{Trk\_val \cdot LD\_FAC_{ij}^l} \quad \text{(B.10a)}$$

where t_{if} is the shipping time by truck from zone i to zone j, $DIR\_Cost_{ij}^l$ is the direct shipping cost in dollars for industry l, JIT_FAC^l is an adjustment factor for a firm engaged in just-in-time manufacturing for industry l, PHR_REL^l is per hour value of reliability in dollars for industry l, and $LD\_FAC_{ij}^l$ is a load factor that reflects the fact that not all deliveries are truck load shipments for industry l. The entire expression is multiplied by 1.1 to reflect the fact that about 10 percent of all truck trips are empty.

For all industries except the services industry, direct shipping cost can be calculated as

$$DIR\_\ Cost_{ij}^l = \frac{(t_{ij} + t_{ji})}{60} \cdot Uni\_Cost^l \quad \text{(B.10b)}$$

where t_{ij} is the shipping time by truck from zone i to zone j, and Uni_Cost^l is the shipping cost in \$/h for industry l. On the other hand, direct shipping cost for the services industry is calculated as

$$DIR\_\ Cost_{ij}^9 = w^l \cdot \frac{(t_{ij} + t_{ji})}{8} + 1.3 \cdot w^l \cdot \sqrt{\frac{\text{var}_{ij}}{1000}} + (0.25(d_{ij} + d_{ji}))/2.5 \quad \text{(B.10c)}$$

where w^9 is \$108.75 and is computed as the average of the median daily compensation for technicians and related support (\$139.20) and services (excluding private households) (\$78.30). The distance matrix does not contain the internal distances within each zone. If we set the internal distance to zero, it causes some downward bias on the estimator of the elasticity of substitution by understating the shipping costs of close-by suppliers, hence overstating the relative shipping costs of farther away suppliers. Using a Monte Carlo method, we can estimate the shipping distance of internal trips. It is shown that one-third of the square root of the zone area is a good estimate of the average internal shipping distance. So we define

$$d_{ii} = \frac{\sqrt{A_i}}{3} \quad \text{(B.11)}$$

where A_i is the land area of zone i.

Estimation of Highway Congestion Scenario Impacts

In this section, we use the estimated elasticity of substitution to analyze the effect of a highway congestion change on business production cost in the case study metropolitan areas. In addition to the value of the shipment, firms have to incur the cost of shipping the product. Moreover, the size of supply that firms can access is reduced by the shipping cost, resulting in an additional cost to business due to a decrease in productivity. A convenient way to model the productivity gain due to the variety effect is to introduce a composite price index for each industry l for firms in each of the N zones. It can be shown that the composite price index is

$$Trk\_val_i^l = \left[\sum_{j=1}^{N} stt_j^l (Trk\_val_{ji}^l)^{1-\sigma^l} \right]^{\frac{1}{1-\sigma^l}} \quad \text{(B.12)}$$

Assuming that firms use capital, labor, and differentiated intermediate inputs for production with Cobb-Douglas production, we can write the cost of operation for firms in zone i as

$$q_i = (P_K)^{Kshare} \cdot (w_L)^{Lshare} \prod_{l=1}^{n} (Trk\_val_i^l)^{ishare} \quad \text{(B.13)}$$

where n is the number of industries, P_K is the price of capital, *Kshare* is the capital share in production, w_L is the wage rate, *Lshare* is the labor share in production, and *ishare* is the share of intermediate inputs in industry l.

A change in highway congestion scenario will change the shipping cost for some or all origin-destination zone pairs. Based on the new shipping cost matrix, firms minimize their cost by buying their input requirements from different zones with the output level fixed (see Equations B.3 and B.4). The optimal price index is determined by the shipping cost matrix and the available supply in each zone (as a partial equilibrium model, we do not consider long-run decisions such as relocation of firms). Because the shipping cost is only a small part of the truck value, changes in composite price indices due to congestion scenario changes tend to be small. Thus, the percentage change in unit cost Δq_i can be calculated as the average percentage change in composite price indices weighted over the production shares. That is

$$\Delta q_i = \sum_{l=1}^{n} (\Delta Trk\_val_i^l \cdot ishare) \tag{B.14}$$

where $\Delta Trk\_val_i^l$ is the percentage change in composite price index of industry l in zone i.

Now we consider a 10 percent uniform decrease in shipping time (2.5 percent decrease in transport cost) due to an overall reduction in congestion. We calculate the shipping total miles, total demand, and total input cost for each zone by each industry before and after the congestion scenario change.

Then, for the purpose of presentation, we aggregate these measures for selected areas. The fixed input cost reflects the change in input cost to firms if they buy the exact same inputs after the scenario change. For simplification, we call the six variables $x_1, x_2, \ldots, x_6$. The total input cost before the congestion scenario change is

$$x_5^1 = \sum_{l=1}^{n} \sum_{i=1}^{N} \sum_{j \in a} (ett_{ij}^l \cdot Trk\_val_{ij}^l) \tag{B.15}$$

where $j \in a$ means the destination zone is in area a. We can calculate the new total input cost x_6 by using the new shipping cost matrix and new optimal truck trip matrix. The new total input cost with no input substitution x_7 can be calculated by using the new shipping cost matrix and the old optimal shipping trip matrix. Finally, the shipping cost share before the scenario change is calculated as

$$x_8^a = \frac{x_5^a - \sum_{l=1}^{n} \sum_{i=1}^{N} \sum_{j \in a} (ett_{ij}^l \cdot Trk\_val^l)}{x_5^a} \tag{B.16}$$

The percentage change in total input cost is then calculated as

$$Y_1 = \frac{x_6 - x_5}{x_5} \tag{B.17a}$$

and percentage change in total shipping miles is

$$Y_2 = \frac{x_2 - x_1}{x_1} \tag{B.17b}$$

The percentage change in input productivity is the negative of the percentage change in demand. That is

$$Y_3 = \frac{x_4 - x_3}{x_3} \tag{B.17c}$$

Percentage change in average shipping distance is calculated by using the demand level and total miles shipped

$$Y_4 = \frac{x_2/x_4 - x_1/x_3}{x_1/x_3} \tag{B.17d}$$

Finally, the percentage change in total input cost with no input substitution is

$$Y_5 = \frac{x_7 - x_5}{x_5} \tag{B.17e}$$

The fact that the percentage decrease in total input cost with substitution Y_1 is greater than the percentage decrease in total input cost without labor substitution Y_5 justifies firms' decision to use a new combination of inputs. The productivity gain Y_3 comes at the cost of a longer shipping distance. A positive value for the percentage change in average trip length Y_4 shows that firms buy inputs farther away to reach a larger supply. Although the reduction in input cost due to the substitution effect is small, the effect on the shipping pattern is more significant.

It can be shown that the change in input cost in area a, IC^a, can be decomposed into three parts: change in input cost due to change in demand, which reflects the productivity gain; change in average shipping trip length; and change in average shipping cost per mile. If s is the shipping cost share in total truck value, then a 1 percent reduction in average shipping trip length or in average shipping cost per mile reduces the input cost by s percent only. Therefore, as a first-order approximation, we can write the percentage change in total input cost in area a as

$$\frac{\Delta IC^a}{IC^a} \approx \frac{\Delta D^a}{D^a} + s\,\frac{\Delta \bar{L}^a}{\bar{L}^a} + \frac{\Delta \bar{C}^a}{\bar{C}^a} \tag{B.18}$$

where $\bar{L}^a$ is the average trip length in area a and $\bar{C}^a$ is the average shipping cost per mile. If we express the above equation in xs and Ys then

$$Y_1^a \approx Y_3^a + x_8^a Y_4^a + x_8^a \frac{\Delta \bar{C}^a}{\bar{C}^a} \tag{B.19}$$

and the average shipping cost per mile can be calculated as

$$\frac{\Delta \bar{C}^a}{\bar{C}^a} = \frac{x_9^a \cdot x_6^a / x_2^a - x_8^a \cdot x_5^a / x_1^a}{x_8^a \cdot x_5^a / x_1^a} \tag{B.20}$$

where x_9^a is the shipping cost share after the scenario change and is calculated in a manner similar to x_8^a (in Equation B.16). Note that this equation can be used to calculate the change in average shipping cost per mile for the base case and the new scenario (both with and without input substitution) by substituting the appropriate values.

PRODUCTION FUNCTION FOR COMMUTER TRAVEL

Commuting Travel: Model Specification

In many econometric problems, counted random variables are assumed to be generated by Poisson processes. In our problem, numbers of commuting trips from one zone to another is a counted variable. We assume that trip numbers follow an independent distribution with their means determined by Equation B.21 below:

$$ct^l_{ab} = \frac{\lambda^l_b (w^l_b + cc^l_{ba})^{1-\sigma_l}}{\sum_{b'=1}^{n} \lambda^l_{b'} (w^l_{b'} + cc^l_{ba})^{1-\sigma_l}} D^l_a \tag{B.21}$$

where ct^l_{ab} is the expected number of commuting trips from zone a to zone b, w^l_b is the reservation wage of a worker living in zone b in occupation l for a job requiring zero commuting cost (we call this wage rate the commuting-free wage rate), cc^l_{ba} is the commuting cost incurred by a worker in occupation l to commute from zone b to zone a, λ^l_b is the number of workers in occupation l living in zone b as a percentage of the total number of workers in occupation l in the closed economy, and D^l_a is the demand of occupation l workers by zone a.

Commuting Travel: Model Estimation

The probability density function for the commuting trips of a certain origin-destination zone pair is

$$f(x) = \frac{e^{-ct} ct^x}{x!} \tag{B.22}$$

where x is the observed number of commuting trips, and ct is the expected number of commuting trips given in Equation B.21.

The maximum likelihood method can be used to obtain a consistent estimator of the technical elasticity of substitution in Equation B.21. The maximum likelihood estimator of the elasticity of substitution is the value for the technical elasticity of substitution at which we are most likely to observe those trips given in the data.

To calculate the maximum likelihood estimator for the technical elasticity of substitution σ, we calculate the total demand for labor D^l in occupation l and percentage supply of labor λ^l in occupation l in each zone

$$D^l_a = \sum_{b=1}^{a} ct_{ba} \tag{B.23}$$

$$\lambda^l_b = \frac{\sum_{a'=1}^{n} ct_{ba'}}{\sum_{a'=1}^{n} \sum_{b'=1}^{n} ct_{b'a'}} \tag{B.24}$$

We assume that the commuting-free wage rate in each occupation is the same in all zones and we use w^l to denote the market wage rate. This assumption allows us to minimize the effects of labor quality difference from various zones on the estimation. Then Equation B.21 can be rewritten as

$$ct^l_{ba} = \frac{\lambda^l_b (1 + rcc^l_{ba})^{1-\sigma_l}}{\sum_{b'=1}^{n} \lambda^l_{b'} (1 + rcc^l_{b'a})^{1-\sigma_l}} D^l_a \tag{B.25}$$

where

$$rcc^l_{ba} \equiv \frac{cc^l_{ba}}{w^l} \tag{B.26}$$

is the commuting cost of an occupation l worker commuting from b to a relative to his or her wage. Note that, although the dollar value of the direct travel costs are the same for workers in different occupations, the relative commuting costs are different for different occupations. For the same dollar value of commuting cost, the higher the wage rate, the lower the proportion to the wage rate.

CALCULATION OF TRAVEL TIME RELIABILITY

The procedure used for calculating travel time reliability is based on the analysis of delays caused by incidents as described in the Phase I report. The following equations were developed from extensive traffic data and incident delay techniques developed by Ball Systems engineering. Travel time reliability is defined as travel time variability (measured in terms of the variance of delay per vehicle mile). The equations developed to estimate travel time variability are shown below.

Equations for estimating mean and variance per mile of delay due to incidents (as a function of number of lanes and V/C ratio): average delay per mile due to incidents (h/mi)

Freeways with two lanes in each direction
$D = 0.0154(V/C)^{18.7} + 0.00446(V/C)^{3.93}$

Freeways with three lanes in each direction
$D = 0.0127(V/C)^{22.3} + 0.00474(V/C)^{5.01}$

Freeways with four or more lanes in each direction
$D = 0.00715(V/C)^{32.16} + 0.00653(V/C)^{7.05}$

where

D = average delay per mile due to incidents (h/mi), and
V/C = volume to capacity ratio.

TABLE B.1 Payload-to-truck conversion factors

	Less than truckload				Truckload			
STCC 2 code	50 mi	50–200 mi	200–500 mi	500 mi	50 mi	50–200 mi	200–500 mi	500 mi
1	7,020	8,814	8,364	8,118	14,975	18,803	17,844	17,319
8	11,756	11,589	9,117	8,300	25,080	24,723	19,450	17,706
9	6,654	7,039	7,188	7,199	14,196	15,016	15,334	15,357
10	14,472	11,168	9,487	9,173	30,874	23,826	20,239	19,569
11	14,472	11,168	9,487	9,173	30,874	23,826	20,239	19,569
13	8,806	10,505	9,397	7,828	18,786	22,412	20,047	16,701
14	14,472	11,168	9,487	9,173	30,874	23,826	20,239	19,569
19	6,654	7,039	7,188	7,199	14,196	15,016	15,334	15,357
20	6,202	6,389	7,512	8,047	13,231	13,629	16,025	17,166
21	6,654	7,039	7,188	7,199	14,196	15,016	15,334	15,357
22	4,550	4,553	6,838	7,300	9,706	9,712	14,587	15,574
23	4,550	4,553	6,838	7,300	9,706	9,712	14,587	15,574
24	7,508	8,750	8,254	7,938	16,017	18,666	17,609	16,934
25	2,460	3,607	5,250	4,542	5,247	7,696	11,200	9,689
26	6,547	6,622	7,504	7,638	13,966	14,128	16,008	16,293
27	6,547	6,622	7,504	7,638	13,966	14,128	16,008	16,293
28	6,590	8,277	7,946	8,976	14,059	17,657	16,952	19,150
29	8,806	10,505	9,397	7,828	18,786	22,412	20,047	16,701
30	4,949	5,481	6,379	7,059	10,559	11,694	13,609	15,060
31	6,654	7,039	7,188	7,199	14,196	15,016	15,334	15,357
32	8,046	7,405	7,550	7,150	17,164	15,798	16,108	15,254
33	7,465	7,876	8,208	8,487	15,925	16,803	17,511	18,106
34	4,509	5,764	6,103	7,225	9,620	12,297	13,019	15,414
35	7,790	6,639	6,233	6,731	16,618	14,163	13,297	14,359
36	7,790	6,639	6,233	6,731	16,618	14,163	13,297	14,359
37	5,497	6,121	6,073	6,497	11,726	13,059	12,956	13,860
38	7,790	6,639	6,233	6,731	16,618	14,163	13,297	14,359
39	6,063	5,616	6,324	6,793	12,934	11,981	13,492	14,491
40	7,074	7,334	7,342	6,630	15,092	15,645	15,664	14,145

Payload is in pounds.

To illustrate the application of these equations, consider a 5-mi (8-km) section of a three-lane freeway that operates at a *V*/*C* ratio of 0.80 and an average speed of 60 mph (96 km/h) if there are no incidents. With 0.80 plugged into the equations for three-lane freeways, $D = 0.00164$ and $V = 0.000503$. For the 5-mi section, the added delay due to incidents is 0.008 h,* the average speed drops from 60 to 54.6 mph (96 to 87,4 km/h),† and the standard deviation of travel time for the 5-mi trip is 0.05 h.‡

ESTIMATION OF SERVICE TRIPS FOR THE PHILADELPHIA REGION

Data limitations did not allow for an independent estimate of elasticities for service trips in the Philadelphia region. Unlike the Chicago model, the Philadelphia regional transportation model does not produce estimates of work-to-work trips based on survey data. Instead, the elasticity estimates for Chicago were used in the Philadelphia congestion cost analysis, which is presented in the Phase II Report. However, a trip table of service trips must first be developed.

* $5 \times 0.00164 = 0.008$.
† $1/(1/60 + 0.00164) = 54.6$.
‡ $(5 \times 0.000503)0.5 = 0.05$.

Service trips for the Philadelphia region were developed in two steps: a simple trip generation equation was derived from the Chicago data, and the resulting trips were converted to a set of origin-destination pairs through the estimation of a trip distribution model.

A simple regression analysis of total employment and service trips was performed on the Chicago data set. The results are as follows: $E_s = 0.183974 \times E_t$, where E_s is service employment and E_t is total employment. The goodness-of-fit statistic for this regression and *t* statistic as shown below indicate a reasonable result from the regression.

Parameter estimate	R^2	*t* statistic
0.183974	0.9904	234.02

The resulting equation produced a matrix vector of service trips when applied to the Philadelphia employment data. To distribute these trips over the Philadelphia traffic zone system, a simple trip distribution model was developed with the following form:

$$T_{ij} = \frac{P_i A_j F_{t(ij)}}{\sum_{j=1}^{n} A_j F_{t(ij)}}$$

where

T_{ij} = number of trips between origin i and destination j,
P_i = number of production (origin) trips from zone i,
A_j = number of attraction (destination) trips to zone j, and
$F_{t(ij)}$ = friction factor describing the decrease in service trip making as trip length increases.

The friction factors are derived from a curve statistically fit to origin-destination trip and travel time data. Such a curve was fit to the Chicago travel time and origin-destination service trip data set. These friction factors were used in the trip distribution model for Philadelphia. Finally, an internal balancing procedure that is part of the trip estimation process ensured that, overall, the total number of trips summed over all origins would equal the total trips summed over all destinations.

The final trip matrix comprises 496,134 trips, compared with 874,391 for the Chicago region.

CONVERSION OF COMMODITY FLOW DATA TO TRUCK TRIPS

The productivity model requires origin-destination truck flows at the traffic zone level. The original data set obtained for model estimation contained origin-destination tonnage at the county or region level. The steps required to convert the data included the development of ton-to-truck conversion factors by commodity and the development of county-to-zone splitting factors. The ton-to-truck conversion factors were developed through an analysis of the most recent data available in the truck inventory and use survey. These factors are stratified by distance and two-digit Standard Transportation Commodity Code (STCC) and are presented in Table B.1. To distribute trips from the county to the traffic zone level, employment categories were associated with the three broad categories of trips developed in relation to commodity truck movements: manufacturing, mining, and agriculture. Factors based on distribution of employment among traffic zones within each county in the metropolitan area were then developed and applied to the aggregate trip file.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

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