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POLICY RESEARCH WORKING PAPER 1554

Rationing Can Backfire

The "Day Without a Car" in Mexico City

In Mexico City, a ban restricting each car from driving on a specified work-day actually increased total driving and congestion.

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Summary findings

In November 1989, Mexico City's administration imposed a regulation banning each car from driving on a specific day of the week. The regulation has been both popular and controversial. Some feel that it is a reasonable concession aimed to alleviate congestion and pollution problems. Others feel it is both inefficient and unfair: inefficient in the way most rationing systems are inefficient, and unfair in that it is costly to some and easily avoided or accommodated by others.

Some feel that it may be so inefficient that it is counterproductive. And Eskeland and Feyzioglu found evidence to support that view. Many households bought an additional car to get additional "driving permits," and the amount of driving increased. Greater use of old cars and increased weekend driving may have contributed to the disappointing results of Mexico's one-day ban on driving: high welfare costs and none of the intended benefits.

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Rationing Can Backfire:
The 'Day Without a Car' in Mexico City

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We would like to thank our colleagues without implicating them.

1. Introduction and Summary

In November 1989, the Mexico City administration imposed a regulation that banned each car from driving a specific day of the week[1]. The regulation has been both popular and controversial: some feel is a reasonable concession from each car owner - aimed to alleviate congestion and pollution problems. Others have felt that it is inefficient and unfair; inefficient in the way most rationing devices are inefficient, unfair because it will be particularly costly to some - easily avoided or accommodated by others. Finally, some feel that the regulation may be so inefficient that it is counterproductive - increasing the levels of congestion and pollution - because some have purchased additional cars to circumvent the ban, and end up increasing their driving. The authors of this study find evidence in support of the latter view.

This paper aims at analyzing this question in a pragmatic, policy oriented fashion. Section 2 briefly presents the idea that the effects of rationing can be analyzed by comparing the demand reductions with those one would obtain by market based implementation mechanisms - mechanisms that systematically rank trips for elimination according to willingness to pay. This theoretical framework is sufficient to illustrate that rationing will entail at least as high welfare costs (using the compensation criterion) as would a market based mechanism producing the same reduction in driving.

Section 3 presents an empirical framework for estimating the demand reductions provided by the regulation. A model of gasoline demand is estimated using aggregate time series data from before the regulation, and used to simulate a counterfactual for demand in subsequent periods - as if the regulation had not been introduced.

Surprisingly, the results of the model are that the regulation - after an initial adjustment period of about six months - actually increased total driving rather than reducing it. The result was surprising because the simple theoretical model allowed for the possibility that regulation should be a costly way of reducing demand, but not that it should be counterproductive in reducing demand.

We pursue the investigation a little further by noting three particular features of this market:

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[1] Called *Hoy no circula* (this one doesn't circulate today), the "Day without a Car" regulation specifies that license plate numbers ending with digits 0 or 1 does not drive on Monday, 2 or 3 not on Tuesday, etc. The regulation applies to all cars (except those of the fire department), and thus to firms as well as households. We use the term household, for simplicity. Registration officials report that "Friday plates" are the least popular among licence plate applicants. Compliance is generally believed to be high - police is visible and fines are heavy.

(a) due to the integer nature of cars and the fact that cars effectively come bundled with "*work-day driving permits*", some households will want *more* cars once their existing cars are made less useful by the regulation; (b) multiple drivers in a family could mean that total car use increases even though an additional car is purchased primarily to substitute for the family's existing car on *its* banned day; (c) effects of congestion, substitution between trips, and differences in fuel efficiency all could blur the basic expected reduction in gasoline consumption per car. Among these possibilities, we are able to investigate empirically only (a) and (b). For (c) we can only add some tentative calculations of plausible numbers.

In section 4, we estimate a car ownership model based on household survey data. The focus is on the fact that cars come in lumpy units, while income and other explanatory variables are continuous variables. Thus, a household owning one car may be in an income range where it is almost indifferent between owning zero or one car, while another one-car household is indifferent between owning one or two. When the regulation effectively expropriates a part of the car's service flow, some households in the first category will rather have no car, and some in the second category will rather buy an additional one, to have two. Whether total demand for cars go up or not depends on some coincidence between the income distribution of households and the income ranges in which the first and second car purchases typically take place.

Our estimated model indicates that the groups are of about the same size - but there will be somewhat more car sellers than buyers. Thus, while increased ownership would have made it easier to understand the observed increase in total gasoline consumption - our model (based on pre-regulation ownership data) does not succeed in capturing and predicting such a response. We discuss some known weaknesses of the model that we are unable to address - in particular transaction costs in the used car market - which would indicate that some "sellers" will decide not decide to sell (this would be an asymmetric correction to the model's predictions: no similar culling of "buyers" would result from transaction costs).

In section 5, we discuss the unresolved puzzles in the light of potential features that our model may have failed to capture. Use *per car* might increase if trips substitute imperfectly for each other

and if less convenient travel is compensated for by more travel[2]. Also, if conditions are congested on workdays, and workday travel is sensitive to congestion, then removed work-day trips in part will be compensated for by additional travel responding to reductions in congestion, so that a slight increase in week-end driving can be enough to leave driving per car unchanged or increased. Finally, casual observation in Mexico City indicate that many families have bought an additional old car, with the effect that Mexico City has imported used cars from the rest of the country[3]. If these cars are less fuel efficient, then it is possible that gasoline consumption would increase as a result of the regulation even if aggregate car use was constant, or slightly reduced.

In section 6, we conclude by making two points: (1) We highlight our finding that car use was increased (or at best held constant) by the regulation, but admit that there are remaining puzzles about what combination of specific mechanisms produced this result. (2) We remind the reader of the original empirical question: how does this rationing scheme compare to market based instruments in terms of the welfare costs of demand reductions? That question was, in the end, rendered uninteresting - as the rationing scheme was found *counterproductive* in delivering demand reductions. With this finding, we also make no apology for not investigating whether the rationing scheme has merits on distributional grounds that could compensate for its problems in the arena of efficiency.

2. Market Based Versus Regulatory Demand Management

Instruments to economize on polluting trips may be gasoline taxes, driving bans, parking fees, toll rings and subsidies to public transport.[4] But when consumers sacrifice trips in response to demand

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[2] One must think carefully about the units involved. As an illustration with other goods, think of beer as an imperfect substitute for wine. If wine prices go up, beer consumption would swell, and in *liters* possibly by more than the observed reduction in wine consumption. For car use, if a leisurely trip (to visit grandma or to go shopping) is moved from Wednesday afternoon to Saturday, it may very well end up being a longer trip.

[3] An admittedly unrepresentative survey (100 households surveyed for a newspaper at a fee-charging parking lot) found 39 percent of drivers stating that an additional car had been their response to the regulation

[4] We shall use *pollution* as metaphor for the policy objective (which may be pollution, congestion, etc.), and *trips* or *gasoline* as metaphor for associated goods, services and inputs. Congestion charges and pollution charges are first-best instruments: if they are used, reductions are provided at the lowest possible welfare costs. Often, and some times with good reason (such as the high costs of monitoring individual flows of emissions) such instruments are not in use. Eskeland (1994) and Eskeland and Devarajan (1995) show how many real world pollution control strategies could be improved by including instruments that discourage car use directly. The reason is that existing programs provide incentives to make cars and fuels cleaner (standards), but fail to discourage their use. Berndt and Botero (1985) and Eskeland and Feyzioglu (1994) estimate demand

management instruments, what are their welfare costs of doing so? We shall make the simplifying assumption that transfers of income can be made costlessly with other instruments - between households, and between the private and the public sector. This allows us to abstract from analysis of income distribution effects, and to apply no penalty or premium to public revenue generation.

Importantly, when a trip is sacrificed due to a marginal increase in the gasoline price, the value of the sacrificed unit to the consumer is the retail price of gasoline. Thus, while there are inframarginal units of gasoline (and trips) that are worth more to consumers, a gasoline price increase will screen out, systematically, the trips that are worth the least. This property of the gasoline tax allows it to reduce trips at the lowest possible welfare cost.

Demand reductions resulting from a regulation will rarely have this selection quality. The "Day without a car program" may curtail trips in households with a very high willingness to pay, and it may block a household's Tuesday-driving, say, even if the household could more easily have sacrificed other trips. Both of these effects resultbecause the regulation does not allow 'trading' of the rationed commodity, with the result that the regulation curtails inframarginal as well as marginal trips. If we compare it with a gasoline tax that would have yielded the same demand reduction as a regulation, the unit costs of the demand reductions delivered by the regulation will be at least as high, and possibly much higher. An illustrative comparison of the welfare cost of a regulation and a tax increase calibrated to give the same demand reductions is shown in Figure 1 below. A key assumption in this argument is that the regulation, if providing emission reductions at all, would provide these through its impact on *aggregate* gasoline consumption. Then, using market forces to allocate *any* reductions (in gasoline consumption, this time, rather than in emissions) will assist in containing the costs of the reductions.

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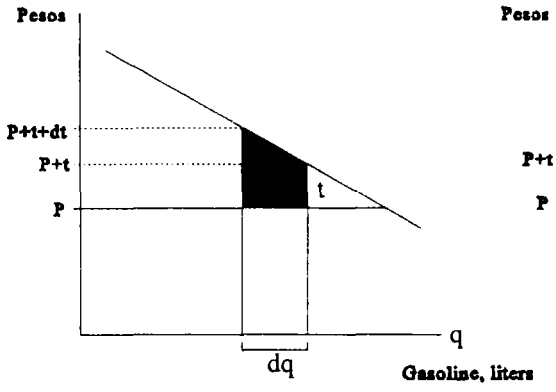
relationships in Mexico, finding demand elasticities for gasoline in the range of -0.7 to -1.25.

Cost of Increase in Tax, dt



Welfare Cost of Driving Ban

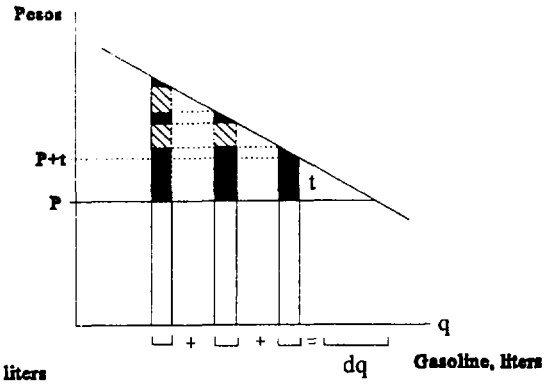


Figure 1:
The crossed area in the figure to the right illustrates the extra costs when the demand reduction is found on different parts of the demand curve, rather than squeezed to the right, selecting the least essential trips, as a tax increase would.

With the particular rationing mechanism used in Mexico City, issues are slightly more complex, because the demand reductions provided by the regulation are unknown. First, the ration applies to the utilization of a plant (the vehicle) which was not at the outset fully utilized (24 hours a day, 7 days a week). For this reason, if users can move trips from one day to another, or exchange car services (on Tuesdays, I drive twice my distance, to pick you up, and on Thursdays, you return my favor), vehicle kilometers may remain unchanged by the regulation even if the number of vehicles were to remain the same. Second, households can purchase an additional car, thereby purchasing four work-day "driving-permits" and 2 weekend "permits". This could increase the total car stock in Mexico City or redistribute car ownership between households with different utilization rates[5]. The latter opportunity places, in effect, an upper bound on the costs of compliance for a household: no household will be subject to a higher cost of compliance than the costs of holding an additional car (for many households, the upper bound is lower, since an additional car would yield benefits additional to substituting for the other car on the banned day). The effect on total driving will depend

[5] There is casual evidence that Mexico City has attracted used cars from the rest of the country.

on the effect on the total car stock, as well as on the distribution of cars amongst households according to usage. We turn now to the estimation of the effect on total driving, as measured by aggregate gasoline demand in the Metropolitan Area.

3. Aggregate Gasoline Consumption

In this section, we investigate the behavior of the aggregate gasoline consumption in Mexico City Metropolitan Area around the time of the ban. We trace the consumption pattern from January 1987 through December 1992. The consumption level is given in Figure 3; driving ban became effective approximately in the middle of the sample. We assume that aggregate gasoline consumption in Mexico City depends on gasoline price and income:[6]

$$c_t = \alpha_0 + \alpha_1 p_t + \alpha_2 y_t + e_t \qquad t = 1,\ldots,T \tag{1}$$

where, c_t is the total gas consumption, p_t is the weighted average of the gasoline prices (types of gasoline, by share in total use), and y_t is income. All variables are in logarithms, therefore coefficients α_1 and α_2 are interpreted as price and income elasticities.

The hypothesis is, of course, that the imposition of the restriction changes consumption patterns, i.e. shifts the demand function (1). Such a change can be in the form of an alteration of the level of consumption, with no change in the elasticities, change in the elasticities without any change in the level, or both. To capture these possible changes, it is standard to introduce a dummy variable that is zero before the restriction was imposed, and one after. This dummy variable and its interaction with price and income would indicate statistically discernible changes in the demand function related to the restriction.

To test the zero hypothesis that the demand function has been changed, we estimate equation (1) with dummy variables for the periods under regulation. The estimation technique and tests applied are discussed in Appendix 1.[7] The estimated elasticities are given in Table 1.

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[6] Other variables like congestion factor, overall car quality, number of cars would have helped, but are not available.

[7] Quarterly data are used. Appendix 1 describes the data, and examines the series for properties related to the econometric estimation. We conclude after testing for unit roots, stationarity etc. that ordinary least squares estimation is appropriate.

Table 1:
Estimated Gasoline Demand Function: Elasticities[8]

	Without Regulation	Under Regulation	Probability of no change
Gasoline Price	-0.24	-0.06	0.05
Income	0.83	1.63	0.05

The key result is that there is a substantial change in the gasoline demand function associated with the regulation. While consumption becomes more elastic with respect to income, it becomes less elastic with respect to gasoline prices. Levels, in terms of the estimated constant, shifts too. We can see the effect of the change in the demand function for the relevant income and price ranges in Figure 2. The constancy term has shifted downward, but in the area of observation the demand surface under regulation is *above* the demand surface without regulation. This is related to the fact that the price and income elasticities have shifted upwards, (the price elasticity downwards in absolute terms).

To quantify the change in gasoline consumption, we simulate consumption to establish a *counterfactual* -- as if the regulation had not been implemented. We estimate the demand function based only on data from the period before the regulation and simulate the counterfactual for demand developments in subsequent periods[9]. The simulated values are shown in Figure 3, together with realized demand figures. The figure also shows a 95% confidence interval for the simulation of demand without the regulation. The simulation indicates that, had the demand system not been subjected to a structural shift at the end of 1989, demand would have been *lower* in all but the two first quarters after the regulation (within the confidence of plus minus one standard deviation of the estimated coefficients).[10]

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[8] The estimated constant, which also changed, is not shown.

[9] We use materialized values of price and income for years 1990 to the end of 1992 and plug them into the function estimated for the first period, to produce the demand simulation. We thus assume that the structural change in the demand system would not have occurred, but that the exogenous variables, gasoline prices and income, would have developed as they did.

[10] In another simulation, we focused on the uncertainty ex ante, inserting *forecasts* of price and income in the demand model, using univariate forecasts (assuming that the shocks to the demand system were known, but future developments in prices and income were not). When taken individually, price looks like a white noise, and income is stationary around a positive trend. We forecast price using only its mean, and income using the estimated trend. The results are more dramatic: These

Figure 2

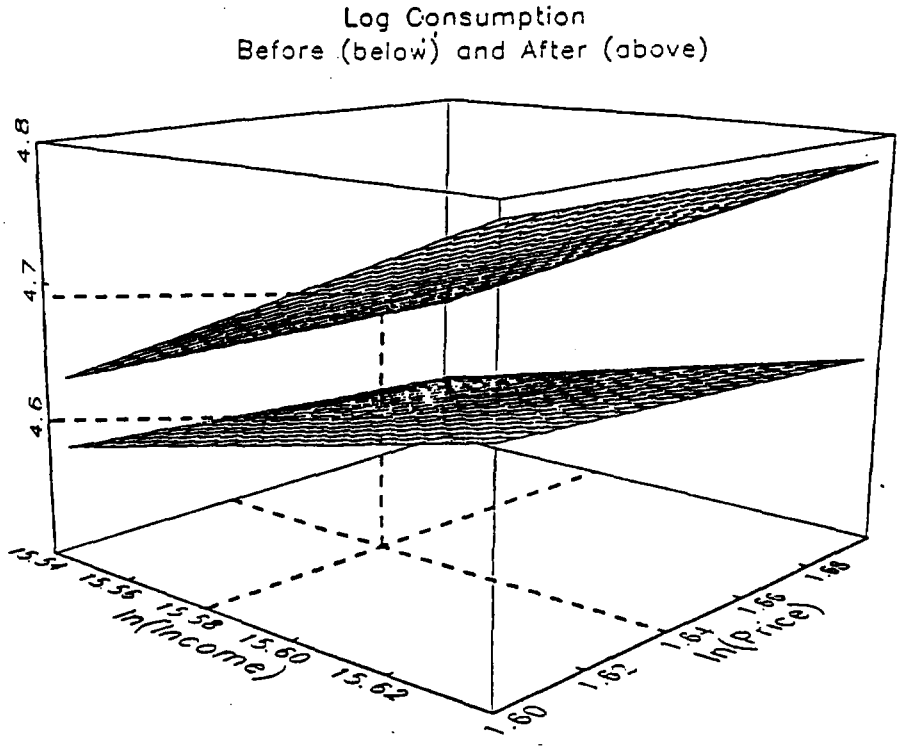
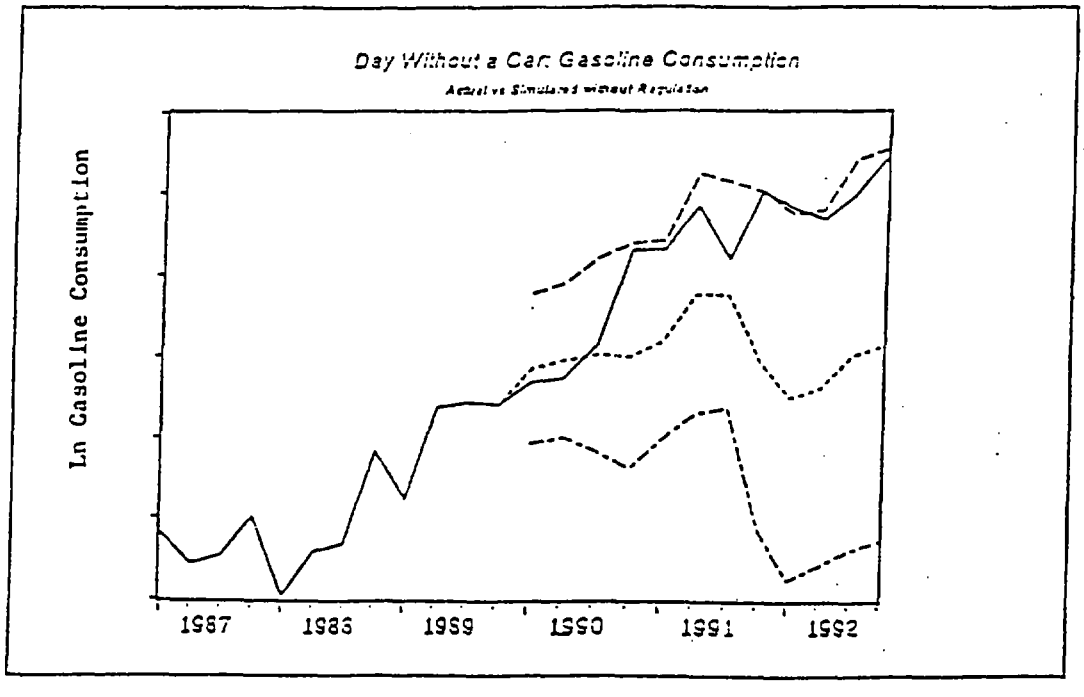


Figure 3



ex ante simulations give lower demand than those realized. Realized demand is outside the confidence interval for all but one observation (note that the confidence intervals do not take into account that the variables used are forecasted too).

The enforcement of the ban is considered to be at least partially successful. While it is not impossible that the regulation should increase usage per car (if one drives extra to "drive around" the regulation - driving longer to pick up a friend than you save when being two in a car) a more likely explanation is that the regulation provoked an increase in the number of cars in the Metropolitan Area - since each car implicitly comes with four "work-day driving permits".

If the regulation leads to some increased car purchases in subsequent periods, while incomes grow, then this could partly be reflected in an expanded income elasticity for gasoline demand. Similarly, gasoline prices increased after the regulation, but the estimate for the price elasticity in that period could be suppressed by two effects: car stocks were given a boost simultaneously, and the car stock could perhaps have been shifted to some extent from marginal, price sensitive users to less price sensitive users.

One way of interpreting the findings from the aggregate time series model, therefore, is that many vehicle-owning households in the outset were in a situation and an income range for which an additional vehicle would be the best response when the service flow from each vehicle was partially expropriated[11]. To examine this hypothesis, we now turn to data from a general-purpose household expenditure survey from the year 1989. It was executed before the regulation, and we will use it to study the socioeconomic determinants of vehicle ownership.

4. Household Behavior

In this section, we look at the car ownership from a household perspective. The advantage of such an approach is that the determinants of car ownership at the household level can yield insights about likely individual reactions to a driving ban. We first present a model of car ownership: a discrete choice model with household characteristics and socioeconomic variables as determinants. We then use household data from Mexico City to estimate the model parameters, using cross section variation from a period prior to the ban. We then make the assumption that demand for the service flow of vehicles is the motivation for owning vehicles, and use the model to simulate behavior when

[11] The "additional car" for those in the outset owning a vehicle is a simplification, based on the presumption that the regulation reduces the service flow only for those presently owning vehicles. If one vehicle in the outset were providing services to several households, say, bringing three household heads to work every day, one would see the regulation cutting service flows to two non-owning households as well, one of which could purchase its first vehicle as a result.

part of the flow is expropriated by the driving ban. Finally, we interpret the results.

4.1 Model

Households are constantly faced with the decision of allocating their scarce resources optimally across durables and non-durables (as well as savings). Let us assume that a durable (such as a car) is owned because of the value of the service flow it offers, and that households behave optimally given their preferences, constraints and resources. Then, for all households owning a car, the net value of the service flow, after subtracting short term variable costs, exceeds the fixed costs of owning the car.

We concentrate on their allocation decisions between car services and other goods and services, assuming that car ownership affects household utility through the net value of its service flow and the budgetary resources demanded.[12] Each household's allocation decision depends on characteristics determining its need and desire for car services, as well as on their income. For example, we expect a car to be more useful the more the people there are in the household, due to economies to scale in utilizing the car's capacity. At the same time, however, for a given household income, more individuals may make a car less affordable. Another expected effect is that cars are in higher demand the higher the wages, since higher wages increase the value of time savings for a given household income.

As distant analysts, we observe the household's choices and a partial list of the household characteristics that could be associated with these choices. We proceed in two steps: *(i)* to understand what, among the characteristics we observe, determines how many cars a household decides to own, and *(ii)* to use this understanding to predict how their choices would change when the service flow from each car is restricted.

We assume that the household maximizes a household utility function subject to a budget constraint:

$$U(TCS_i, OC_i) \qquad i = 1, 2, \ldots, m \tag{2}$$

[12] Ben-Akiva and Lerman discusses in detail the assumption underlying discrete choice modelling, emphasizing car ownership and travel mode choice models. Berkovec (1985) estimates a car ownership model based on U.S. data.

$$I_i = p_c D_i + p_o OC_i \tag{3}$$

where, U is the utility function for household i, TCS_i is the transportation services household i obtains from the its cars, D_i, OC_i is the consumption of all other goods and services, I_i is the total expenditure of household i, p_c is the annualized cost of owning and using a car, and p_o is the price of all other goods and services.[13]

We restrict the choices to three: no car, one car, and two or more cars; this is to simplify the notation and to be consistent with the underlying data.[14] We assume that the value of the service flow family i obtains from owning j cars is a function of the characteristics of the family:

$$TCS_{ji} = f_j(z_i) \qquad j = 0, 1, 2. \tag{4}$$

where z_i is a vector of household characteristics, and $f_j(z_i)$ allows corresponding differences amongst households in the utility they gain from services of j cars. A household would optimally choose to own one car only if more cars, and no cars, both would make it worse off.

We shall introduce the possibility that the household's car ownership decision also depends on unobserved variables. Then, the observed variables are determinants of the *probability* of a household owning j cars, since some of the household's unobserved characteristics may lead them to choose a different number of cars. We assume that on average, the effects of these unobserved characteristics add up to zero. Hence, the the assumption that the observed choice, $y_i = j$, is optimal implies that the probability of household i choosing j vehicles is the probability that its total utility is maximized by owning j vehicles[15]:

$$Prob(y_i = j) = Prob(U_i(j) > U_i(k)), \qquad k,j = 0, 1, 2, \quad k \neq j \quad i = 1, 2, \ldots, m. \tag{5}$$

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[13] Prices in this cross-section of households from Mexico City are assumed to be uniform.

[14] In our data of 1037 households, only 2% possess more than 2.

[15] This is a joint probability distribution: $U(j) > U(i)$, and $U(j) > U(k)$, $j \neq k$, $j \neq i$. For a similar modelling, see Manski and McFadden (1981).

where $k,j=2$ denotes two or more cars. The model lets us analyze the possible effect of a driving ban. A driving ban would diminish the total car services a household gets, which in turn effect the probabilities of owning a car. Such modifications are discussed in sections 4.3 and 5.

4.2 Results

Car ownership is given by equation (5). This probability can be expressed in terms of observables once we assume that household utilities are linear in their arguments and that errors have a log Weibull distribution:[16]

$$Prob(y_i = j) = exp(X_i\beta_j)/(\sum_{k=0}^{2} exp(X_i\beta_k)), \qquad j = 0,1,2 \quad i = 0,1,...,m \tag{6}$$

where X_i includes household characteristics as well as total expenditure (one may interpret total expenditure as a proxy for disposable income). Household characteristics and total expenditure feed into the utility functions through the coefficients β_0, β_1, and β_2. For example, β_1 tells us the importance of each of the household characteristics and income in determining the value of one car, relative to none, and β_2, similarly, for two cars. If $X_i\beta_1$ is greater than $X_i\beta_2$ and $X_i\beta_0$, household i would choose to own one car. Since utility functions are estimated on the basis of ordinal rankings, the interpretation of the coefficients is how the variable increases the utility of having j cars, as opposed to having zero cars.

As household characteristics, we used number of children in the household (Child), number of adults (Adult: proxying, perhaps inter alia, for driver's licenses), number of people with high level and intermediary level education (HighEd) and (MedEd), and average wages earned by the wage earners (WagePW). The vector of exogenous variables include these household variables plus a constant (C), and total expenditure (TotExp), which we may interpret as disposable income.

We estimate the parameters of the model by maximizing the multinomial logit likelihood function that is defined in Appendix 2. We use a two step procedure: first maximizing the likelihood

[16] See Appendix 2 for the derivation.

function with respect to all variables, subsequently re-estimating the model using only the variables that were significant in the first step. The results are given in Appendix 2, Table A2.1. To give an impression of how well the model fits actual car ownership, we compare actual with predicted in Appendix 2, Table A2.2. The results indicate that the more children a household has, or the more of the members have higher education, the more they prefer to have a car, given similar incomes. The importance of education and wages per worker is higher for the second car. Approximately 72% of the households' car ownership decision is captured by the model.

4.3 Simulation of a reduction in the service flow from each car

In this section, we use our model of car ownership to examine the likely response to a driving ban. We take the estimated utility functions as given, and use the parameters to simulate the response to the car useage restriction.[17]

The ban effectively reduces the service flow a household gets from each car it ows. If it owns more than one car, then we make the simplifying assumption that it can substitute one for another on the restricted days, so the restriction has little or no effect[18]. Such a reduction in car services due to a ban is reflected in the model as follows: for households with one car, the utility becomes

$$U(\alpha_1 * TCS_i, OC_i) \tag{7}$$

where α_1 summarizes the effective car useage restriction for one car, α is equal to one for

[17] This approach is potentially vulnerable to a "Lucas critique": There is no guarantee the regulation would not also change the parameters of the estimated car ownership model. However, given the aim and ambition of this study, the assumption that the estimated parameters are *not* themselves changed by the ban seems to be a plausible baseline for the analysis of the likely response to a ban. The nature of the experiment is to assume that we know something about how the value of car ownership will be changed. We perform sensitivity analysis and discuss potential weaknesses in the concluding section.

[18] If the household has only one driver, this would be accurate. For a two-driver household, the regulation cuts the service flow from two cars 5 workdays to 2 cars 3 workdays and 1 car 2 workdays. Thus, if a two-car household would otherwise use its second car only 3 days a week, this assumption is accurate. Otherwise, it is an approximation, and it would be wrong if households with two cars have the same difficulty managing without every car on each workday as has a one-car household. Our modelling assumptions should be interpreted as the effective reduction in the value of the service flow for a one car household in comparison to a multicar household.

households with more than one car, and no change is also assumed for households without any car[19]. For households with one car, if travel days have no substitutability and the car is used only every workday, α_1 amounts to 4/5; if the car is used approximately evenly acoss the week and the weekend, then α_1 would be 6/7. If a household can comply with the restriction without losing any service value (say, it is used for some trips every week, but they can be moved from one day to another without any costs) then α_1 would be 1, and on the other extreme, if the household needs the car exactly on the day the restriction is binding, α_1 would be 0. This latter case represents an unlikely possibility, given that the car registry process as well as the car market allows owners to influence which weekday is banned for their car.

Once the value of the car's service flow is restricted, the households' optimization problems have changed (we assume, in these calculations, that prices do not change, including those of used cars). Households for whom the value of the service flow at the outset only marginally exceeded car ownership costs may want to sell their car. Others, on the other hand, will buy additional cars. Some households that owned only one car may now find a second car justified because it can substitute for the expropriated service flow and perhaps provide additional services. Finally, we assume that households without cars will not change their behavior, since optimization theory implies that an added constraint can change the optimal choice only if it bars the originally optimal choice.

In Figure 4a, we have illustrated the main mechanisms, by "condensing" the model to a two-dimensional one: utility as a function of income given that the household owns zero, one or two cars.

For each household, a separate utility level is calculated under three different pre-regulation scenarios: given that it owns zero cars (U_0), given that it owns one car (U_1), and given two or more cars (U_2). We plot these utilities against their income levels.[20] Given their income and other

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[19] Loosely speaking, optimization theory shows that a constraint making cars less useful can change behavior only for households that would, in the absence of the constraint, want to have a car. We shall see later that a it may be overly simplistic to describe the regulation as merely making cars less useful: if it reduces congestion, it might make the road network more useful, and cars more useful to some, including to some that would otherwise choose not to own cars.

[20] The curves are drawn as follows: For U_1, use the estimated one-car coefficients, plugging in the variables for each household in the data set in, to calculate 1037 utility levels, given that they have one car. Next, regress these utility levels in a univariate OLS model to a constant and total expenditure. For U_2, follow the same procedure, but with the two-car coefficients. U_0 is only a comparator - the horizontal line. U_1', utility as a function of income given one car under the restriction, is calculated using a shift parameter alpha of .8 (see text).

Figure 4.a
Utilities under different scenarios

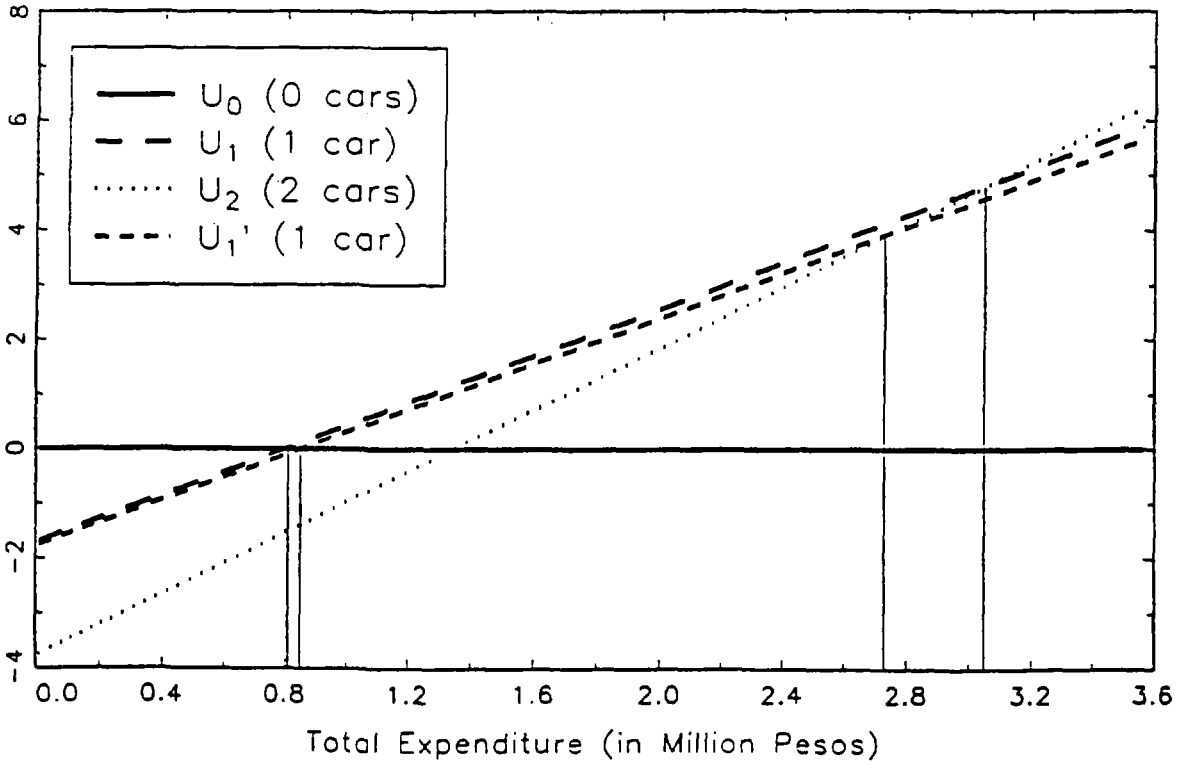
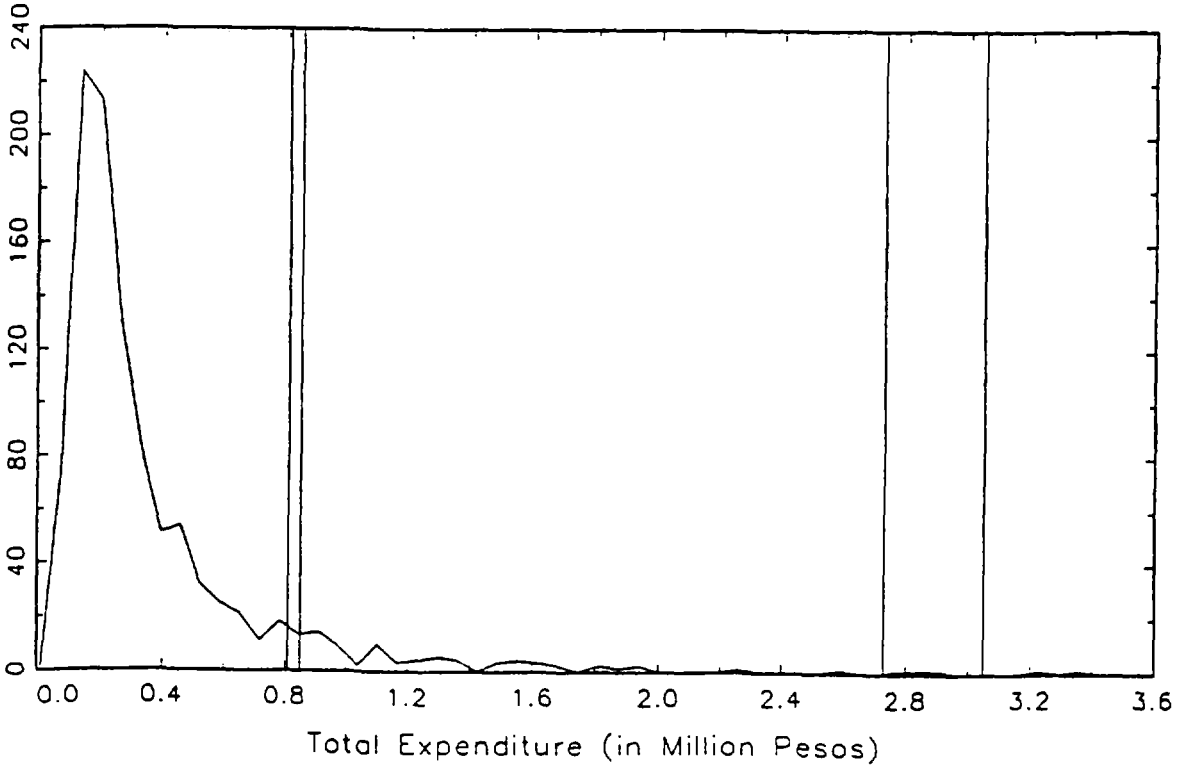


Figure 4.b
Total Expenditure Frequency



characteristics, households choose the number of vehicles that give them the highest utility. We can see that each of the conditional utility functions U_0, U_1 and U_2 has an income range for which it gives the highest utility. This is the income range for which that specific number of cars is optimal. For the lowest income range, U_0 is highest, so zero cars is the optimal choice for households in that range. As income increases, the utility of having one car increases (the slope of U_0 is normalized to zero). In the income range to the right of where U_0 and U_1 intersect, households typically own one car. At an even higher income range, households typically own two or more cars.

U_1' shows the utility of having one car after the restriction is imposed, using a restriction factor of 80% (i.e. 80 percent of the service flow remains). As compared to U_1, U_1' lies lower, and we thus have a reduction in the *size* of the income range for which one car is the optimal choice. Actually, two new income ranges of relevance appear. The first one represents an income range for which the optimal number of cars has shifted from one to zero. These households, in this simplistic model, would sell their car[21]. Another effect of substituting U_1' for U_1 is a range of incomes in which households would want to expand vehicle ownership from one to two (or more). The two zones reflect that the income threshold that a household needs to have passed in order to buy its first car has moved upwards, while the income threshold for buying a second car has moved downwards.

Figure 4b graphs the income distribution of the households surveyed. We can see that there is a greater density of households in the range of sellers than in the range of buyers, but the latter range is larger. Finally, the latter region is supported by greater per-household incomes.

For sensitivity analysis, we can use alternative restriction factors to calculate the total number

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[21] Simplicity refers in particular to (i) used car prices, and (ii) sunk costs. Used car prices are assumed to be unaffected by the ban. When part of the service flow from cars is expropriated, ceteris paribus the value of used cars would fall. However, for the regulation in question, cars simultaneously are given a value as bundles of implicit driving permits, so the effect of the regulation on (used) car prices is not known a priori. The working assumption underlying the estimation of who would buy and who would sell cars is: given that used-car prices are unchanged.

A separate simplification is when we abstract from the sunk cost aspect of investing in a car. If car purchases involve sunk costs (households would generally make a loss if first purchasing, then selling a car, even if it has not deteriorated), then uncertainty would lead households not t o invest before they have progressed far into the income region in which they would like to *hold* a car. This effect, not reflected in this analysis, introduces an asymmetry if a regulatory change reduces the service flow from a car: owners who would want to sell, had there been no sunk costs involved, will hesitate, and many of them will not sell. No corresponding hesitation applies to the households that would want to purchase an additional car. These effects are explored in the option pricing theory (not buying a car leaves you with the option of buying one later), and this particular effect is called *hysteresis* (Dixit and Pindyck, 1994, pg 136). In a market for used cars, transactions costs may be high due to asymmetric information about quality, giving a theoretical underpinning for the existence of sunk costs (Akerlof, 1970).

of cars to be bought and sold as a result of the restriction, maintaining the simplifying assumptions that there are no transaction costs for cars and that prices do not change. Results for different restriction coefficients are given in Table 4.

Table 4
Simulation of the Effects of the Regulation
(as percentage of predicted car stock)

α_1	Sellers	Buyers
0.95	5%	3%
0.90	8%	6%
0.85	11%	8%
0.80	14%	12%
0.75	18%	16%

The model indicates that, for restriction factors in the range of .8 to .9, about 10 percent of car-owners would want to adjust the number of cars they own. It also indicates, however, a somewhat greater number of "sellers" than of "buyers". Thus, if the model were completely adequate, and Mexico City were a closed economy, one would expect used-car prices to be shifted downwards as a result of the restriction, to allow net car purchases to be zero in equilibrium[22]. Most observers believe that Mexico City imported used cars from the rest of the country, implying that, in reality, more households wanted to buy than sell. Such a finding would also be more consistent with our finding in section one - an increase in total gasoline consumption is most easily explained by an increase in the total number of cars registered.

Our analysis can not be used to shed more light on that question, apart from showing that a very simplistic model results in a number of sellers in the same order of magnitude as the number of buyers. As we have noted (footnote 18), one of the simplifying assumption, the absence of sunk costs in car purchases, could imply that we overestimate the number of households that would want to sell,

[22] Used car "values" for *Mexico* are provided only for insurance purposes, and reflect standard depreciation factors rather than market conditions.

whith no similar bias for the number of buyers. There are many other ways in which the analysis is overly simplistic, however, such as the lumping together of all multi-car households in a category owning two or more cars, and the assumption that underlying parameters are not changed by the regulation.

The contribution given by this section was *(i)* to provide a theoretical model of car ownership, showing how a regulation creates buyers as well as sellers, and *(ii)* estimate a simple model to explore orders of magnitude. While the model cannot be said to lend direct support for an expansion in car ownership in Mexico City as a result of the regulation, it indicates that the number of "buyers" will be substantial.

5. Congestion, and week-end travel: An attempted Reconciliation

In the above cross section model, the direct way in which the regulation works is to make cars less useful. As such, one would expect a reduced interest in car ownership, as indeed the model indicates. Even in the simplistic model estimated, however, increased aggregate interest in car ownership could not be ruled out a priori. Taking the restriction factor of 90% as a point of reference, however (Table 4), the model indicates that interest in car ownership would fall by about two percent (8 percent of car owners would sell, 6 percent would buy). In contrast, the model based on time series analysis of aggregate gasoline demand - the only one which includes analysis of post-regulation behavior - indicates that the use of cars were increased. In this section we discuss features not included in the ownership model which could account for its lack of consistency with observed consumption levels. The arguments will explore additional model features, and whether plausible parameter values can reconcile the findings.

First, let us note that the ownership model assumes that the regulation reduces the service flow from your car *ceteris paribus*. With high congestion levels, as the service flow from other cars is reduced as well, congestion levels will go down, travel speeds will pick up, in turn making the car more useful to you. To explore this effect, let demand, v^d (we now represent the vehicle and its services with one variable, abstracting from the distinction between ownership and use) consist of an exogenous component, k, and a component sensitive to travel time, t (say, the average time that it takes you to drive to work, given the congestion levels) $v^d = k + v(t)$. Further, to describe the road

network's capacity, let travel time be a function of demand, $t=t(v)$. If the regulation makes a reduction in the exogenous component of demand, k, the equilibrium effect will be dampened by a *resurge* due to increased speeds (details in Appendix 3):

$$\frac{dv}{dk} = \varepsilon^{d}_{v,t}\ \varepsilon^{s}_{t,v} + 1 \tag{8}$$

The first elasticity (travel demand with respect to times) is negative. The latter (The elasticity of the road network's supply of travel time, with respect to additional entering vehicles) is positive, so the speed-induced resurge implies that any direct effect that a regulation will have on demand will be dampened. We can see that if either of the elasticities - or both - is zero, the equilibrium effect on demand will simply be the direct effect: a car removed from the streets on Tuesday simply reduces overall traffic on Tuesday by one car. On the other hand, if the two elasticities mulitiplied by each other approaches minus one, then the equilibrium reduction after reducing traffic by one car on Tuesday is approaching zero - since other vehicles enter the roads to take advantage of the reduced congestoin.

To speculate on likely parameters, we solve (Appendix 4) a model in which cars are bought partly because of the time savings they offer, l^v, partly because consumers derive utility from their services (l^v is the difference between the travel time by alternative mode and the travel time by car, so the elasticities differ in sign and by the fraction of time savings to travel time - which may be one). The model shows that:

$$\varepsilon_{v,l^v} = -\frac{w \cdot l^v}{p_v}\varepsilon_{v,p_c} \tag{9}$$

Thus, the elasticity of vehicle demand with respect to time savings is equal to minus the elasticity with respect to vehicle prices, corrected for the role that the value of time savings play in motivating car purchases: $w \cdot l^v/p_v$. Thus, assuming that the value of time savings, $w \cdot l^v$ justifies three quarters of the costs of car ownership and use (i.e the car also delivers some "direct" utility, apart from time savings, accounting for 25 percent of its value), then the elasticity of vehicle demand with respect to time savings is three quarters of the elasticity with respect to the costs of owning and using a car. Thus,

since demand elasticities with respect to price for cars, or for gasoline (a combination would better reflect ownership *and* use) are often found in the range of -.5 to -1.25 (See Eskeland and Feyzioglu, 1994, or Berndt and Botero, 1985), values for the demand elasticity with respect to travel times in the range of -.5 to -1 would appear plausible.

For supply conditions, only a few estimates exist in the literature for how travel times (or speeds) respond to additional vehicles entering the road, and none exist for Mexico City. In severely congested conditions the elasticity is greater than one, meaning that the entry to the road (or the network) of an additional vehicle reduces the total throughput of a road link. From Kenneth Small's book ("Urban Transport Economics, model 3.5, page 70 - no link to Mexico City), an elasticity of 2.5 reflects conditions in the middle of a range. Turning back to equation 8, above, we can see that combinations of demand and supply elasticities which would allow the resurge in demand to "wipe out" almost all of a reduction in traffic is not implausible; a demand elasticity of -.8 found by Eskeland and Feyziogly, for instance, would result in a travel time demand elasticity of .6, which requires the supply elasticity to be not higher than 1.5. The congestion-induced resurge can, however, only make an adjustment to the direct demand reduction approaching but not surpassing hundred percent[23]. Thus, even with some additional travel demand due to greater speeds, an initial, direct reduction of vehicle demand can only be reduced - it can not be changed into an increase[24].

So how, then, could a reduction in traffic on weekdays - however slight it be - conceivably result in an increase? One unmodelled mechanism that could reconcile these findings is to distinguish between weekdays and weekends. It is evident that total gasoline consumption could increase if the increase in weekend travel resulting from the regulation is as large as the reductions in weekday travel. If weekend travel was perfectly substitutable with week-day travel, all trips suppressed on weekdays would show up as weekend trips, but such an effect is not necessarily plausible. Now, however, we have seen that a significant share of an initial reduction in week-day travel is compensated for by a resurge on the same weekdays in congestion sensitive travel. Then it is not so

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[23] Thus, in the case of traffic, we can preclude effects like the one observed for Baseball audiences by Yogi Barra:"Nobody comes to the stadium anymore - it's too crowded".

[24] The stability condition that a reduction in traffic should not lead to an increase in traffic is a very plausible one: as soon as the resurge in traffic approaches hundred percent of the removed traffic, travel times are actually approaching those under the initial conditions, so the travel-time sensitive part of demand can hardly surpass the hundred percent point.

implausible that an increase in total driving could be the result of a regulation on work-day driving - though it does imply that more travel is one of the costs of less convenient travel.

6. Summary and conclusions

We estimated a demand function based on time series, aggregate data, to analyze the aggregate reductions in driving resulting from the driving ban. The time series analysis indicated strongly that total car use in Mexico City was shifted *upwards* by the regulation, indicating that positive net car purchases should play a major role (since one would expect the many households that would not increase car ownership to reduce, or keep unchanged, their car use).

Assuming that car ownership is motivated by the service flow that cars offer, we then introduced a model of the individual household's ownership decision. Using household survey data from Mexico City to estimate the model, we simulated individual responses to the ban. This model showed that some households would want to buy more cars as a result of the regulation, while a somewhat greater number of households would want to reduce their number of cars.

The cross section model has a known weakness in the assumption that cars are bought and sold without transaction costs, and that car prices would be unchanged by the regulation. The first of these could mean that many households predicted to sell would not want to sell, so that the number of predicted sellers is overestimated. Thus, the model sheds some light on the observation that the regulation increased total car use. It shows that adjustments in car ownership status will be significant, and thus that increased car ownership in Mexico City would not be implausible, even though it is not directly predicted by the model.

We then noted features excluded in the model. One is that congestion sensitive travel demand could imply that a resurge in travel demand on weekdays due to reduced congestion could eliminate much of the direct travel reduction. If, then, some supressed weekday trips would show up as weekend trips (or if some extra travel is part of the consequences of inconvenient travel) - then more of the pieces in the puzzle may be in place. Another is that use-weighted travel may have shifted towards less fuel efficient cars, opening the possibility that aggregate gasoline consumption would increased even if travel were constant or slightly reduced,

From the perspective of policy making, the lessons are somewhat stronger than our

confidence in the estimated sign of the change in car use. The reason is that any reduction in car use can be achieved by instruments which, if we refer to theory and invoke the compensation criterion, can always provide the reductions at a lower social cost than a regulation. Thus, even if one rejects the conclusion that aggregate car usage was *increased*, one may see the *small* reductions as evidence that the rationing scheme resulted in high compliance costs for many households. The high compliance costs are an important lesson in itself, but not less so if many sought a compliance strategy which implied that they offered negative or zero reductions in car use. Finally, if that compliance strategy involved acquiring a used car with lower technical standard, it could result in contributions to accidents and pollution which are worse than what is indicated by total gasoline consumption.

One should observe, finally, that the arguments about *social costs* in this study do not imply that we have analyzed consequences in terms of income distribution across households. Indeed, disentangling the income distribution effects of awarding driving permits to existing and future cars, while expropriating a certain fraction of these, would be a sizeable analytical task. We have abstained from analyzing them (and comparing them to those of alternative demand management instruments) for this reason, but also because we suspect more important distributional goals would pertain to households not owning cars, and that other policy instruments could attain likely distributional goals at lower social costs[25].

[25] Eskeland and Kong (in process) analyzes distributional implications of various pollution control strategies for Indonesia (a study for Mexico, by other authors, is in progress).

Appendix 1

Time Series Properties and Estimation Results of the Aggregate Data

A1.1 Time Series Properties:

In this section, we analyze the time series properties of each variable separately. There are two issues that we pay special attention to: seasonality and non-stationarity. Test results for each series are reported in Table A1.1.

Table A1.1

Time Series Properties of Aggregate Data

	Gasoline Consumption	Gasoline Price	Income
Unit Root in ACF	No	No	No
Unit Root in ADF	No	Yes	No
Deterministic trend	Yes	No	Yes
Seasonality	No	No	Yes

ACF: Auto-Correlation Function

ADF: Augmented Dickey-Fuller Unit Root Test

Given these results, we seasonally adjust income. For price series, due to conflicting results from DF and ACF, we made further tests. Price in itself is not the focus point, but rather as a factor that affects consumption. We therefore run a regression with consumption, price and income. We know that consumption and income are stationary. This implies that the residual will have the same stationarity properties as the price. Our tests show that the residual is stationary. We therefore, conclude that, for our purposes, it is sufficient to model price as a stationary variable.

A1.2 Regression Results:

We estimated equation (1) using OLS:

Table A1.2

Regression of Aggregate Gasoline Consumption

Dependent variable: Ln(Total Consumption)

Variable	Coefficient	Standard error	1-tail Significance
Constant	-7.93	5.40	0.08
Ln(Price)	-0.24	0.08	0.00
Ln(Income)	0.83	0.35	0.01
Dummy	-12.57	7.02	0.05
Dummy*Ln(Price)	0.18	0.10	0.05
Dummy*Ln(Income)	0.80	0.45	0.05
Adjusted R-squared	0.96	F-statistic	113.04
Durbin-Watson stat	1.99	Prob(F-statistic)	0.00

$Dummy_t = 0 \quad 1987.1 \leq t \leq 1989.4$

$= 1 \quad 1990.1 \leq t \leq 1992.4.$

Appendix 2
Derivation and Estimation of Household Choice Model

A2.1 Derivation

First, we combine the budget constraint and the definition of total transportation services from cars with the utility function by substituting equation (3) and equation (4) into equation (2):

$$U_{ji} = U(f_j(z_i),(I_i - p_c D_j)/p_o). \tag{A2.1}$$

where, U_{ji} is the utility of household i if it were to have j cars. Second, we assume that the utility function is linear in its arguments:

$$U_{ji} = \mu_{ji} + e_{ji} \qquad j = 0,\ 1,\ 2 \qquad i = 1,\ 2,\ \ldots,\ m. \tag{A2.2}$$

and $\mu_{ji} = X_i\beta_j$.

Third, we establish the probability distribution of owning j cars. For the the probability of i's not owning any vehicle, we obtain

$$\begin{aligned} Prob(y_i = 0) &= Prob(U_{0i} > U_{ki}), \qquad k \neq 0, \\ &= Prob((e_{0i}-e_{1i} > \mu_{1i}-\mu_{0i}),\ (e_{0i}-e_{2i} > \mu_{2i}-\mu_{0i})). \end{aligned} \tag{A2.3}$$

If e_{ji} has a log Weibull, then, the probability of choosing j vehicles is a logistic function:

$$Prob(y_i = j) = exp(X_i\beta_j)/(\sum_{k=0}^{2} exp(X_i\beta_k)), \qquad j = 0,1,2 \qquad i = 0,1,\ldots,m \tag{A2.4}$$

This is equation (6) in Section 4.

For estimation, since utility is ordinal, we normalize utility to be zero for the case of no cars, so that the model estimates the additional utility from owning a positive number of cars. The

decision process is restated in terms of deviations from the utility of owning no cars:

$$Prob(y_i = j) = exp(X\beta_j')/(\sum_{k=0}^{2} exp(X\beta_k')), \qquad j = 0,1,2 \quad i = 0,1,...,m \tag{A2.5}$$

where $X\beta_j' = X\beta_j - X\beta_0$. The decision process of number of cars to own by all households can be put together into a standard multinomial logit likelihood function:

$$L = \prod_{i=1}^{m_0} P(y_i = 0) \prod_{i=m_0+1}^{m_0+m_1} P(y_i = 1) \prod_{i=m_0+m_1+1}^{m_0+m_1+m_2} P(y_i = 2) \tag{A2.6}$$

where, m_0, m_1, and m_2 indicate number of households in each cathegory in the data set that is sorted with respect to number of vehicles owned.

A2.2 Results

Results from household data are given in table A2.1.

Table A2.1
U(j cars) - U(no car) = $X\beta_j + e$

Variable (X)	β_1 (one car)	β_2 (two or more cars)
Constant	-2.37 (0.21)	-4.92 (0.27)
Child	0.12 (0.05)	-
Adult	-0.19 (0.07)	-
Second. Lev. Education	0.20 (0.08)	-
High Lev. Education	0.79 (0.11)	1.32 (0.12)
Wage per Worker	0.12 (0.03)	0.19 (0.03)

Total Expenditure	1.62 (0.27)	1.87 (0.28)

Standard errors are in paranthesis. Some variables are not included in the second column of the results because they were not significant in the first stage. All the coefficients are significantly different from zero with 95% confidence.

The interpretation of the coefficients are as follows: The coefficient of wage income is 0.12 for 1 car, which means that if the average wage income of the household increases by 1, then the extra utility they get from owning a car as opposed to not owning any is 0.12. The corresponding coefficient for 2 cars is 0.19, which means that if wage income increases by 1, then the extra utility of owning 2 cars as opposed to 1 or no car is 0.07 and 0.19 respectively. Similar interpretations follow for the other coefficients.

The predictive power of the model is illustrated by in Table A2.2.

Table A2.2

Car Ownership: Actual versus Predicted

		Predicted			
		No Car	1 Car	2 Cars	Total
Actual	No Car	654	36	4	694
	1 Car	172	60	17	249
	2 Cars	25	38	31	94
	Total	851	134	52	1037

Finally, while using a restriction factor of 0.8, as is used in Figures 4a and 4b, 33 come out as sellers, while 38 of the one-car households would want an additional car (these figures are reflected in Table 4, line 4). As predicted percentages of the stock of cars among the 1037 households, indicated purchases and sales come out as 12% and 14% respectively.

Appendix 3
Equilibrium change in traffic when there is an exogenous change in demand for travel

The question we ask in this section is how travel responds in equilibrium if the road's capacity to supply rapid travel times is declining in traffic levels and if travel demand is sensitive to congestion levels.

Say demand for vehicle use is the sum of two components: one depends on congestion levels, represented by the time you will spend making a certain trip, t - the other demand component is exogenously given:

$$v = f(t) + k,$$

while the road-link's capacity to get the vehicle through within a certain time depends on the number of vehicles entering the road:

$$t = g(v).$$

The following condition identically represents equilibrium:

$$v = f(g(v)) + k$$

Imagine now that a regulation produces a reduction in the exogenous part of travel demand. For equilibrium travel, we have:

$$\frac{dv}{dk} = \frac{\partial f}{\partial t}\frac{\partial g}{\partial v} + 1 = \varepsilon^{d}_{v,t}\varepsilon^{s}_{t,v} + 1$$

The demand elasticity of travel with respect to travel times is negative (travel times go up, you are less interested in travelling), while the supply elasticity of travel times with respect to entering vehicles is positive (more vehicles on the road, traffic slows, travel time for a given trip rises). Thus, unless one of the elasticities (or both) are zero, the equilibrium effect on travel will be less than one, i.e. less than the exogenous reduction in demand. A stability condition is that the multiplum of the two elasticities be greater than minus one - otherwise a reduction in traffic would lead to an increase in traffic, and we can see that any combination of elasticities which yields a mulitiplum close to or equal to minus one would reflect "Downs law": any change leading to a reduction of congestion levels would immediately lead to an increase in travel demand swamping the initial effect, so that congestion levels are back at "normal".

More cautiously argued, what are plausible values? For supply, we can immediately establish that $\varepsilon^{s}_{t,v} = 0$ represents an extreme case of road conditions in which vehicle density is so low that an additional vehicle does not slow down other vehicles. Positive values represents "natural conditions" in which there is a positive shadow price for road capacity (natural for urban roads and intercity highways, see Hau, 1989) and values greater than one represents heavily congested

conditions, in which and additional vehicle reduces the total throughput of the road-link per time unit (a one percent increase in entering vehicles increases travel times for all vehicles by more than one percent).

For the elasticity of travel demand with respect to travel times, what are plausible values? The following modelling framework, focusing on vehicle travel as a timesaving alternative to other alternatives, may shed light on that question.

Appendix 4
A model with time savings as part of the motivation behind the demand for vehicles

Let utility be defined over cars, other goods and services, and leisure, $u = u(c,o,l)$, and let the individual budget constraint be $p_c c + o = w(\overline{L} + l^c c - l) + I$, where the price of other goods and services is normalized to one, l^c are the time savings offered per vehicle (c is to be interpreted as a continuous variable - we may view this as a model of a representative consumer), L is the endowment of human capital, and I is lump sum income.

The Lagrangian of the consumer's maximization problem can be written:

$$L = u(c,o,l) - \lambda(p_c - wl^c)c + o - w(\overline{L} - l) - I)$$

The first-order conditions are:

I $\quad u_{cl} = \dfrac{-(p_c - wl^c)}{w}$,

II $\quad u_{ol} = \dfrac{-1}{w}$

III $\quad (p_c - wl^c)c + o - w(\overline{L} - l) - I)$

where u_{cl}, u_{ol}, are marginal rates of substitution. The interpretation of the first equation is that the value of time savings "justifies" parts of the costs of cars, and this part is subtracted from the cost, p_c / w, that would otherwise be equated with the marginal rate of substitution between cars and leisure.

To study relationships between demand elasticities, let us differentiate the first-order conditions with respect to the time savings offered per car:

$$\frac{\partial u_{cl}}{\partial c}\frac{\partial c}{\partial l^c} + \frac{\partial u_{cl}}{\partial o}\frac{\partial o}{\partial l^c} + \frac{\partial u_{cl}}{\partial l}\frac{\partial l}{\partial l^c} = 1$$
$$\frac{\partial u_{ol}}{\partial c}\frac{\partial c}{\partial l^c} + \frac{\partial u_{ol}}{\partial o}\frac{\partial o}{\partial l^c} + \frac{\partial u_{ol}}{\partial l}\frac{\partial l}{\partial l^c} = 0$$
$$(p_c - wl^c)\frac{\partial c}{\partial l^c} + \frac{\partial o}{\partial l^c} + w\frac{\partial l}{\partial l^c} = wc.$$

Let us give name to the coefficient matrix:

$$A = \begin{bmatrix} \frac{\partial u_{cl}}{\partial c} & \frac{\partial u_{cl}}{\partial o} & \frac{\partial u_{cl}}{\partial l} \\ \frac{\partial u_{ol}}{\partial c} & \frac{\partial u_{ol}}{\partial o} & \frac{\partial u_{ol}}{\partial l} \\ p_c - wl^c & 1 & w \end{bmatrix}$$

Assuming A is nonsingular, we may use Cramer's rule to solve for:

$$\frac{\partial c}{\partial l^c}|A| = \begin{vmatrix} 0 & \frac{\partial u_{cl}}{\partial o} & \frac{\partial u_{cl}}{\partial l} \\ 1 & \frac{\partial u_{ol}}{\partial o} & \frac{\partial u_{ol}}{\partial l} \\ wc & 1 & w \end{vmatrix}.$$

Similarly, when we differentiate the first-order conditions with respect to car prices, we obtain:

$$A \begin{bmatrix} \frac{\partial c}{\partial p_c} \\ \frac{\partial o}{\partial p_c} \\ \frac{\partial l}{\partial p_c} \end{bmatrix} = \begin{bmatrix} 0 \\ -\frac{1}{w} \\ -c \end{bmatrix}.$$

Again using Cramer's rule, we have:

$$\frac{\partial c}{\partial p_c}|A| = \begin{vmatrix} 0 & \frac{\partial u_{cl}}{\partial o} & \frac{\partial u_{cl}}{\partial l} \\ \frac{-1}{w} & \frac{\partial u_{ol}}{\partial o} & \frac{\partial u_{ol}}{\partial l} \\ -c & 1 & w \end{vmatrix}.$$

For matrix A, let C_{kl} be the cofactor of row k, column j. We may write

$$\frac{\partial c}{\partial l^c}|A| = C_{21} + wc \cdot C_{31}$$
$$\frac{\partial c}{\partial p_c}|A| = -\frac{1}{w}C_{21} - c \cdot C_{31}.$$

Thus:

$$\frac{\partial c}{\partial l^c} = -w\frac{\partial c}{\partial p_c} \Rightarrow \frac{\partial c}{\partial l^c}\frac{l^c}{c} = -\frac{\partial c}{\partial p_c}\frac{p_c w l^c}{p_c} \Rightarrow$$

$$\varepsilon_{c,l^c} = -\varepsilon_{c,p_c}\frac{wl^c}{p_c}.$$

Thus, the elasticity of car demand with respect to the time savings offered per car is wl^c/p_c times minus the elasticity of car demand with respect to car prices. Referring back to first-order condition 1, we may see that wl^c/p_c is the share of time savings in justifying car purchases at the margin (the other share being the direct utility drawn from cars):

$$\frac{-u_{cl}w + wl^c}{p_c} = 1.$$

It remains to relate the concept of time savings to the concept of travel times: an analysis of the road is more likely to give you a change in travel times than a change in time savings.

So let us note that:

$$\frac{\partial c}{\partial l^c}\frac{\partial l^c}{\partial t} = \frac{\partial c}{\partial t} \Rightarrow \frac{\partial c}{\partial l^c}\frac{l^c}{c}\frac{t}{l^c} = -\frac{\partial c}{\partial t}\frac{t}{c} \Rightarrow$$

$$\varepsilon_{c,t} = -\varepsilon_{c,l^c}\frac{t}{l^c}$$

The adjustment thus is simply the ratio of travel times to time savings offered by the car. It takes positive values, and would often be in the range of .5 to 2. For instance, if your regular trip takes you half an hour, and the alternative would have been a bus & walk combination that takes 1 hour, then both time savings and travel times are half an hour, and $\varepsilon_{c,t} = -\varepsilon_{c,l^c}$. On the other hand, if your car trip is twenty minutes and the alternative mode would take you thirty, your elasticity of travel demand with respect to travel time is double your elasticity of travel demand with respect to time savings (not because of different behavioral response - rather because a given change in travel time is smaller as a percent of travel time than as a percent of time savings, but it leads to the *same* change in travel demand.

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