TRAFFIC MANAGEMENT POLICIES FOR INTERURBAN HIGHWAYS: AN EMPIRICAL IMPACT ANALYSIS

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ABSTRACT

An empirical analysis was conducted using a multiple linear regression model to evaluate the impact of three different traffic management policies on a major interurban controlled-access highway in Chile. The policies, introduced in order to reduce congestion and increase vehicle capacity, were: i) lane reversibility; ii) heavy truck restrictions; and iii) night-time toll reductions. The results of the model showed that the lane reversal and truck restriction measures had statistically significant impacts on the highway's vehicle flows. The toll reductions, however, had no such impact, as reflected in the low values found for price (toll) elasticity of demand for highway use. The effects of weather factors (rain, temperature) were also estimated. We conclude that the lane reversal and truck restrictions were successful in generating significant traffic flow increases on the highway.

Keywords: traffic management policies, intercity controlled-access highways, reversible lanes, trucks, tolls, elasticity, road capacity, weather conditions

1. INTRODUCTION

This article presents empirical estimates of the impact on vehicle flows of traffic management policies applied to a major intercity controlled-access highway in Chile. The analysis is built around a multiple linear regression model and a set of high frequency time series data. The three policies covered in our study are: "reversibility", that is, reversible highway lanes, used to adapt supply to demand; time-of-day restrictions prohibiting heavy truck traffic; and night-time highway toll reductions. During periods of high-demand for the highway (long weekends, Independence Day holidays) these measures have been implemented simultaneously.

The conclusions of our analysis are that reversible lanes and truck restrictions are significant in modifying traffic patterns on the highway and thus improve the performance of the existing highway infrastructure. In the case of toll reductions, however, the results were not conclusive.

The dependent variable in the regression model is the vehicle flow, measured as vehicles per hour at a toll plaza outside the city. Seasonality control is achieved through dichotomous variables representing time of day, day of the week and month of the year. Additional dichotomous variables represent Independence Day (two consecutive days), long weekends and the first and last days of these holiday periods. Also controlled for using dummy variables are weather factors affecting traffic flows such as temperature and precipitation.

Our study focuses on Chile's Route 5 South ("Ruta 5 Sur"), the main road connecting Santiago, Chile's capital and most populous urban area, with the southern regions of the country, the traditional destination of most holiday traffic. It is a controlled-access divided highway (hereafter simply "highway") with two lanes in each roadway. All vehicles entering or leaving Santiago on Route 5 South must stop and pay a toll at the Angostura toll plaza 50 km south of the city.

Under normal conditions the route's two roadways operate in opposite directions as in any highway, an arrangement we will call 2x2. However, at times when a large vehicle outflow from Santiago is expected, the highway administrator, subject to the approval of the relevant authorities, may assign a third lane to exiting (southbound) traffic, leaving just 1 for returning (northbound) traffic. This traffic management policy, consisting of assigning 3 lanes to the high-demand direction and 1 to the low-demand direction, will be called reversibility or 3x1 (see Figure 1).

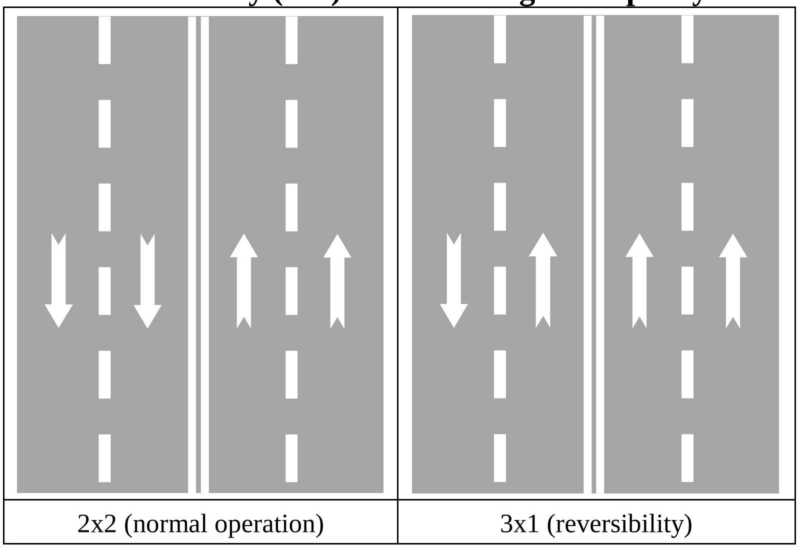
Reversing lanes in this manner was implemented on 5 occasions in 2012 and 2013 to facilitate vehicles heading out of the city and 11 times for vehicles coming back. Typically, it was applied on the first and last days of long weekends and the Independence Day holidays. The measure has enabled increases in highway traffic flows at times of high demand when the highway's maximum capacity is reached. Theoretically, 3x1 should augment capacity in the high-demand direction by up to 50% but in practice the rise is considerably less at 18% for exiting vehicles and 28% for those returning. The difference between these two figures will be explained later; the reason they are both well below 50% is that the separation of a single roadway into lanes operating in opposite directions tends in practice to generate "friction" between their respective traffic flows and thus significantly reduces vehicle capacity. (Note that traffic in the low-demand direction never exceeded the single-lane capacity of 900 vehicles per hour).

The restriction prohibiting multiple-trailer trucks (i.e., those with 3 or more axles, hereafter simply "trucks") during high-demand periods when the infrastructure is operating at capacity has a positive effect on the flows of light (i.e., all other) vehicles. We estimate that these flows rise by about 1.9% for each 1% reduction in the percentage of trucks using the highway (semi-elasticity). Since trucks make up about 10% of the total highway flow, applying this restriction generates an increase in light vehicles of about 19%.

Finally, as regards night-time toll reductions, our price elasticity of demand estimates for highway use were not statistically significant, implying that this measure would not be effective in modifying highway traffic flows. Of course, this result is not hard evidence that the variable parameters are actually zero, but it does mean that with the available data such a conclusion cannot be ruled out. In this sense, the low variability of the toll rates in our sample prevented a clear identification of their effects at the margin.

It should be noted that the results just outlined refer only to the effects of the three policies on vehicle flows. In fact, they can also be expected to impact other aspects of highway operation such as speeds and trip times. The available data did not, however, allow us to make any evaluations beyond the evaluation of flow effects measured at the toll plaza.

Figure 1
Reversibility (3x1) traffic management policy



The remainder of this article consists of five sections. Section 2 surveys the relevant literature on traffic management policies for urban and interurban highways, Section 3 briefly describes our data, Section 4 develops our econometric model and defines the explanatory variables, Section 5 sets out and discusses the results of the model, and Section 6 presents our conclusions.

2. LITERATURE REVIEW

The design and analysis of traffic management tools for boosting efficiency in the use of road infrastructure have focussed largely on urban as opposed to interurban road networks. Whereas few articles reporting quantitative estimates of the impact of management policies on interurban highways can be found in the specialist literature, many studies have been published on measures in an urban context such as road pricing, highway access control and high-occupancy vehicle lanes, to name just a few. There is also an extensive list of works on the management of entrance and exit ramps and the use of online information as well as concrete examples of other policies that have improved urban highway performance, but these measures are not necessarily applicable to interurban highways.

Various TDM (traffic demand management) schemes are analyzed by Meyer (1999), who argues that price management is the most effective measure in regional transport contexts. Hoffman et al. (2013) arrive at similar conclusions. May and Milne (2000) discuss the effect of different pricing arrangements on traffic in central London. Ferguson (1999) analyzes the complex impacts of TDM strategies on policy goals and the traveller behaviour, concluding that these impacts should be considered in strategy choices. A report by the U.S. Federal Highway Administration (FHWA, 2012) gives numerous examples for analyzing the efficiency of TDM measures.

On the subject of highway access control, a range of studies address the problem of congestion at highway access ramps. The most popular solution is to control entrance ramp flows using ramp metering. Chung et al. (2007) set out a detailed analysis of the causes of this type of congestion. A number of proposals for solving or at least mitigating the problem have been presented (Daganzo et al., 2002; Jacobson et al., 2006 NO APARECEN EN REFERENCIAS). These include:

a) Ramp Metering. Uses a technology to control flows entering the highway via on-ramps. The most common system consists of a variable-cycle traffic signal that responds to conditions observed in the immediate area and allows one vehicle to enter per green.

b) Ramp Closure. Involves closing a ramp to all traffic or certain vehicle classes for a definite or indefinite time interval. This approach is generally employed for safety reasons in places where there are geometric design limitations.

c) Lane Assignment. Aims at reducing the friction due to lane-changing by clearly defining the segments where lane changes are permitted. The strategy can be implemented using variable message signs (VMS) to indicate less problematic locations, such as straight segments with no entrance ramps or upcoming exits, and what lane to be in for a given destination. These messages can be maintained for fixed time periods or be traffic-actuated.

d) Ramp Treatments. These are utilized to deal with specific problems, and include such techniques as widening acceleration lanes, adding more queueing storage and improving signage and signals.

e) Dynamic Speed Limits. Consider a highway with two lanes in each direction. If for either direction the traffic in one of the lanes is moving faster than in the other and there is more demand for (that is, more vehicles attempting to use) the faster lane than the slower one, a situation may arise in which total demand is less than the maximum for the two lanes but demand for one of the lanes—in this case, the faster lane—is more than its maximum. In such cases, a good solution for reducing congestion may be to reduce the speed limit in the faster lane. Comte (2000) discusses the concept of Intelligent Speed Adaptation, a system that acts to prevent drivers from exceeding the speed limit. The system can either adjust the maximum driving speed to the speed limit or notify drivers when they are exceeding it.

Other traffic management measures related to ramp metering have been studied by Hegyi et al. (2005) and Bellemans et al. (2006), who incorporate optimal control models to obtain more robust results regarding traffic operation.

In a more empirical vein, Levinson and Zhang (2006) estimate the highway capacity increases generated by ramp metering using a large set of data on bottlenecks. The two authors develop their work further in Zhang and Levison (2010).

Another solution for improving highway traffic is lane management. May (2003) analyzes the treatment of high occupancy vehicles (HOV), which consists in defining an exclusive lane for vehicles with multiple passengers. The author concludes that this measure increases both average traffic speed and safety. HOV schemes had been studied previously in the context of carpooling (Giuliano et al., 1990).

From a traffic stability and road safety perspective Darbha et al. (1999) and Davis (2004) study adaptive cruise control (ACC), a radar-based system that extends conventional cruise control by its ability to detect the location of the vehicle immediately ahead in the same lane and adjust the speed of the vehicle it is installed in to maintain a safe distance between them. If there is no vehicle ahead, the system maintains the speed preset by the driver.

Block (2009) expounds a basic theory of privatization applied to roads and highways, an approach he suggests would improve road safety and reduce traffic congestion. In his view, government ownership and management has failed, a conclusion he bases on U.S. data for the number of road deaths, severe congestion during peak hours in urban areas and the poor state of the highway network. These arguments have been partially refuted by Carnis (2009).

DaBlanc et al. (2014) examine the effectiveness of truck transport management policies such as parking regulations and emission reduction incentives. Their real impact is difficult to quantify, however, due to the lack of data. Some years earlier, Holguín-Veras et al. (2006) studied the effect of pricing measures on commercial carriers in congested urban areas.

Forkenbrock and Hanley (2003) analyze accidents involving multiple-trailer trucks. Although the focus of the study is safety, such incidents are also relevant to traffic issues given that their impact may be great enough to force highway closures. This paper is complemented by Hanley and Forkenbrock (2005), in which the authors analyze the effect of vehicle length on safety and traffic operating conditions.

Winston and Mannering (2014) enumerate a series of traffic management policies that could be implemented using existing technologies. These include real-time pricing for light vehicles and trucks, information for on-street parking, truck size and weight limits, variable speed limits, traffic signal timing adjustment and optimization using photo-enforcement technology, and actions to expedite incident response. Such measures have not yet been implemented, according to the authors, due to a status quo bias stemming from the limitations of official agencies, regulatory restrictions, political forces and a lack of specialized knowledge.

The three traffic management measures we study in the present article (lane reversal, truck restrictions and economic incentives in the form of toll reductions) are analyzed in an interurban context to which the studies just described, framed mainly in urban contexts, may not be generalizable. Indeed, there are important differences between the two settings that should be noted. One is that lane reversal tends to be more difficult to implement on urban highways because lane direction is often fixed by on-ramp and off-ramp configurations. Another difference is that in the urban case there are generally multiple unmetered alternatives for any given route whereas in the interurban case the alternatives are usually few if any.

3. DATA

The data gathered for our study consisted of hourly traffic flow measurements taken at the Angostura toll plaza located on the Route 5 South highway south of Santiago. The information collected identified the type of vehicle (light, bus, truck or motorcycle). The sample covered the period between January 2011 and December 2013. Some descriptive statistics on the traffic flows in both directions that were used in the derivation of our estimates are shown in Table 1.

Table 1
Traffic Flows on Highway Route 5-South

Segment		No. of observations	Av. flow (veh/h)	Std. Dev.	Min	Max
Angostura Toll	North-South	26,046	579	401	7	3,539
Angostura Toll	South-North	26,046	571	440	4	3,517

A typical example of flow behaviour at selected hours of the day recorded at the Angostura toll plaza (in both directions) over 12 consecutive in September 2013 is plotted in Figure 2. Chile's two-day Independence Day holiday is celebrated on the 18th and 19th of September, which in 2013 fell on a Wednesday and Thursday and was thus immediately followed by a long Friday-Sunday weekend. The result was the longest holiday of the year, generating a massive movement of vehicles out of and then back to Santiago with flows reaching some 3,500 vehicles per hour. The daily flows for the 12-day period embracing this extended holiday are indicated in Figure 3; the north-south daily flows for the entire month of September are given in Figure 4 for the years 2011, 2012 and 2013.

Figure 2

Traffic Flows for Selected Hours at Angostura Toll (12 days, September 2013)

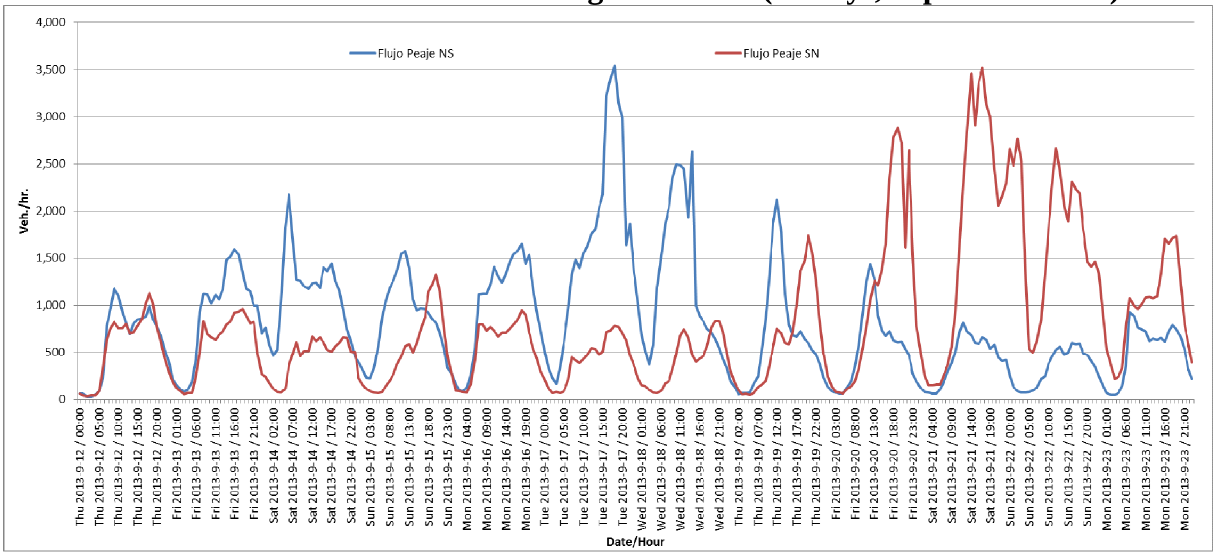


Figure 3

Daily Traffic Flows at Angostura Toll (12 days, September 2013)

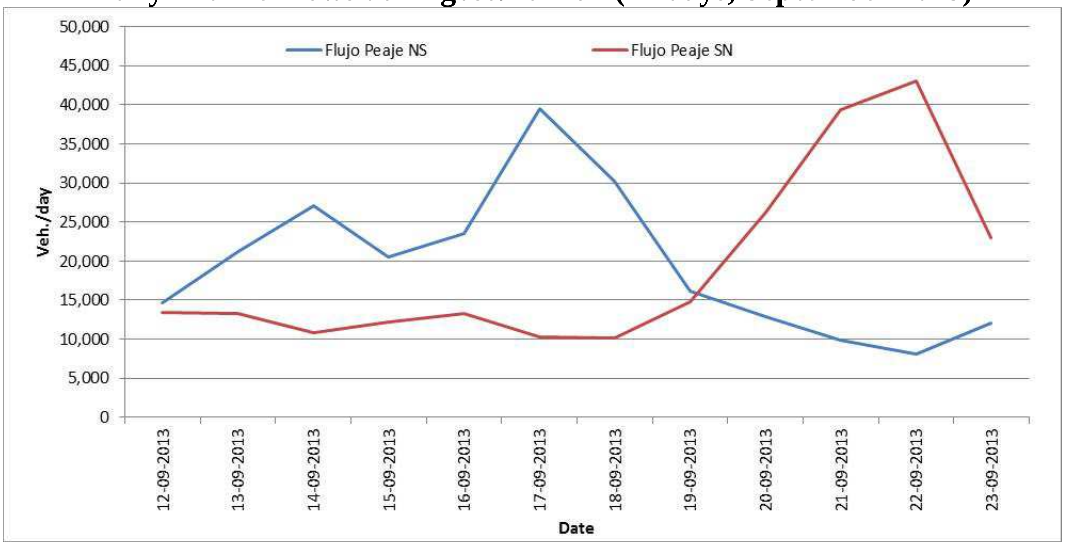
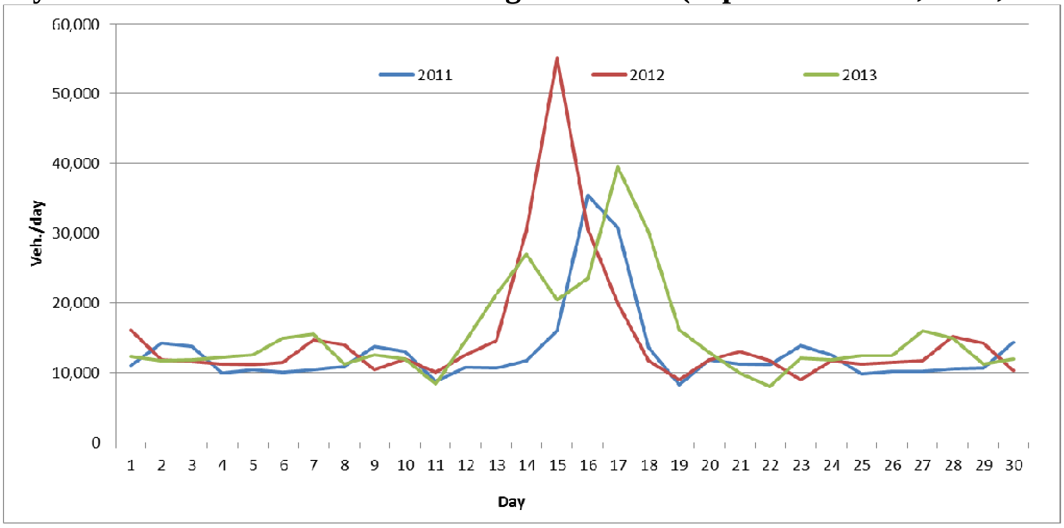


Figure 4
Daily North-South Traffic Flows at Angostura Toll (September 2011 , 2012, 2013)



4. METHOD

The multiple linear regression model we developed to estimate the effects on highway traffic flows of the three traffic management policies (reversible lanes, truck restrictions and toll reductions) is specified by (1). The explained variable $y_{t,a}$ is the natural logarithm of the flow on highway segment *a* in period *t* (periods are 1 hour). The explanatory variables representing the three policies are, respectively, a dichotomous variable for days when reversible lanes are implemented, the proportion of trucks on the highway, and the natural logarithm of the toll in real terms (adjusted daily for inflation).

As for the explanatory control variables, dichotomous variable sets representing the time of day, the day of the week and the month of the year control for seasonality and a continuous variable is included for linear trend (τ). Dichotomous variables for long weekends, the Independence Day holidays and the first and last days of these holiday periods control for the massive inflows and outflows they generate to and from Santiago. A further set of dichotomous variables control for weather conditions, that is, days of rain and of low and high temperatures.

In formal terms, the model is stated as follows:

$$y_{t,a} = \beta_0 + \phi \cdot \tau + \sum_k \beta_{k,a} x_{k,a,t} + \sum_r \delta_{r,a} D_{r,a,t} + \varepsilon_{t,a} \qquad (1)$$

where

$y_{t,a}$: natural logarithm of the flow of light vehicles on highway segment *a* in period *t*.

$x_{k,a,t}$: value of the k^{th} policy variable for highway segment *a* in period *t*. The three policy variables are:

- natural log of inflation-adjusted toll for segment *a*.
- dummy for implementation of 3x1 reversible lane measure; equals 1 if implemented in period *t* and 0 otherwise (i.e., 0 if normal 2x2 operation is in effect).
- dummy for implementation of 3x1 reversible lane measure in the opposite direction, hereafter called 1x3 to avoid confusion.
- proportion of trucks, defined as the flow of trucks divided by the total vehicle flow on highway segment *a* in period *t*.

$D_{r,a,t}$: Sets of dichotomous control variables:

- time of day
- day of the week
- month of the year
- dummy for long weekend
- dummy for Independence Day holidays
- dummy for first day of long weekend or Independence Day holidays (and second day if more than 3 days)
- dummies for the last day of a long weekend or Independence Day holidays (and second-to-last if more than 3 days)
- dummy for rain; equal to 1 if it rained during a day in any period *t*, otherwise equal to 0
- dummy for minimum temperature; equal to 1 if the temperature during a day fell below 10° Celcius in any period *t*, otherwise equal to 0
- dummy for maximum temperature; equal to 1 if the temperature during a day rose above 30° Celcius in any period *t*, otherwise equal to 0

τ: linear trend; incorporated to capture exogenous factors such as increases in the motorization rate or per-capita income.

$\beta_{k,a}, \delta_{r,a}, \phi$: calibration parameters

$\varepsilon_{t,a}$: model error term

Although the implementation of the 3x1 reversible lane measure is triggered in periods of expected high demand, this variable is exogenous in an econometric sense (uncorrelated with the error term), since the implementation of the 3x1 measure is determined in advance by the authorities based on the expected demand and is independent of contingent shocks. The 3x1 measure is not implemented automatically every time the highway reaches certain level of congestion.

Note that the denominator of the truck proportion variable incorporates the number of light vehicles, which is a function of the dependent variable, thus making the truck proportion variable endogenous by construction. This implies that ordinary least squares estimates of (1) will be biased and inconsistent. We therefore estimate the parameters using two-stage least squares (2SLS) in which the instrumental variables are the proportion of trucks in each highway direction and all of the model's explanatory variables values lagged by 12-48 hours. The main assumption justifying the validity for 2SLS of this set of instruments, which we consider to be reasonable, is that the proportion of trucks on the highway 12 or more hours previous is orthogonal to a shock in the (natural log of the) light vehicle flow.

In the absence of error term autocorrelation, the best lags for use as instruments are the shortest ones. But if autocorrelation is present in the error, which is the case here, the shorter lags are also endogenous and must be avoided. At the same time, however, the longer lags risk being poorly correlated with the variable it is desired to instrumentalize. In the present case, using the longest ones—from 24 to 48 hours—did not effect the results qualitatively.

Finally, because of the error term autocorrelation we used the Newey-West estimator, which is robust to autocorrelation and heteroscedasticity (Newey and West, 1987), with 5 lags for the autocovariance matrices.

5. RESULTS

The parameter estimates for the model's explanatory variables and their respective statistical significance values are shown in Table 2. To simplify the presentation, the values of the dummy variable coefficients are not reported.

Table 2
Parameter Estimates for Model (1)

Explanatory variable and description	Parameter	
	North-South	South-North
ln(fare) Natural log of inflation-adjusted toll	-0.2132 (0.2045)	-0.0475 (0.2849)
3x1 Dummy equal to 1 if 3x1 lane reversal policy implemented, otherwise 0	0.2823* (0.1558)	0.1871** (0.0850)
1x3 Dummy equal to 1 if 1x3 lane reversal policy implemented, otherwise 0	-0.2190*** (0.0514)	-0.3620*** (0.1330)
Truck Flow Proportion of trucks in total traffic flow	-2.0107*** (0.1040)	-3.2650*** (0.1098)
Trend Linear trend	7.20e-06*** (5.49e-07)	5.67e-06*** (6.21e-07)
Rain Dummy equal to 1 if rained during the day, otherwise 0	-0.1249*** (0.0456)	-0.0906* (0.0487)
Tº min Dummy equal to 1 if minimum Tº during the day was below 10ºC, otherwise 0	-0.0713*** (0.0111)	-0.0711*** (0.0128)
Tº max Dummy equal to 1 if maximum Tº during the day was above 32ºC, otherwise 0	-0.0641*** (0.0213)	-0.0652*** (0.0214)
No. of Observations	26,142	26,142
R^2	0.8874	0.8668

Standard errors in parentheses. ** indicates significance at the 5% level and *** at the 1% level.
Dependent variable: ln(flow).

As can be seen, the value of the toll variable parameter is negative but not statistically significant for either direction (North-South or South-North). Note also that in absolute terms the North-South (exiting Santiago) value of 0.2132 is considerably higher than the South-North (entering Santiago) value of 0.0475.

This indicates that on average, travellers are more sensitive to the toll value when heading out of the city than when coming back, suggesting in turn that toll management would be more effective if applied to exiting rather than returning traffic. However, although we cannot be sure that the parameters are 0, the available data do not allow us to reject the possibility.

The parameter of the 3x1 dummy variables has a positive sign and a high statistical significance in both directions. We can therefore conclude that the reversible lane policy in either direction would help increase traffic flow by boosting highway capacity in high demand periods. The size of the flow improvement would be about 18,7% north-south and 28,2% south-north. The higher south-north value may be explained by the geometric design characteristics of the normally south-north lanes, which pass through a tunnel that restricts their capacity per lane. This means that adding a third south-north lane by reversing one of the normally north-south lanes, which do not have a tunnel, results in a greater capacity increase in percentage terms than that obtained by reversing a normally south-north lane.

Also noteworthy is that the 3x1 percentages for both directions are significantly less than the theoretical 50% rise one might have expected from an increase of 2 lanes to 3. As explained in the introduction, this is due to the friction that exists between the traffic flows in two lanes of a single roadway that normally operate in the same direction.

The negative signs on the 1x3 variable parameters are the inevitable result on flows in the lower demand direction of increasing the number of lanes in the higher demand direction from 2 to 3, as this necessarily involves reducing the number of lanes in the lower demand direction from 2 to 1.

The parameter for the truck flow variable is both negative and significant. The reason is that a decrease in trucks as a proportion of total flow leads to an increase in the flow of light vehicles. In the extreme case where trucks are prohibited during certain hours (under normal conditions they make up about 10% of the total), the increase in the light vehicle flow would be 19%, confirming that the presence of truck traffic reduces highway capacity.

This result is illustrated in Figure 5, which compares the queues that formed at the toll plaza at two different times with similar total flows (approximately 2,100 veh/h). In the left-hand photo, taken on Friday 13 September 2013 at 4:30 in the afternoon, no truck restriction was in effect, the flow was 2,078 vehicles per hour and congestion was evident. But in the right-hand photo, taken on Saturday 14 September 2013 at 8 in the morning, a truck restriction was in effect, the flow was 2,120 vehicles per hour and there was no congestion. Clearly, highway capacity and toll payment times improve considerably when trucks are prohibited.

Figure 5
Vehicle Queues at Toll Plaza, With and Without Truck Restriction

Vehicle queue WITH trucks	Vehicle queue WITHOUT trucks

The dummy variable for rain is negative and significant in both cases (leaving Santiago, -0.1249; returning to Santiago, -0.0906). Since the explained variable is the natural log of the flow, these results indicate that traffic flows fall between 9% and 12% on rainy days.

Finally, the dummy variables for minimum and maximum temperature are both negative and significant. This corroborates our original hypothesis that on (relatively) cold or hot days, which for Santiago may be taken as less than 10° Celsius or more than 30° Celsius respectively, fewer highway trips are made. The flow reduction on such "extreme" temperatures is roughly between 6% and 7%.

6. CONCLUSIONS

An empirical analysis was conducted using a multiple linear regression model to determine the effectiveness of three traffic management policies implemented on a major intercity controlled-access highway in Chile. The focus of the analysis was the divided highway connecting Santiago to the country's southern regions. The route has two lanes in each roadway and a toll plaza outside the city where vehicle flow data was gathered.

The three management policies studied were: lane reversibility, used to adapt supply to demand; restrictions on heavy truck traffic; and night-time toll reductions. Each of these measures was represented in the model by an explanatory variable and additional variables were incorporated to control for weather (rain, temperature) and seasonality.

The first conclusion of the analysis is that reversing one of the lanes when demand in one direction is high, thus expanding capacity in that direction from two lanes to three, generated traffic flow increases of 18% to 28%. The expected theoretical increase of 50% was not achieved because of the less favourable operating conditions in the reversed lane, caused by the friction between the vehicles in it and those in the unreversed lane of the same roadway. It is also likely that drivers exhibited some reluctance to use a lane not operating in the usual direction.

The second conclusion is that the truck restriction induced significant improvements in both highway capacity and toll payment times. The total prohibition on trucks, which accounted for an average of 10% of highway traffic, resulted in an average increase in highway capacity for light vehicles of about 19%.

The third conclusion is that price (toll) elasticity of demand for highway use was low. This was particularly true for drivers returning to Santiago, for whom the elasticity was only -0.0475, whereas for those exiting the city it was -0.2132. Neither figure was statistically significant, however. The higher number (in absolute value) for drivers heading out of Santiago was probably due to the fact that greater restrictions tend to be imposed on days when heavy returning traffic is expected. These results suggest that a toll management policy would be more effective at times when large numbers of drivers are leaving the city.

As regards the effect of weather conditions, our findings indicated that both high (above 30° C) and low (under 10° C) temperatures cut highway demand between 6% and 7%. Rain had a similar impact on traffic flows.

To summarize, two of the implemented traffic management policies—lane reversal and heavy truck restrictions—clearly boosted the effective capacity of the intercity highway.

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