ANALYSIS

Quantification of the environmental impacts of road conditions in Brazil

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1. Introduction

In the 1990s, Brazil’s freight transport road model accounted for more than 60% of all cargo moved within the country. According to the Brazilian National Confederation of Freight Carriers’ Center of Logistics Studies (CEL-CNT), the excessive dependency of Brazilian transport on the road model is clear when compared with the transport matrix in other extremely large countries. In the United States, 26% of cargo transport is over the country’s roadways; in Australia it is 24%, and in China, it accounts for only 8% (CEL; CNT, 2002). When matched up with the United States alone, Brazil’s road model appears inefficient: Brazilian cargo transport productivity is 22% lower, energy consumption per unit transported is 29% higher, and...
196,000 km are paved (CNT, 2005b). According to CNT (2005a),
to the tune of 2% of the continent’s GDP (IRF and GTZ, 1996).
America’s dreadful road infrastructure is linked to damages
Latin America (CEPAL) and World Bank estimate that Latin
vehicle maintenance costs; a 50% increase in the number of
increase in the consumption of fossil fuels, a 38% increase in
conservation (Table 1). These degraded roads represent a 58%
54.6% of the Brazilian Federal road system’s 81,944 paved
45% of Mexico’s, and 6% of the USA’s (CEL; CNT, 2002).
Brazil has 1.6 million kilometers of roadway, but only
196,000 km are paved (CNT, 2005b). According to CNT (2005a),
54.6% of the Brazilian Federal road system’s 81,944 paved
kilometers are in “Deficient”, “Poor” or “Terrible” states of
conservation (Table 1). These degraded roads represent a 58%
increase in the consumption of fossil fuels, a 38% increase in
vehicle maintenance costs; a 50% increase in the number of
accidents, and up to a 100% increase in travel time (Magazine
CNT, 2001, p. 1). Reports from the Economic Commission for
Latin America (CEPAL) and World Bank estimate that Latin
America’s dreadful road infrastructure is linked to damages
to the tune of 2% of the continent’s GDP (IRF and GTZ, 1996
apud SENNA et al., 1998).
Road transport’s dependency on fossil fuels makes it an
important energy consumer and major user of petroleum
derivatives. In 2004, road transportation accounted for more
than 60% of Brazilian petroleum derivative consumption,
followed by the energy sector at 16%, and was responsible
for 47.3 billion tep (petroleum equivalent tons) of the country’s
total energy consumption of 191.1 million tep (Brasil, 2005).
Between 1994 and 2004, Brazilian road transportation energy
use in tep increased 39.2%, with the Brazilian transport
sector’s diesel oil consumption increasing 37% (BRASIL,
2005). The road model accounts for 92% of the Brazilian
transport sector’s diesel consumption. Fig. 1 illustrates the
growth of Brazilian diesel consumption due to the road model.
Fig. 2 shows the relation between the fuel consumption of
individual Brazilian productive sectors (measured in tep) and
that sector’s contribution to GDP (in US$). Measured by value
produced per unit of energy consumed, the transport sector is
much less energy efficient than the other sectors. In 2004,
for each unit of transport sector GDP, 3.56 units of energy were
consumed. This rate was 0.39 for the industrial sector; 0.35 for
the energy sector; 0.14 for the agricultural sector, and 0.03 for
the commercial sector (Brasil, 2005).
Diesel has fueled almost all Brazilian new trucks since
1996. According to Lima (2006), diesel accounted for 16.8% of
the total annual cost of operating a truck in Brazil in 1996; a
percentage that increased to 31.8% in 2004. According to the
same study, about 55% of all diesel consumed in Brazil in 2004
was destined to road transport. This is equal to 21.7 billion
liters of diesel and 32.3 billion Brazilian reals.
Between 1990 and 1994, the transport sector’s average
growth rate was 15%. Over this period, Brazil’s road model
showed an emission increase of about 17% while the rail
model’s emissions dropped 21%. The heavy road vehicle
fleet’s dependency on fossil fuels highlights the importance
of road transport in terms of CO2 emissions. In 1994, the
“transport” segment accounted for 40% of Brazil’s energy
sector’s CO2 emissions, or 9% of the country’s total carbon
dioxide emissions, and for almost 90% of the transport
segment’s emissions (Fig. 3).
The aim of our study is to quantify and value the effect of
paved road surface deterioration on carbon dioxide emissions
and to answer the questions, do well-maintained roads result in
greater energy efficiency and lower CO2 emissions, and if they do,
how much greater? The answers to these questions become
especially relevant when considered in light of the coming end
of the Kyoto Protocol’s first commitment period in December
2012 and the possibility to set emission standards.

<table>
<thead>
<tr>
<th>Pavement</th>
<th>Total extension</th>
<th>Under state management</th>
<th>Outsourced Management</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Km</td>
<td>%</td>
<td>Km</td>
</tr>
<tr>
<td>Optimal</td>
<td>26,295</td>
<td>32.1</td>
<td>17,592</td>
</tr>
<tr>
<td>Good</td>
<td>10,916</td>
<td>13.3</td>
<td>10,070</td>
</tr>
<tr>
<td>Deficient</td>
<td>24,551</td>
<td>30.0</td>
<td>23,875</td>
</tr>
<tr>
<td>Poor</td>
<td>14,029</td>
<td>17.1</td>
<td>13,757</td>
</tr>
<tr>
<td>Terrible</td>
<td>6153</td>
<td>7.5</td>
<td>6153</td>
</tr>
<tr>
<td>Total</td>
<td>81,944</td>
<td>100.0</td>
<td>71,447</td>
</tr>
</tbody>
</table>


pollutant emissions, measured in grams of carbon monoxide
released per ton transported 1 km, is 2.6 times higher (CEL;
CNT, 2002). The Brazilian road system is also less extensive
than the road systems of many comparable countries,
negatively impacting the model’s performance. Brazil has
69% of China’s roadway per km2 of territory, 55% of Canada’s;
45% of Mexico’s, and 6% of the USA’s (CEL; CNT, 2002).

Table 1 - Pavement conditions of Brazilian Federal roads (2005)

2 The tenth issue of the Road Research CNT assessed 100% of
the paved federal road system, including federal roads, federal
roads managed by the states and toll roads: a total of 81,944 km.
3 International Road Federation – IRF; Deutsche Gesellschaft
Für Technische Zusammenarbeit - GTZ. Concessiones en Argen-

2 In 2000, only 117 gasoline powered trucks were sold.
Global warming is an example of an externality. While developed countries are the major causes of that externality, its effects can be felt in other countries, which then need to adjust to the changes. There is a tendency for an externality’s producer to ignore the unintended negative effects of their actions, unless the negative externalities affect either themselves or their neighbors, making it easier to identify costs and input them to the externality producing project.

Under the perspective of cost allocation, the ideal situation would be to entirely internalize externalities, that is, to establish a market price for the incidental sub-product. However, the number of eligible externalities is limited. Pollution or adverse effects to the environment, according to Contador (1997), are impossible to discharge through such a procedure.

Although there is no established or accepted ideal methodology for the quantification of externalities, Contador (1997) devised a system of trade-offs, called “compensatory variations”, with the goal being a situation in which collective welfare is not reduced. People or companies that were in a better situation because of the action which causes a negative externality would be willing to pay a positive amount ($V_i$) to compensate for the negative external effect. On the other hand, people or companies damaged by the externality would demand a minimum amount, negative ($V_i$), to tolerate the negative external effect and return to their original level of welfare. If external effects impact individuals and companies in a way that the arithmetical sum of distinct compensatory variations is positive ($\sum V_i>0$), then the externality is considered positive (it must be taken as a benefit of the project).

Considering perfect competition, Fig. 4 shows the level of activity that generates pollution on the horizontal axis ($Q$) and the monetary costs and benefits on the vertical axis. BMLP is the private net marginal benefit. The polluting agent will incur costs in carrying out the polluting activity and will accrue benefits in the form of income. The difference between incomes and costs is the net private benefit. CEM is the marginal external cost, that is, the cost of the damage caused by the pollution increase as a result of the activity, and this cost rises according to the level producing activity’s pollution ($Q$).

The optimal point is found at $E^*$, the crossing of BMLP and CEM. Since both curves are cost and benefit marginal, the areas below the curves correspond to total benefits and total costs, that is, the area below BMLP is the total private net benefit of the polluting agent and the area below CEM corresponds to total external cost. In order to obtain the best results for society, the positive difference between total benefits and total costs should be maximized.

Triangle $OXE^*$ is the larger area of net benefits and, consequently, $OXE^*$ is the optimal level of the activity. The
optimal quantity of economic damage corresponds to the optimal level of pollution \( Q^* \) and is given by the area \( O\right Q^* Q \), also corresponding to the optimal level of externality.

Schematically, there are:

Area \( A \) = optimal level of social benefits
Area \( B \) = optimal level of externality
Area \( A+B \) = optimal level of private net benefits of the polluting agent
Area \( C+D \) = non-optimal level of externality which needs to be removed
Area \( C \) = level of private net benefits socially not justified
\( Q^* \) = optimal level of the economic activity
\( Q_\pi \) = level of the economic activity that generates the most private benefits

Fig. 4 shows that there is a divergence between private and social costs in the presence of the externality. In \( Q_\pi \), the private benefit is maximized in \( A+B+C \), but the external cost is \( B+C+D \). So, the social benefit is \( A+B+C-B-C-D=A-D \), which is smaller than \( A \), the social net benefit corresponding to \( Q^* \).

The level \( C+D \) of externality is Pareto relevant, as its removal leads to net positive social benefit (Pareto superior) while the level of externality \( B \) is Pareto irrelevant, as its removal has no effect.

Graphically, a program for road recovery is equal to increasing the supply, or availability, of the asset, by increasing the level of road usability. Fig. 5 illustrates that a project that increases availability of non-appraised goods from \( Q_0 \) to \( Q_1 \), dislocates the perfectly inelastic supply from \( S_0 \) (without project) to \( S_1 \) (with project). The benefit derived from an increase in goods consumption (from \( Q_0 \) to \( Q_1 \)) corresponds to an increase in the consumer surplus (benefit) equivalent to \( Q_0ABQ_1 \), the area below the demand curve, and limited by quantities with and without the project.

2.2. Analytical reference

2.2.1. Primary data collecting

The required data were collected from trials during which trucks equipped data collecting computers were driven over roads in different states of conservation. The on-board computers linked with truck mounted hardware recorded various parameters, such as average speed, maximum speed, percentage of time the driver remained above the speed limit. Installation of the computers (Blue Bird), final data collection, decodification of results, and data submission were the responsibility of Netz Engenharia\(^6\). A record was also kept of trip duration, fuel consumption, load weight, and type of route.

A total of 88 trips were taken by three types of trucks over six distinct routes. The routes were differentiated according to the condition of the paved surface as determined by CRT “Road Research” (CNT, 2005a,b), shown in Table 2.

The same controls were preserved on all trips, that is, the same load, the same time for the trip, the same weather conditions, and the same drivers. In all cases, the truck traveled at its full load capacity with respect to the different vehicle/implement types. Fuel consumption was used as the proxy for emissions.

Two sets of road trials were undertaken: Experiment 1 and Experiment 2. Experiment 1 used Volvo FH12 trucks traveling over routes (a) thru (d). Experiment 2 used both Scania and Mercedes trucks traveling over routes (i) and (ii). The results are presented for each experiment in Tables 3 and 4, and in an aggregated form in Table 5.

2.2.2. Estimating and valuing environmental parameters

Fuel consumption figures from the trials in experiments 1 and 2 were put through statistical analysis to test the hypotheses that the condition of the paved surface traveled over affects fuel consumption, admitting that the variances are unknown, but supposedly different (Hoffmann, 1991). The null hypothesis was that the condition of the paved road surface does not affect fuel consumption. An alternative hypothesis, that travel over poorly maintained roads is less fuel efficient than travel over well maintained roads, was also tested.

\(^5\) Analysis based on Randall (1987).
2.2.2.1. CO₂ emissions. The environmental variable is the amount of carbon dioxide emitted per kilometer driven over roads in different states of conservation. In spite of being the subject of a number of international studies to quantify pollutant emissions (global and local), road conditions have never been considered a determinant of vehicle emissions. In general, these studies’ methodologies use specific software to determine emissions, but these programs, being linked to default values from the North-American and European fleets, do not adequately reflect the Brazilian reality.

The methodology used in the current study was developed from IPCC (1997), Bartholomeu (2001), and Brasil (2002a). It permits use of a sequence of calculus procedures for estimating emissions from freight hauling road vehicles that take into consideration the effects of road conditions on fuel consumption. As expected (2002b), Brazilian heavy road transport greenhouse gas (GHG) emissions are effectively from diesel oil combustion, as road load transportation is predominantly powered by diesel fuel. It was assumed that combustion is complete and all the fuel’s carbon is converted into carbon dioxide during combustion (in this sense, CO and NMVOC emissions were not considered because they are converted into carbon dioxide in the atmosphere). Following the methodology adopted by Álvares and Linke (2003) and suggested by the GHG Protocol (2006), N₂O and CH₄ emissions were also not considered.

According to Branco et al. (2003), vehicle emissions are affected by traffic characteristics, such as traffic volume, average speed, road grade, number of lanes, and types of vehicles. Vehicle emissions also depend on the vehicle: its age, the technology it represents, its weight class, its condition, and the way it’s operated (load, speed and driving technique).

The current study adopts a diesel to carbon dioxide emission factor of 2.75 kg/l, an average value suggested by Brasil (2002b) and Bartholomeu (2001). This value does not consider specifications collected by Branco et al. (2003) but does correspond to a general estimate that considers the characteristics of diesel supplied in Brazil.

The following equation was used to estimate truck carbon dioxide emissions, and its result is differentiated by the condition of the paved surface traveled over:

\[ E_j = CEM_{dj} \times FE \]  

(1)

where:

\( E_j \) = average CO₂ truck emissions when traveling on a road in a distinct state of repair or condition \((j=\text{road condition: "Better", "Worse"})\), in kg CO₂/t km; \( CEM_{dj} \) = average “specific fuel consumption” of the group of trucks traveling over a route representative of one of the two types of road conditions considered (Better, Worse) in liters of fuel per ton of cargo.
transported each 100 km (l/t 100 km); \( FE = \text{CO}_2 \text{ emission factor for diesel with an adopted value of 2.75 kg/l.} \)

“Specific fuel consumption” is determined using the following equation [Eq. (2)], and is used to negate the need to consider load weight variability in other calculations.

\[
CE = \frac{CC}{P \times D \times 100}
\]  

(2)

where:

- \( CE = \text{Specific fuel consumption (l/t 100 km)} \)
- \( CC = \text{Fuel consumption (l)} \)
- \( P = \text{Total gross weight adjusted (t)} \)
- \( D = \text{Distance traveled (km)} \)

Average specific consumption corresponds to the simple average of specific consumption found for each trip, aggregated into groups determined by the condition of the road traversed. Truck emissions will be estimated using fuel consumption multiplied by the emission factor.

In short, the value found for \( E_I \) corresponds to an “emission index” per heavy road vehicles according to road condition and reflects the amount of carbon dioxide released to transport 1 t 100 km over roads in different states of conservation considered by this research. Knowing the load transported and the distance traveled, it is possible to estimate the emissions resulting from each trip. Aggregation then makes it possible to estimate a transportation company’s or even an economic sector’s \( \text{CO}_2 \) emissions.

2.2.2.2. Valuing environmental benefits: reduction of negative externalities due to \( \text{CO}_2 \) emissions. The environmental benefit (}\( B_e \)) is equivalent to the reduction of the negative externality (emissions level) from investment in road repair. The value of this benefit (\( V_{Be} \)) is estimated using the average amount of \( \text{CO}_2 \) emitted from travel over poorly maintained roads less the average amount of \( \text{CO}_2 \) emitted from travel over well maintained roads and the average price estimated by Stern Review Report on the Economics of Climate Change (US\$ 85.00).

The value of benefit (\( V_{Be} \)) is estimated using Eq. (3):

\[
V_{Be} = \frac{B_e \times \text{Cprice} \times 1000}{1000}
\]

(3)

where:

- \( V_{Be} = \text{value of benefit (reduced \( \text{CO}_2 \) emissions) resulting from travel on a well maintained road, in US\$/t 100 km;} \)
- \( B_e = \text{benefit, in kg \( \text{CO}_2 \)/t 100 km from travel over well maintained roads;} \)
- \( \text{Cprice} = \text{price of \( \text{CO}_2 \)e ton (US\$/t).} \)

3. Results

3.1. Data collected

Tables 3 and 4 show average vehicle speed and fuel consumption data from experiments 1 and 2.

3.2. Estimates of environmental benefits

The environmental benefits considered are directly related to carbon dioxide emissions from fuel combustion. Fuel consumption
data from the trials were rather consistent in that they show low dispersion from the average, resulting in a small variance (Table 5). The average value approaches the mode value; however, the trip from Campo Grande to Santos by a Mercedes Benz truck presented no repeated values, so had no mode.

Travel on the best routes resulted in an average 5.07% fuel savings over travel on the worse routes. Due to the aggregation of different vehicles performance, the standard-deviation was high: In one instance, a 10-wheel truck consumed more fuel per kilometer than an 18-wheel truck.

Table 6 presents results from the hypothesis test. With the exception of the first worse-better route comparison using the Volvo and the first worse-better route comparison using the Mercedes Benz, all cases rejected the null hypothesis in favor of the alternative hypothesis, with *P<0.05: travel over the poorly maintained roads caused higher fuel consumption per kilometer ton of cargo than travel over the well maintained routes.

Table 7 illustrates the emission index (in kg CO2/t of cargo transported 100 km) for all routes. Routes (b) and (i) of experiments 1 and 2, respectively, present the lowest fuel consumption and lowest carbon dioxide emissions for each experiment. Both routes were over roads in “better” condition, indicating that adequate road maintenance brings environmental benefits.

Table 8 presents the emissions reduction benefits from travel over well maintained roads. The table is based on data collected during experiments 1 and 2. Total truck weight was 42.5 t in Experiment 1 and 57 t in Experiment 2.

Data from Experiment 1 indicate that if pavement conditions on worse route (c) were equivalent to those on better route (a) or better route (b), CO2 emissions per ton of freight transported 100 km would be reduced by 6.7 g and 45.7 g, respectively (better route b is in better condition than better route a).

As the difference between the conditions of the better and worse roads increases, it was found that the difference in fuel efficiency and environmental benefit per unit of weight and distance increases. If the route between Sao Paulo and Feira de Santana (Experiment 1 d) were well maintained, there would be a hypothetical average reduction of 162.2 g CO2/t 100 km. In Experiment 2, if the road pavement conditions of route (ii) were as good as those of route (i), 206.42 fewer grams of CO2 would be emitted for the transportation of each ton of freight 1 km using the Scania truck and 146.45 fewer grams of CO2 using the Mercedes truck.

In order to use this study’s experimental data to generate a countrywide estimate of the value of the environmental benefit from travel over well maintained roads, the roadways of the State of Sao Paulo were discounted because they are generally in a better state of repair than roads in the rest of Brazil. For that reason, none of this study’s experimental trips could be entirely within the Sao Paulo, removing about 40% of all Brazilian road freight hauling from consideration7. Extrapolation of the results from experiments 1 and 2 shows that if the remaining 60% of all Brazilian road freight (291 billion TKU) was carried over well maintained roads, the aggregate value of the estimated environmental benefit would have been US$ 33.2 million in 2004. This

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7 According to the Economic Development Index of Transport (Fundação Instituto De Pesquisas Economicas – FIPe; CNT, 2005a, b), in 2004, almost 37% of loads transported on roads were concentrated in the state of São Paulo (they had origin and destination within that state).
Table 8 – Reduced CO₂ emissions benefits from travel over well maintained roads

<table>
<thead>
<tr>
<th>Route</th>
<th>Vehicle</th>
<th>Environmental Benefit (kg CO₂/t 100 km)</th>
<th>Value of Benefit (VBe), in US$/100 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worse Route(1)-Better</td>
<td>Volvo</td>
<td>0.007</td>
<td>2.44</td>
</tr>
<tr>
<td>Route(1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worse Route(1)-Better</td>
<td>Volvo</td>
<td>0.046</td>
<td>16.51</td>
</tr>
<tr>
<td>Route(2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worse Route(2)-Better</td>
<td>Volvo</td>
<td>0.143</td>
<td>51.58</td>
</tr>
<tr>
<td>Route(1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worse Route(2)-Better</td>
<td>Volvo</td>
<td>0.182</td>
<td>65.65</td>
</tr>
<tr>
<td>Experiment 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worse – Better</td>
<td>S R124 420</td>
<td>0.206</td>
<td>100</td>
</tr>
<tr>
<td>Route(1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worse – Better</td>
<td>MB 1944 S</td>
<td>0.146</td>
<td>70.95</td>
</tr>
<tr>
<td>Aggregation (1 + 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worse – Better</td>
<td>All</td>
<td>0.1343</td>
<td>56.80</td>
</tr>
</tbody>
</table>

Source: Research results.

value corresponds to 0.3% of the resources needed to repair Brazil’s paved road system (CNT, 2005b).

4. Conclusions

Study results confirm the hypothesis that travel over well maintained roads has environmental benefits over travel on poorly maintained roads. In both study experiments, in spite of the differences in magnitude, an improvement in energy efficiency was observed from travel over better roads. Statistical tests indicated that, in the case of average fuel consumption, the null hypothesis is statistically significant.

In Experiment 1, fuel consumption fell between 0.22% and 6% when the trial vehicle traveled over the better maintained routes. The hypothesis tests applied show that the fuel consumption difference between travel over better maintained roads and travel over poorly maintained roads was statistically significant, rejecting the hypothesis that there would be no difference in favor of the hypothesis that average fuel consumption over better maintained roads is lower than over poorly maintained roads. Travel over the better maintained roads was found to reduce emissions between 0.1gCO₂/t km and 1.8gCO₂/t km: a 0.01% to 0.2% reduction of the negative externalities related to CO₂ emissions.

Results from Experiment 2 corroborated those obtained in Experiment 1. Finally, the aggregated results also indicated environmental benefits from travel over the better maintained routes. The aggregated results also showed less variation than the results from each experiment individually. The statistical tests applied also indicated that, in the case of average fuel consumption, the null hypothesis is statistically significant.

The study found that investment in highway maintenance generates private and environmental benefits and that the reduction of individual vehicle fuel consumption, brought about by travel over well maintained roads, causes an expressive drop in the Brazilian diesel consumption. Aggregated study results showed that there would be a 5.06% reduction in fuel consumed from travel over the paved road systems if it was well maintained. This reduction would have equaled 1.10 billion liters less diesel fuel consumed in 2004 and a savings of US$ 0.9 billion,


It is important to emphasize that all indirect benefits from increased fuel efficiency and the concurrent emissions reductions were not evaluated, and the benefit from travel over well maintained roads was likely underestimated (there are many other routes in worse conditions in Brazil).

It is hoped that this study’s results can assist in the creation of programs, whether public, private, or a combination of both, to improve the efficiency of Brazil’s road transportation system, especially from the economic and environmental perspectives. It is also important that Brazil develop sustainable solutions to reduce carbon dioxide emissions in view of the possible Kyoto Protocol’s emissions target at the beginning of 2013. Nevertheless, an increase road use derived from improved road maintenance in Brazil could have two simultaneous effects: to maintain the benefit, in terms of gCO₂/t 100 km; and to reduce total benefits, in terms of gCO₂.

REFERENCES


8 Considering that US$ 1.00 = R$ 1.80.