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ANALYSIS

Quantification of the environmental impacts of road conditions in Brazil[☆]

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ABSTRACT

This study evaluates the impacts of Brazilian highway conditions on fuel consumption and, consequently, on carbon dioxide (CO_2) emissions. For the purpose of this study, highway conditions refer to the level of highway maintenance: the incidence of large potholes, large surface cracks, uneven sections, and debris. Primary computer collected data related to the fuel consumption of three types of trucks were analyzed. The data were derived from 88 trips taken over six routes, each route representative of one of two highway conditions: better or worse. Study results are initially presented for each type of truck being monitored. The results are then aggregated to approximate the entire Brazilian highway network. In all cases, results confirmed environmental benefits resulting from travel over the better routes. There was found to be an increase in energy efficiency from traveling better roads, which resulted in lower fuel consumption and lower CO_2 emissions. Statistical analysis of the results suggests that, in general, fuel consumption data were significant at $^*P<0.05$, rejecting the null hypothesis that average fuel consumption from traveling the better routes is statistically equal to average fuel consumption from traveling the worse routes. Improved Brazilian road conditions would generate economic benefits, reduce dependency on and consumption of fossil fuels (due to the increase in energy efficiency), and reduce CO_2 emissions. These findings may have additional relevancy if Brazil needs to reduce carbon dioxide emissions to reach future Kyoto Protocol's emissions targets, which should take effect in January 2013.

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

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

Pavement	Total extension		Under state management		Outsourced Management	
	Km	%	km	%	Km	%
Optimal	26,295	32.1	17,592	24.6	8703	82.9
Good	10,916	13.3	10,070	14.1	846	8.1
Deficient	24,551	30.0	23,875	33.4	676	6.4
Poor	14,029	17.1	13,757	19.3	272	2.6
Terrible	6153	7.5	6153	8.6	–	–
Total	81,944	100.0	71,447	100.0	10,497	100.0

Source: CNT (2005a).

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 km^2 of territory, 55% of Canada's; 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)[2], 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 infra-structure is linked to damages to the tune of 2% of the continent's GDP (IRF and GTZ[3], 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[4]. 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 CO_2 emissions. In 1994, the "transport" segment accounted for 40% of Brazil's energy sector's CO_2 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 CO_2 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.

2. Material and methods

2.1. *Theoretical reference*

According to Welfare Economics Theory, "externalities" are considered one source of market inefficiency and occur whenever production processes have an unintended positive or negative effect on the well-being of others. The instigators of this externality do not pay or receive anything for the externality. The externality is an incidental and involuntary result of a process. Moreover, the event responsible for generating the externality cannot be avoided without incurring additional expenses.

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[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 Argentina. **Reforma**: Conservação Vial, Santiago de Chile, n. 1, Jul. 1996.

[4] In 2000, only 117 gasoline powered trucks were sold.

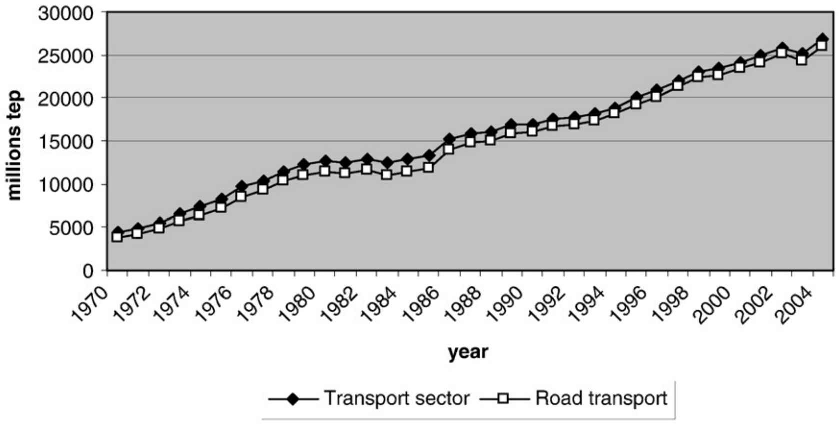

Fig. 1 – Diesel oil consumption by road model, from 1970 to 2004 (in millions tep) Source: Based on Brasil (2005).

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

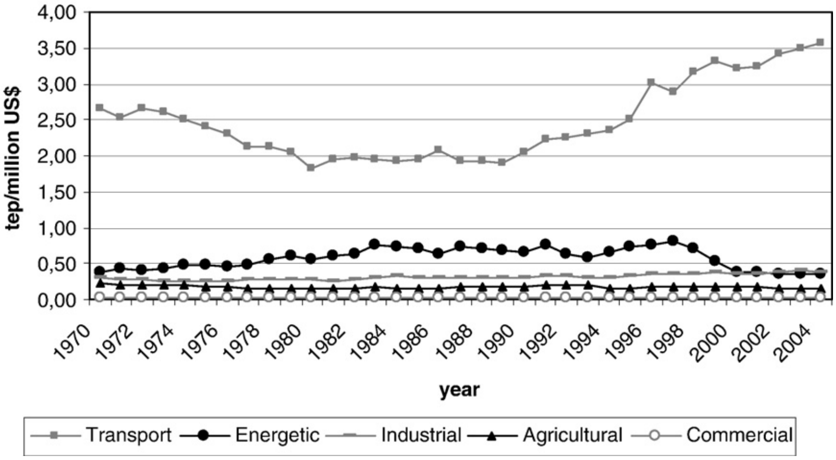

Fig. 2 – Energy intensity per sector (1970–2004) Source: Based on Brasil (2005).

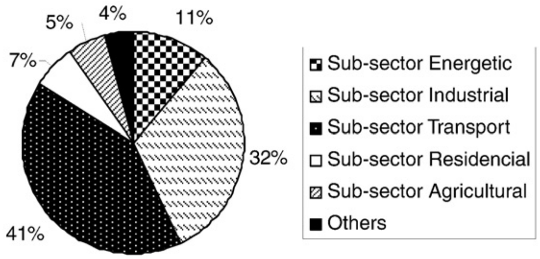

Fig. 3 – CO_2 emissions of sub-sectors under the scope of the "energy" sector (1994). Source: Brasil (2004).

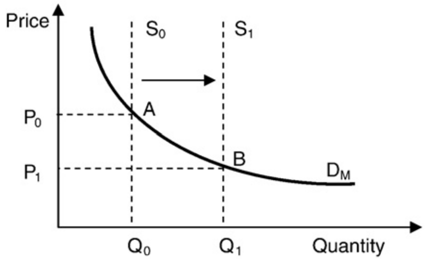

Fig. 5 – A non-marginal increase of supply: a change in the consumer surplus[5].

optimal quantity of economic damage corresponds to the optimal level of pollution (Q^*) and is given by the area OE^*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 Q0 to Q1, dislocates the perfectly inelastic supply from S0 (without project) to S1 (with project). The benefit derived from an increase in goods consumption (from Q0 to Q1) corresponds to an increase in the consumer surplus (benefit) equivalent to Q0ABQ1, the area below the demand curve, and limited by quantities with and without the project.

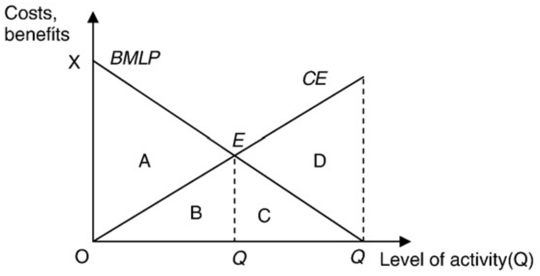

Fig. 4 – Economic definition of optimal pollution Source: Based on Pearce and Turner (1994).

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.

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[5] Analysis based on Randall (1987).

[6] Netz Engenharia. Information available at: <http://www.netz.com.br>.

Table 2 – Characteristics of vehicles and trips carried out to collect data

Route	Route Classification	Truck model	Total Gross Weight	Total number of trips	Period of trips
(a) Cubatão to Campinas (198 km)	Better	Volvo FH12	42.5	12	March/2005
(b) Ribeirão Preto to Bauru (205 km)	Better	Volvo FH12	42.5	12	January/2005
(c) São Paulo to Goiânia (951 km)	Worse	Volvo FH12	42.5	12	March/2004
(d) São Paulo to Feira de Santana (1.790 km)	Worse	Volvo FH12	42.5	12	April and May/2006
(i) Campo Grande to Santos (1.100 km)	Better	Scania R124-420	57	12	April/2005
		MB 1944S		8	April/2005
(ii) Rondonópolis to Campo Grande (480 km)	Worse	Scania R124-420	57	12	July/2005
		MB 1944S		8	July/2005

2.2.2.1. CO_2 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), N_2O and CH_4 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:

$$E_j = CEMed_j \times FE \tag{1}$$

where:

E_j = average CO_2 truck emissions when traveling on a road in a distinct state of repair or condition (j = road condition: "*Better*", "*Worse*"), in kg CO_2/t km; $CEMed_j$ = 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

Table 3 – Results from trials over the four routes of experiment 1 using a Volvo FH12/2004

Cubatão–Campinas			Rib. Preto–Bauru			S. Paulo–Goiânia			S. Paulo–Feira Santana		
(a) Better(1)			(b) Better(2)			(c) Worse(1)			(d) Worse(2)		
Veh	Vmed^1	km/l^2	Veh	Vmed^1	km/l^2	Veh	Vmed^1	km/l^2	Veh	Vmed^1	km/l^2
1	62	2.24	4	55	2.27	7	60	2.20	10	59	2.12
1	63	2.31	4	57	2.31	7	59	2.17	10	57	2.14
1	60	2.37	4	53	2.24	7	56	2.22	10	56	2.20
1	58	2.29	4	54	2.23	7	61	2.21	10	57	2.18
2	57	2.20	5	55	2.28	8	57	2.16	11	57	2.11
2	59	2.27	5	55	2.23	8	55	2.19	11	58	2.09
2	61	2.18	5	54	2.30	8	58	2.22	11	55	2.13
2	58	2.15	5	56	2.27	8	55	2.26	11	56	2.12
3	57	2.24	6	52	2.25	9	58	2.22	12	55	2.07
3	58	2.22	6	56	2.26	9	54	2.29	12	57	2.09
3	58	2.12	6	55	2.21	9	59	2.30	12	56	2.10
3	60	2.14	6	53	2.22	9	55	2.21	12	56	2.11

Source: Research results, based on data supplied by Netz Engenharia.
Notes: *Veh*: vehicle.
Vmed: average speed of the trip on the road (km/h).
km/l: average fuel consumption (km/l).

transported each 100 km (l/t 100 km); $FE = CO_2$ 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.

$$CE = \frac{CC}{P \times D \times 100} \tag{2}$$

where:

CE = Specific fuel consumption (l/t 100 km);
CC = Fuel consumption (l);
P = Total gross weight adjusted (t); and
D = 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_j 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 the 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 CO_2 emissions.

Table 4 – Results of trials taken for the two routes studied in Experiment 2

Vehicle	Model	Campo Grande–Santos (i) *Better*		Rondonópolis–Campo Grande (ii) *Worse*	
		Vmed[1]	km/l[2]	Vmed[1]	km/l[2]
1	Scania R124 420	67	1.94	64	1.78
1	Scania R124 421	68	1.78	66	1.65
1	Scania R124 420	69	1.85	69	1.68
1	Scania R124 420	68	1.91	69	1.73
2	Scania R124 420	67	1.79	70	1.58
2	Scania R124 421	68	1.89	71	1.61
2	Scania R124 420	71	1.74	66	1.80
2	Scania R124 420	70	1.86	65	1.81
3	Scania R124 420	73	1.64	63	1.82
3	Scania R124 420	66	1.87	67	1.58
3	Scania R124 420	69	1.86	69	1.55
3	Scania R124 420	72	1.79	69	1.77
4	MB 1944S	72	1.75	70	1.52
4	MB 1944S	72	1.70	71	1.63
4	MB 1944S	65	1.88	66	1.74
4	MB 1944S	67	1.87	69	1.75
5	MB 1944S	72	1.66	72	1.65
5	MB 1944S	65	1.79	67	1.74
5	MB 1944S	69	1.77	68	1.77
5	MB 1944S	66	1.82	65	1.72

Source: Research results, based on data supplied by Netz Engenharia.
Notes: [1] *Vmed*: average speed of the trip on the road (km/h).
[2] *km/l*: average fuel consumption (km/l).

Table 5 – Statistical analysis of the data collected on fuel consumption (l/100 km)

Route	Vehicle	Average	Standard deviation	Mode
Experiment 1				
a) Cubatão to Campinas (*Better(1)*)	Volvo	44.94	1.50	44.64
b) Ribeirão Preto to Bauru (*Better(2)*)	Volvo	44.34	0.62	44.05 and 44.84
c) São Paulo to Goiânia (*Worse(1)*)	Volvo	45.04	0.87	45,04
d) São Paulo – Feira de Santana (*Worse(2)*)	Volvo	47.15	0.82	47.17; 47.39 and 47.85
Experiment 2				
i) Campo Grande to Santos (*Better*)	S R124 420	54.85	2.59	53.76 and 55.86
i) Campo Grande to Santos (*Better*)	MB 1944 S	56.27	2.46	—
ii) Rondonópolis to Campo Grande (*Worse*)	S R124 420	59.13	3.54	63.29
ii) Rondonópolis to Campo Grande (*Worse*)	MB 1944 S	59.31	3.13	57.47
Aggregate (1 + 2)				
Better	All	49.53	5.76	
Worse	All	52.05	7.02	

Source: Research results.

2.2.2.2. Valuing environmental benefits: reduction of negative externalities due to CO_2 emissions. The environmental benefit (*Be*) is equivalent to the reduction of the negative externality (emissions level) from investment in road repair. The value of this benefit (*VBe*) is estimated using the average amount of CO_2 emitted from travel over poorly maintained roads less the average amount of 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 (*VBe*) is estimated using Eq. (3):

$$VBe = \frac{Be \times Cprice}{1000} \tag{3}$$

where:

VBe = value of benefit (reduced CO_2 emissions) resulting from travel on a well maintained road, in US$/t 100 km;
Be = benefit, in kg CO_2/t 100 km from travel over a well maintained road;
$Cprice$ = price of CO_2e 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 CO_2/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), CO_2 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 gCO_2/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 CO_2 would be emitted for the transportation of each ton of freight 1 km using the Scania truck and 146.45 fewer grams of CO_2 using the Mercedes truck.

Table 6 – Test of hypothesis results for the average fuel consumption

Route	Vehicle	Variable t' obtained	Liberty degree (g)	Value t0
Experiment 1				
Better Route(1)/ Worse Route(1)	Volvo	0.209	18	2.101
Better Route(2)/ Worse Route(1)	Volvo	2.300	20	2.086
Better Route(1)/ Worse Route(2)	Volvo	4.481	17	2.110
Better Route(2)/ Worse Route(2)	Volvo	9.490	20	2.086
Experiment 2				
Better / Worse	S R124 420	3.379	20	2.086
Better / Worse	MB 1944 S	2.157	13	2.160
Aggregate (1+2)				
Better /Worse	All	1.835	83	1.990

Source: Research results.

Table 7 – Average values of specific fuel consumption and of CO_2 emissions

Route	Vehicle	Average specific fuel consumption (l/t 100 km)	CO_2 emissions (kg CO_2/t 100 km)
Experiment 1			
a) Cubatão – Campinas (*Better (1)*)	Volvo	1.0574	2.908
b) Ribeirão Preto – Bauru (*Better (2)*)	Volvo	1.0432	2.869
c) São Paulo - Goiânia (*Worse (1)*)	Volvo	1.0598	2.915
d) São Paulo – Feira de Santana (*Worse (2)*)	Volvo	1.1093	3.051
Experiment 2			
i) Campo Grande - Santos (*Better*)	S R124 420	0.962	2.646
i) Campo Grande - Santos (*Better*)	MB 1944S	0.987	2.715
ii) Rondonópolis – Campo Grande (*Worse*)	S R124 420	1.037	2.853
ii) Rondonópolis – Campo Grande (*Worse*)	MB 1944S	1.040	2.861
Agregado (1+2)			
Better	All	1.01	2.7908
Worse	All	1.06	2.9252

Source: Research results.

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 consideration[7]. 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 CO_2 emissions benefits from travel over well maintained roads

Route	Vehicle	Environmental Benefit (kg CO_2/t 100 km)	Value of Benefit (VBe[a]), in US$/100 km
Experiment 1			
Worse Route(1)-Better Route(1)	Volvo	0.007	2.44
Worse Route(1)-Better Route(2)	Volvo	0.046	16.51
Worse Route(2)-Better Route(1)	Volvo	0.143	51.58
Worse Route(2)-Better Route(2)	Volvo	0.182	65.65
Experiment 2			
Worse – Better	S R124 420	0.206	100
Worse – Better	MB 1944 S	0.146	70.95
Aggregate (1+2)			
Worse – Better	All	0.1343	56.80

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 was 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 0.1gCO_2/t km and 1.8gCO_2/t km: a 0.01% to 0.2% reduction of the negative externalities related to CO_2 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[8], considering data from Lima (2006).

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 gCO_2/t 100 km; and to reduce total benefits, in terms of gCO_2.

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[8] Considering that US$ 1.00 = R$ 1.80.

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