Smart Transportation Alliance

Analysis of the relationship between road pavement maintenance condition, fuel consumption and vehicle emissions

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Authors

Elena de la Peña
Deputy Director for Technical Affairs, Spanish Road Association
Chair, TC1 (Smart Mobility), STA

Jacobo Díaz
Director General, Spanish Road Association

1. Background

There are several international research works showing that a road in proper maintenance condition is linked to a reduction of the vehicles' fuel consumption and emissions. The main conclusions of these works are included below, in terms of reduction of fuel consumption and CO_2 emissions, although it is well known that there are other pollutant gases which are also harmful:

- Improvement in road surface condition can reduce CO_2 emissions up to 5%.
- The effect of the reduction of the International Roughness Index (IRI) can lead to a fuel consumption saving up to 3% for light vehicles and 1-2 % for heavy vehicles, per each 1 m/km and depending of speed.
- The increase of fuel consumption in very bad condition roads (IRI close to 6 m/km), if compared with roads in very good condition (IRI close to 1 m/km) can reach up to 13% (light vehicles) or 8% (heavy vehicles).

The following figure, based on the conclusions of the publication "Estimating the Effects of Pavement Condition on Vehicle Operating costs" (National Cooperative Highway Research Programme, 2012), shows the variation of light and heavy vehicles' emissions under different IRI values (the origin of the figure is IRI = 1 m/km, where a value of fuel consumption of 1 l/100 km is considered).

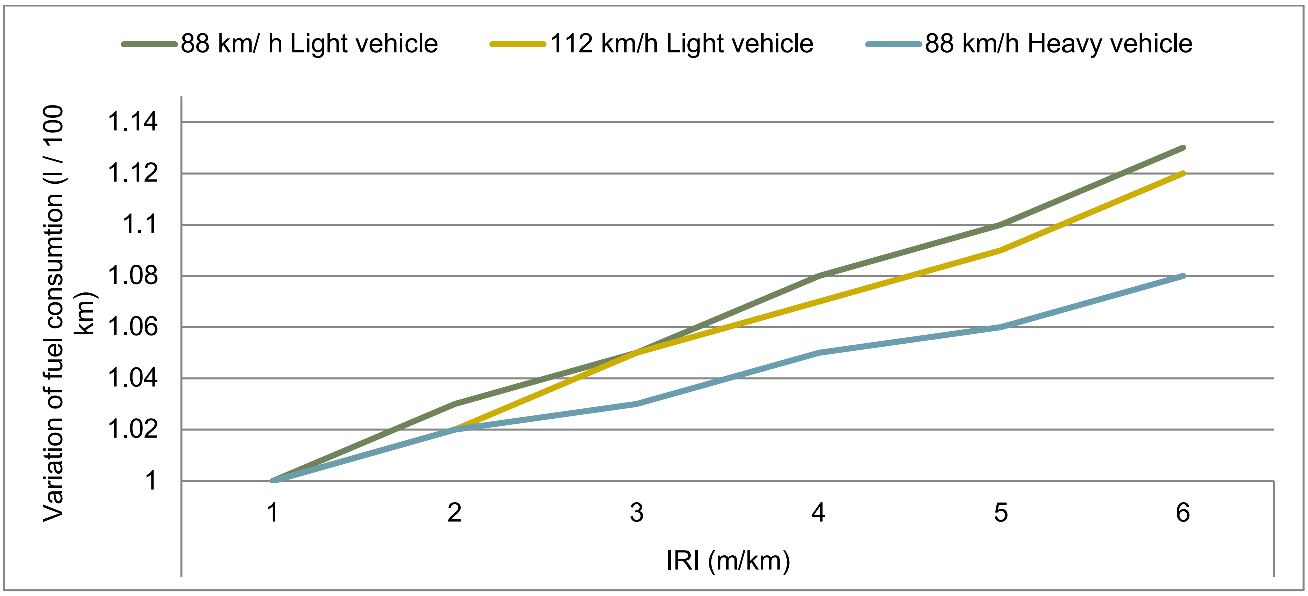

Figure 1: Variation of fuel consumption under different IRI values (Source: prepared with data from "Estimating the Effects of Pavement Condition on Vehicle Operating costs" NCHRP, 2012)

Thus, for a light vehicle, fuel consumption, which is proportional to CO_2 emissions, varies in the following way:

- Reduction of 3% when IRI changes from 2 m/km to 1 m/km (88 km/h).
- Reduction of 2% when IRI changes from 2 m/km to 1 m/km (112 km/h).
- Reduction of 5% when IRI changes from 3 m/km to 1 m/km (88 and 112 km/h).

In addition, for a heavy vehicle at 88 km/h, fuel consumption and CO_2 emissions vary as follows:

- Reduction of 2% when IRI changes from 2 m/km to 1 m/km.
- Reduction of 3% when IRI changes from 3 m/km to 1 m/km.

2. Objectives and description of tests

The Spanish Road Association conducted a before & after research work based on real test on roads in bad surface condition (before) and after resurfacing operations (after). It was developed with the support of the following organisations: Becsa, Eiffage Infraestructuras, Mercedes, Ponle Freno and Probisa. The research was planned with the following objectives:

- Show the importance of road surface condition on the fulfilment of the emission reduction commitments.
- Quantify the variation of vehicle fuel consumption in a road with good / bad surface condition.
- Quantify the consequent variation of CO_2 emissions.
- Assess potential CO_2 emissions linked to a whole road network in proper maintenance condition.

The research is based in real tests of fuel consumption conducted with light and heavy vehicles, and also in the conclusions of the work “Maintenance investment needs in the Spanish road network”, published by the Spanish Road Association in 2018.

Real tests were conducted in several road sections of the Spanish dual carriageway A-5, under bad maintenance conditions and after paving works; thousands of data from vehicle consumption and performance were collected, together with information from external conditions of tests. Vehicles' characteristics are included in table 1:

BRAND	MERCEDES BENZ	MERCEDES BENZ
MODEL	220 CDI COUPE	ACTROS 1846
YEAR	2018	2017
POWER (KW/CV)	140/190	338/460
WEIGHT (Kg)	1,735	42,000
TYRE PRESSURE (bar)	Front 2.5 Rear 2.5	9.0

Table 1: Vehicles' characteristics (own source).

Road section is located in A-5, from km 144 to 168.1 (growing way) and 16.1 to 146 (decreasing way), meaning a 46.2 km long road section.

Initial test journeys (test 1) were done when the road was in a bad surface maintenance condition, in June 2018. In November 2018, after paving works, tests were repeated (test 2). The total length of test journeys was 199 kilometres for light vehicles and 215 kilometres for heavy vehicles, having into account that several trips were done over the same road section. The length of test journeys for light and heavy vehicles is different due to the need to find a proper link for the U-turn of the heavy vehicle.

IRI values measured before paving were close to 2 m/km, while after paving IRI values were close to 1 m/km.

The following measures were registered for the light vehicle:

	Test 1 (before paving)	Test 2 (after paving)
LENGTH OF TRIP (km)	199	199
AVERAGE CONSUMPTION (On board computer) (l/100 km)	**5.50**	**5.40**
TIME OF TEST	1h 53´36"	1h 47´46"
AVERAGE SPEED (km/h)	107.00	110.00
TOTAL FUEL CONSUMPTION (l)	11.63	11.22
AVERAGE FUEL CONSUMPTION (l/100 km)	5.84	5.64
WEIGHT (Kg)	1,735	1,735

MAXIMUM/AVERAGE TEMPERATURE (ºC)	30.2 / 25	17.1 / 14.8
TYRE PRESSURE (mbar)	978	956
WIND SPEED (km/h)	0.00	15/31 East direction

Table 2: Data registered in test 1 (before paving) and test 2 (after paving) for light vehicle (own source).

For the light vehicle, there are differences of fuel consumption up to 3.5% less in roads in proper maintenance condition after paving.

The following measures were registered for the heavy vehicle:

	Test 1 (before paving)	Test 2 (after paving)
LENGTH OF TRIP (km)	215.1	215.1
AVERAGE CONSUMPTION (On board computer) (l/100 km)	**25.41**	**24.36**
TIME OF TEST	2h 39´50"	2h 40`02"
AVERAGE SPEED (km/h)	80.7	80.7
TOTAL FUEL CONSUMPTION (l)	54.7	52.5
AVERAGE FUEL CONSUMPTION (l/100 km)	25.43	24.37
WEIGHT (Kg)	42,000	42,000
MAXIMUM/AVERAGE TEMPERATURE (ºC)	32.9 / 23.2	12 / 10
TYRE PRESSURE (mbar)	978	980
WIND SPEED (km/h)	0.00	14.7/25 East direction

Table 3: Data registered in test 1 (before paving) and test 2 (after paving) for heavy vehicle (own source).

For the heavy vehicle, there are differences of fuel consumption up to 4% less in roads in proper maintenance condition after paving.

3. Results of the research work

3.1. Assessment of road pavement condition in vehicles' fuel consumption.

Following the results previously shown, table 4 includes data from fuel consumption for light and heavy vehicle during test 1 (before paving) and test 2 (after paving).

	Light vehicle	Heavy vehicle
Fuel consumption during test 1 (litres)	11.63	54.7
Fuel consumption during test 2 (litres)	11.22	52.5

Difference of fuel consumption between test 1 and 2 (litres)	0.41	2.20
Difference of fuel consumption in the 46.2 km long test road section (litres)	0.095	0.473
Difference of fuel consumption between test 1 and 2 (litres / km)	0.002	0.010

Table 4: Estimated fuel consumption in test 1 and 2 (own source).

Fuel consumption during test 2 (after paving) are 3.5% less for light vehicle and 4% less for heavy vehicles, if compared with test 1 (before paving).

Test road section (46.2 km long) shows an average daily traffic of 18,000 vehicles, with 14% of heavy vehicles. The following table summarizes fuel savings in the test road section, according to the data about traffic volumes collected from official sources:

	Light vehicles	Heavy vehicles
Fuel savings in the test road section (litres daily)	1,473	1,191
Fuel savings in the test road section (litres yearly)	537,820	434,628

Table 5: Estimated fuel savings in the test road section (own source).

Consequently, a total of 972,447 litres of fuel can be saved yearly, after paving the test road section.

3.2. Assessment of road pavement condition in vehicles' CO_2 emissions.

Considering 2.63 kg of CO_2 per litre of fuel as an average reference data for a diesel engine, the following calculations summarizes the estimations for CO_2 emissions reduction:

	Light vehicle	Heavy vehicle
CO_2 emissions during test 1 (kg of CO_2)	30.6	143.9
CO_2 emissions during test 2 (kg of CO_2)	29.5	138.1
Difference of emissions between test 1 and 2 (kg of CO_2)	1.1	5.7
Difference of emissions in the 46.2 km long road test section (kg of CO_2)	0.250	1.241
Difference of emissions between test 1 and 2 (kg of CO_2 per kilometre)	0.0054	0.0269

Table 6: Estimated CO_2 emissions in test 1 and 2 (own source).

CO_2 emissions during test 2 (after paving) are 3.5% less for light vehicle and 4% less for heavy vehicles, if compared with test 1 (before paving), as emissions are considered as proportional to fuel consumption.

The following table summarizes the data on CO_2 emissions saving in the test road section, considering its corresponding traffic volumes:

	Light vehicles	Heavy vehicles
CO_2 emissions savings in the test road section (kg of CO_2 daily)	3,875	3,127
CO_2 emissions savings in the test road section (kg of CO_2 yearly)	1,414,465	1,141,479
CO_2 emissions savings in the test road section (tonnes of CO_2 yearly)	1,414	1,141

Table 7: Estimated CO_2 emissions reduction in the test road section (own source).

The tests estimated that, after paving the road section, a total of 2.556 tonnes of CO_2 have been saved yearly.

3.3. Summary of results.

After the real tests and measurements of fuel consumption and CO_2 emissions, the research group extracted the following conclusions, assuming that the IRI values change from 2 m/km (before paving) to 1 m/km (after paving):

- Results of the test show that reduction of fuel consumption and CO_2 emissions are up to 3.5% for light vehicles and 4% for heavy vehicles; these figures are bigger than the conclusions of the publication “Estimating the Effects of Pavement Condition on Vehicle Operating costs” (National Cooperative Highway Research Programme, 2012); that publication shown emissions reduction of 2% for light vehicles (88 km/h and 112 km/h) and heavy vehicles (88 km/h), for a change in IRI from 2 m/km to 1 m/km.

The difference between both research works is summarized in the following tables, where there is a reference of conclusions of real tests and hypothesis:

		Reduction of fuel consumption / CO_2 emissions	
		"Estimating the Effects of Pavement Condition on Vehicle Operating costs" (National Cooperative Highway Research Programme, 2012)	Data and hypothesis of this research work[1]
Light vehicle (112 km/h)	From IRI 2 m/km to 1 m/km	2%	3.5% (real tests)
	From IRI 3 m/km to 1 m/km	5%	8.75 % (hypothesis)
	From IRI 4 m/km to 1 m/km	7%	12.25% (hypothesis)
Light vehicle (88 km/h)	From IRI 2 m/km to 1 m/km	3%	5.25% (hypothesis)
	From IRI 3 m/km to 1 m/km	5%	8.75 % (hypothesis)
	From IRI 4 m/km to 1 m/km	8%	14% (hypothesis)
Heavy vehicle (88 km/h)	From IRI 2 m/km to 1 m/km	2%	4% (real tests)
	From IRI 3 m/km to 1 m/km	3%	6% (hypothesis)
	From IRI 4 m/km to 1 m/km	5%	10% (hypothesis)

Table 8: Comparison of fuel consumption and CO_2 emissions under different changes of IRI (source: own research and publication "Estimating the Effects of Pavement Condition on Vehicle Operating costs" NCHRP, 2012).

- Reduction of fuel consumption and CO_2 emissions for light and heavy vehicles linked to an improvement of road pavement maintenance condition could be higher than it is concluded in international research studies, according to the real tests developed by the Spanish Road Association.
- IRI of the test road section, with a value around 2 m/km, does not reflect a very bad condition of pavement; thus, reductions of fuel consumption and CO_2 emissions would be higher if the road condition was really bad (IRI over 3 m/km), which have not been calculated in this research work. It is necessary to enhance the scope of the research in order to conclude with more details on this area of work.

[1] Data considered as hypothesis should be understood as estimations based on the conclusions of the real test (multiplying factor from NCHRP research of 1.75 for light vehicles and 2 for heavy vehicles).

4. Example of application of results in the Spanish rural road network

The next stage of the research conducted by the Spanish Road Association was the application of previous conclusions to the Spanish road network. This was based on the results of the work "Maintenance investment needs in the Spanish road network", published by the Spanish Road Association in 2018, already mentioned:

- Approximately 34% of the national and regional road network (total length of 101,700 km) shows a very bad maintenance condition of pavement, with strong structural damage (34,300 km of single carriageways and 1,200 km of dual carriageways).
- Approximately 19% of the national and regional road network shows bad maintenance condition of pavement, with surface damage (15,300 km of single carriageways and 3,200 km of dual carriageways).

A similar assumption is considered for the local road network (total length of 63,900 km):

- 34% of the network shows a strong structural damage (21,700 km).
- 19% of the network shows surface damage (12,100 km).
- Thus, 53% of the mentioned road network is in bad condition, assuming that 47% is in good condition, which is a conservative hypothesis of work.

Regarding traffic volume data, it is summarized in the following table:

	Average daily traffic	% of heavy vehicles
Dual carriageways (national and regional road networks)	25,000	13%
Single carriageways (national and regional road networks)	4,000	8%
Local road network	600	8%

Table 9: Average daily traffic volumes (Source: Statistical yearbook of the Spanish Ministry of Public Works, 2017).

It was assumed that light vehicles circulate at 112 km/h in dual carriageways, while circulation at 88 km/h is considered for single carriageways; for heavy vehicles, only circulation at 88 km/h is considered, for both single and dual carriageways.

The conclusions of the application of the results to the Spanish road network is as follows:

- The improvement of the road pavement condition of the Spanish rural road networks would allow the saving of almost 600 million litres of fuel yearly.
- Consequently, a total of 1.6 million tonnes of CO_2 emissions would be avoided yearly.

The following table include this information in the road networks considered:

	Estimation of fuel consumption saving (litres yearly)	Estimation of reduction of CO2 emissions (tonnes of CO_2 yearly)
National and regional road network	556,192,762	1,463,815
Local road network	39,332,773	103,416
Total	595,525,535	1,567,231

Table 10: Summary of fuel savings and reduction of CO2 emissions linked to an improvement of road pavement conditions in the Spanish rural road network (own source)

5. Conclusions

Improving road pavement maintenance condition leads to significant reductions of fuel consumption and CO_2 emissions. Only in the rural Spanish road network, a reduction of 600 million litres of fuel and 1.6 million tonnes of CO_2 emissions yearly has been estimated.

The conclusions of this analysis are assumed to be lower than the real situation, as only road sections with strong pavement damage have been considered. The hypothesis linked to a 47% of the road network in proper condition is conservative.

Conclusions of the tests show that the potential of reduction of fuel consumption and CO_2 emissions are higher than those estimated in international research studies.

Lowering the budget for investment in road maintenance makes it difficult the fulfilment of compromises of global reduction of emissions.

It should also be noted that there are other impacts linked to road maintenance conditions, mainly in road safety, but also regarding tyre deterioration and other damage in vehicles.

It is necessary to analyse in depth new research lines, mainly regarding measurement of fuel consumption and CO_2 emissions for light and heavy vehicles, under several speeds, and different road pavement condition and IRI indexes.

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