sustainability MDPI

Supplementary material

Towards road sustainability – Part I: Principles and holistic assessment method for pavement maintenance policies

Anne de Bortoli [1,*], Adélaïde Féraille [2] and Fabien Leurent [1]

[1] LVMT, Ecole des Ponts, Univ Gustave Eiffel, 4-20 Boulevard Newton, Cité Descartes, Champs-sur-Marne F-77447 Marne-la-Vallée Cedex 2, France (anne.de-bortoli@enpc.fr; fabien.leurent@enpc.fr)
[2] Navier Lab, Ecole des Ponts, Univ Gustave Eiffel, 6-8 avenue Blaise-Pascal, Cité Descartes, 77455 Marne-la-Vallée, France (adelaide.feraille@enpc.fr)
* Correspondence: anne.de-bortoli@enpc.fr

Table of contents

List of tables

List of figures

Nota bene: 2.09E+02 is the scientific notation of a number and must be read as $2.09 \times 10^2 = 209$

1. Annual deaths in France due to particulate matter formation from transportation

48 000 deaths would occur each year in France due to PM2.5 pollution (Santé publique France 2016). And 18% of PM2.5 are emitted by road transportation (National SECTEN data, see Figure S1). The sector would thus be responsible for 8,640 annual deaths.

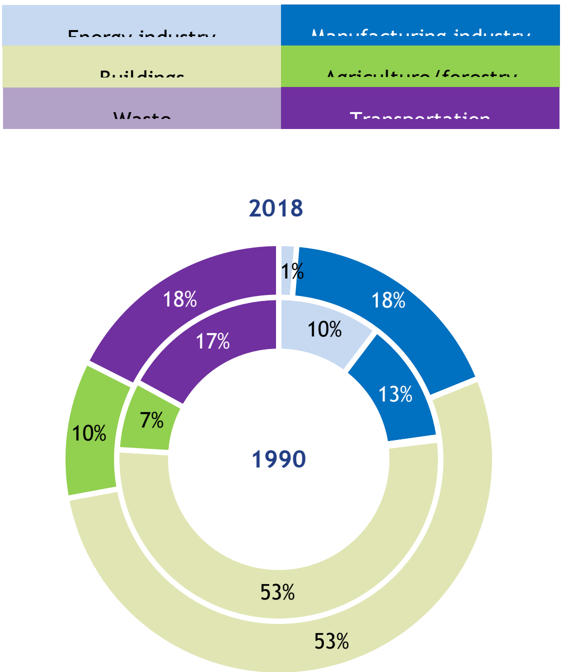

Figure S1 PM2.5 emissions by sector in France in 2018

2. Selection of indicators

The four thinking schemes of socioeconomic ethics

The question of what is enviable, desirable for humans, is of a philosophical and metaphysical order, in the sense that it addresses both the role of humans in the universe and the organization/functioning / the desired state for all humans in the social whole. That is to say one's condition, but also one's action, since ideally, society is built and structured to meet human needs and humans are expected to behave in such a way as to meet the rules of the society they belong to. The answer is, therefore, neither simple nor consensual. An individual goal that is at the same time popular, timeless, and universal is the "good life", that is to say, the achievement of well-being or even happiness. Well-being having a connotation of material ease allowing a pleasant existence while signifying a "pleasant condition resulting from the satisfaction of the needs of the body and of the calm of the spirit" (French Larousse dictionary definition). Happiness is " the condition of complete satisfaction "with a circumstantial connotation. Social thinkers often put forward an "ideal of a free and equal society, inherent to democratic societies", which is anchored in the discipline of economics and social ethics (Arnsperger and Van Parijs 2007). If the conceptions of the good life vary, Arnsperger and Van Parijs propose a classification in four categories of the thought of this economic and social ethics for the optimization of the development of the individuals in the society: utilitarianism, libertarianism, Marxism, and liberal-egalitarianism. Libertarians consider 3 fundamental principles of a fair society: self-ownership, fair circulation (i.e. voluntary transfers), and original appropriation (Arnsperger and Van Parijs 2007). The Marxist ethical project aims to abolish the alienation of man from man, the human purpose being first to provide for his needs and then to fulfill oneself (Arnsperger and Van Parijs 2007). Utilitarianism and liberal egalitarianism come together on a fundamental principle of maximization of gains (i.e. well-being), called "global utility of individuals" in the case of utilitarianism, and "extent of access to fundamental freedoms" in the case of liberal-egalitarianism (Arnsperger and Van Parijs 2007). However, liberal-egalitarianism according to Rawls adds two constraints: differentiation (i.e. equal respect with regard to all conceptions of the good life), and the "maximin" principle according to which, with equal maximum gains between several social systems, one chooses the system according to which the gain of the most disadvantaged class of individuals is the highest (Rawls 1999). In these four approaches, there is a consensus on the notion of a good or fair society: that which best meets the needs of all men, i.e. "public utility". Dissensus appears in the definition of human needs. Also, public utility "is never given straight away; it must be discovered, rather constructed, often standing out from the complex web of particular interests " (Desportes and Picon 1997, p45).

Selection of indicators

The generic societal objectives that can be linked to road maintenance are studied in the light of several types of documents: an academic literature review focusing mainly on social and environmental ethics as well as the economics of welfare and happiness, then the reference texts of the French social contract. This analysis will lead us to identify performance indicators related to road maintenance that must be part of a sustainable policy evaluation method.

Main findings of the economics of welfare and happiness

In the economics of welfare and happiness, the literature on the good life allowed us to identify some recurring factors of satisfaction that may be linked to road maintenance. The economy is a determinant of happiness. In particular, one's would have to exceed a given income threshold to be happy (Easterlin 2003). However, once this threshold is reached, free time (even more when shared) [1] (Young and Lim 2014)), and, even more, control over this time (Eriksson, Rice, and Goodin 2007), is substantially significant in the happiness of the individual, much more than income. But despite the fact that unemployment results in more free time, it would be the biggest destroyer of happiness due to anxiety relating to job hunting, poor social recognition and loss of income (Young and Lim 2014). Health, as well as physical and mental "non-disability" can also be an important factor according to Easterlin (2003). Quality social ties are a factor of satisfaction that we regularly find in the literature, whether it is family or friends: it also relates to the factor of shared free time. Education is also important - and even doubly important if you consider that it allows you to make better choices for your own happiness - as well as working conditions (Easterlin 2003).

Fundamental rules applicable to road maintenance in the original French texts theoretically driving the national social contract

The French Constitution refers to the founding texts of the national unity, which sets out the French fundamental principles through four corpora: the Constitution of October 4, 1958[2], the Declaration of the Rights of Man and the

[1] Young and Lim (2014) explain that happiness fluctuates during the week - at its lowest on Monday, it gradually increases until the peak of the weekend - including for the unemployed because free time does not have the same value if it is shared.

[2] https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=LEGITEXT000006071194

Citizen (DDHC in French) of 1789[3], the Preamble to the constitution of October 27, 1946[4], and the 2004 Environmental Charter[5]. These four texts have the theoretical function of uniting individuals through a set of operating principles, rights, and duties within the French society: they have constitutional value, in the double sense of legal value and unification. In our opinion, the last three texts contain elements that allow for indirectly defining the performance criteria of road maintenance policies. These texts recall several important notions regarding social objectives and how to achieve them. In essence and to quote Antoinette Rouvroy[6] «politics or society is a transcendence of individual interests for the benefit of a collective project ". According to these texts, the collective project aims at a fundamental objective of personal development, happiness for all, or common utility, which can be understood as a certain level of well-being and an aim of fairness.

Synthesis

After a thorough analysis, **the socioeconomic factors of happiness that are related to the strategies of road maintenance are: health, safety and security, employment, leisure, free time, resources, and natural environment**. Leisure requires free time and personal funds or public incentives. Thus, **financial considerations must be done for all the different financial stakeholders of road maintenance** due to tax systems. The public authorities, financed by the contribution of individuals according to their means, assume the sovereign powers, including those related to the preservation of natural resources and ecosystems from the Environmental Charter of 2004.

3. French calibrations of the relationships between IRI and fuel consumption

Selection and adaptation of the model

Fuel consumption models based on Pavement-Vehicule Interactions: a review

HDM-4 is a software developed by academic researchers and used by the World Bank to grant road infrastructure loans. The software contains the seminal algorithm for taking into account Pavement-Vehicule Interactions (PVI), and especially for linking the international roughness index (IRI) to vehicle consumptions. In the absence of field data and of an experiment to calibrate the HDM-4 consumption model under French conditions (or another country), the question is whether it is better to use IRI-sensitivity consumption trends from the HDM-4 default model, the HDM-4 model calibrated in Michigan by Chatti and Zaabar in 2012, or the MIRIAM models. This point is crucial because it will then condition a significant part of the financial and environmental impact of maintenance plans. We must therefore understand where the default parameters of the model come from, how the parameters from Chatti and Zaabar (2012) were calculated and measured, and how close are the conditions in France. Note that the results of the consumption model depend both on input data relating to the characteristics of the vehicles (aerodynamics, mass, engine, tires), the road (slope, surface condition), and the climate. It is therefore these variables to which we will be sensitive.

---

[3] https://www.legifrance.gouv.fr/Droit-francais/Constitution/Declaration-des-Droits-de-l-Homme-et-du-Citoyen-de-1789

[4] https://www.legifrance.gouv.fr/Droit-francais/Constitution/Preambule-de-la-Constitution-du-27-octobre-1946

[5] https://www.legifrance.gouv.fr/Droit-francais/Constitution/Charte-de-l-environnement-de-2004

[6] « Le numérique fait-il de nous un numéro ? », 1/3/17, France Culture, Table ronde enregistrée à la Sorbonne dans le cadre du forum « L'année vue par les sciences » le 25 février 2016.

HDM-4 model

According to the report by Chatti and Zaabar (2012), the basic coefficients of the HDM-4 model are found in volume 4 of the software documentation devoted to model adaptation (Bennett and Greenwood 2003). Nevertheless, having bought the last version of the software in 2013, we can only access a volume written by Bennett and Paterson in 2000, in which these same coefficients, the date of which is attributed to 2003 by the American researchers, for example, are referenced in our documentation as follows: "NDLI 1995" for the stiffness coefficients of the tires. We were unable to find the document referenced by the American researchers. We will therefore study the model in more detail.

Parametrization and calibration coefficients

The fuel consumption model presents default parameters relating to vehicles (aerodynamics, engine, tires (pressure, type), mass, etc.), climate (temperature, relative humidity, wind), and the road (IRI, slope, Mean Profile Depth, type of pavement structure). It also uses three setting coefficients: Kcr2 in the calculation of the rolling resistance factor on the roadside, KCS in the calculation of tire stiffness, and KPea in the calculation of the power required for the use of auxiliaries.

Model parameters

Infrastructure and climate

Regarding the road, the surface condition is an input parameter of the model. There is therefore no similarity to look for, except in the range of IRIs tested by Chatti and Zaabar (2012), a range that corresponds to IRIs that can also be found on the roads in France. The slope levels are generally equivalent between the two geographical areas. The types of structures tested are 80% made of Portland cement concrete (PCC) and only 20% of asphalt mixture. The highest speeds are permitted on concrete sections (112km/h). However, the influence of this characteristic has been studied on fuel consumption results: this variable does not influence light vehicles (LV) but it is not negligible on heavy vehicles (HVs) (+ 4% on asphalt pavement).

Vehicle fleet

If the American road vehicle fleet may differ from the French fleet - we will think in particular of the power and mass of the vehicles - the advantage of the study by Zaabar and Chatti is that the consumption model has been developed for several categories of vehicles. It is therefore necessary to study the equivalence of vehicles between the American fleet and the French fleet.

Nevertheless, it is likely to find more similarities in the vehicles coefficients (engine speed, consumption, power, etc.) in the French fleet and the experiments by Chatti and Zaabar than in the HDM-4 documentaiton. Indeed, vehicles in Chatti and Zaabar's work are more recent (2005 to 2008) than those from HDM-4 (90s or 2000s). Road vehicles must have strongly evolved within 10 to 15 years, these periods corresponding to a fleet renewal time. The coefficients of Chatti and Zaabar (2012) are also often 2 to 3 times lower than those of Bennett and Greenwood (2003, in Chatti and Zaabar 2012).

The base model of HDM-4 has 15 vehicle classes. Chatti and Zaabar used 5 classes representative of the American fleet to set their models: an average car (Mitsubishi Galant 2008), a sport utility vehicle (SUV) (Chevrolet Tahoe 2009), a van (Ford E350 2008), a light truck (GMC W4500 2006), and an articulated truck (International, 9200 6X4, 2005; 6 axles). These are also the 5 types of vehicles caracterized in the HDM-4 default model. Indeed, there is no differentiation made in the models between small, medium, and large cars, while the conceptual framework allows for a differentiation.

Compared to the French fleet, we raise several probable differences. First, the internal engine friction power/auxiliary power ratio is often relative to the size of the vehicle, and also depends on the climate and fuel consumption. A study announced an average overconsumption of road vehicles due to air conditioning of 2 to 5% in France (Gagnepain 2006). Although this should be supported by appropriate figures, it is likely that the use of automotive air conditioning is lower in France than in the USA if we stick to observations on general behavior (air conditioning is responsible for 6% of electricity consumption in the USA). Then, aerodynamic resistance is expressed as follows: Fx = ½.ϱ.V².S.Cx, with ϱ density of the air (in kg / m3), V speed of the vehicle in relation to the air (in m / s), S master-torque (in m2), Cx drag coefficient (without unit). The density of air depends on temperature and humidity. It will be considered identical in Michigan (location of the model) and France. The speeds of the vehicles tested in the USA (56km/h, 88km/h, and 112km/h) correspond to the speeds practiced in built-up areas and on interurban roads excluding highways. The model was not set for speeds practiced in France by LVs on highways (approximately 130 km/h). The master torque of passenger cars (PCs) varies between 1.5 m² for small cars in the A-segment (example: Twingo) and 2.5 m² for large PCs (eg: Espace) (Leclerc 2008). The values of American LVs (1.9m² chosen in the model) are probably close to those of France (ex: S = 1.74m² for a French city car). Finally, the drag coefficients of the PCs changed a lot after 1970 (0.45 at that time) to stabilize from the 1990s around 0.3 (Leclerc 2008). Trucks have Cx values in the range of 0.6 to 0.9, figures consistent with those of the US study. We will consider that the American coefficients of all the categories of vehicles are relatively relevant also for France although perhaps still a little higher. A quick calculation estimates for LVs an overestimation of the French aerodynamic resistance of 30% maximum (1.74m² * 0.3 in France Vs 1.9m² * 0.4 in the USA). Finally, rolling resistance - on which the characteristics of vehicles depend according to the HDM-4 model - are mass, tires (type, diameter, stiffness, pressure), and other adjustment factors. Regarding the mass of representative vehicles, the average car is a little lighter in France than in the USA. The large truck (44t) has an empty mass of 15t close to the large American truck.

Calibration coefficients

Among the 3 models setting coefficients, Chatti and Zaabar (2012) did not set K_{CS} which remains equal to 1 regardless of the vehicle considered according to the parameters suggested by Bennett and Paterson (2000) for HDM-4. They also adapted the value of the default parameters of Bennett and Greenwood (2003) to their experimental conditions in Michigan. They then calculated the calibration coefficients Kcr2 and K_{Pea} by iteration to reduce the sum of the standard deviations.

These calibration coefficients "explain the inexplicable": they correct the finiteness of a model that cannot perfectly match an eminently more complex reality. Without a field measurement, we cannot be sure that the calibrated fuel consumption functions relative to the IRI are closer to the French case than the functions of the base model proposed by HDM-4. However, for the sake of consistency of the model and because of the argument previously advanced on the probable best representativeness of vehicle types in the most recent model, we will use the calibrated models from Chatti and Zaabar (2012).

Sensitivity to speed

The characteristics of the typical vehicles and of the pavements which were used to calibrate the consumption model of HDM-4 under American conditions are of the same order of magnitude as those of the vehicles which could be considered as typical in France. Nevertheless, they can present significant variations, for example, lower consumption: around -30% of aerodynamics (see above), 18% of mass for the average PC, etc. This is reflected moreover in the values of average consumption calculated by Chatti and Zaabar (2012): 7L / 100km at 50km/h, 8.3L / 100km at 88km/h, and 11L / 100km at 112km/h for an average car. We also compare these values with the COPERT IV consumption values for the 2004 French fleet ("COPERT 2007") and with those of the HDM-4 base model in Figure S2. On the three typical speeds considered in HDM-4 models, the consumption/speed curves of the HDM-4 models (base and calibrated) seem to present a relatively similar shape to that of the COPERT curves, although of obviously higher values. We also see that the model calibrated by Chatti and Zaabar seems to diverge slightly from the Copert model with the increase in speed (from 56 km/h) for the American case, unlike the base model which seems to converge strongly. The PC data show that the high consumption of the representative American light commercial vehicles (LCV) amplifies the differences in consumption between COPERT values and American values, while for the basic HDM-4 model, the shape of the PC curve is more similar.

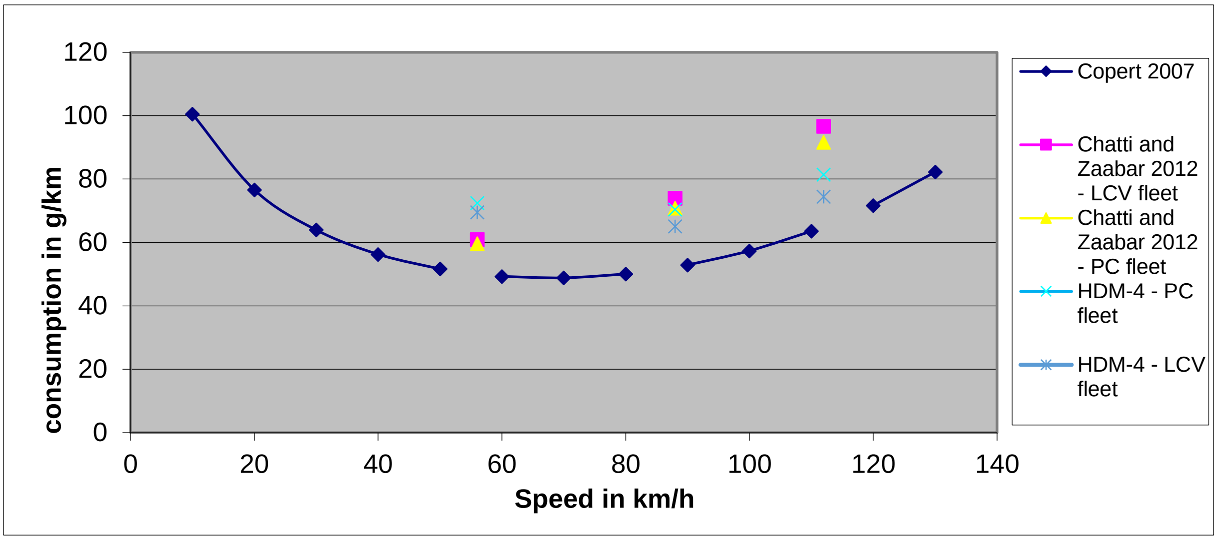

Figure S2 Average French fleet fuel consumption (77% PC and 33% LCV), PC and LCV fuel consumption as a function of speed: comparison of the Copert model in blue and the values of the HDM-4 models – by default or calibrated in Michigan (Chatti and Zaabar 2012)

The challenge is to select the model which presents the closest curve to the variation in consumption as a function of speed over the speed ranges practiced on French interurban roads (from 82 to 118 km/h at average speeds practiced by LVs), without taking into account the absolute value of consumption. According to these criteria, our observations confirm our decision to select the sensitivity curves of vehicle consumption to IRI from Chatti and Zaabar (2012). However, we would of course gain in accuracy by setting the model in French conditions. We will not directly use the software developed based on the work of Chatti and Zaabar for several reasons. Mainly due to aggregation of monetary data (and not updated or indexed to inflation) instead of physical models, to the limit of speed ranges considered (for example, French LV speeds on highways are too high to be calculated with their tool), to IRI limited to maximum 6 m/km, as well as to the underlying basic consumption assumptions[7].

Adaptation of HDM-4 model calibrated for the US to the conditions of French intercity roads

We will only consider 4 of the 5 vehicle categories from Chatti and Zaabar to represent the French fleet: PCs, LCVs, small heavy gross vehicles (HGVs) (= loaded weight between 3.5 and 7.5t) and large HGVs (= loaded weight > 7.5t). SUVs are not represented in the French fleet.

[7] En revanche l'avantage serait de pouvoir combiner les effets de variations d'IRI et de PTE (+ éventuellement température et type de revêtement – asphalte ou béton) sur les variations de consommations véhiculaires

Sensitivity of the excess fuel consumption to IRI: Chatti and Zaabar linear extrapolations

We now want to establish the equations that will allow us to calculate the consumption of our vehicles according to IRI. To do this, we plot the points relating to the results of the study by Chatti and Zaabar (2012) on Excel®, then we look for the trendline that gives the best correlation coefficient R^2. This represents 3 graphs, one for each average speed (56km/h, 88km/h, 112km/h), and 5 clouds of points per graph corresponding to the 5 typical vehicles: PC, LCV / minibus, 4x4, small trucks and busses and large trucks, articulated buses, and coaches).

Most of the curves obtain the best R^2 with linear regression, except for the LCV / minibus category at 112km/h which goes from an R^2 of 0.9613 in linear regression to an R^2 of 0.9789 with a polynomial regression. Since this difference is small, we decide to keep linear regressions for all vehicles to be consistent. The excess-fuel consumption (EFC) equations thus calculated are summarized in Table S1.

Table S1 Linear regressions and correlation coefficients of the sensitivity of EFC to IRI for each speed and vehicle type

(Base: 1 for IRI = 1)

American model			
		Function EFC=f(IRI)	R^2
56 km/h	PC	EFC = 0.0254 IRI + 0.976	0.9970
	LCV/minibuses	EFC = 0.0237 IRI + 0.9753	0.9958
	SUV	EFC = 0.0226 IRI + 0.976	0.9962
	Small HV	EFC = 0.0126 IRI + 0.986	0.9878
	Large HV	EFC = 0.01 IRI + 0.99	1.000
88 km/h	PC	EFC = 0.0254 IRI + 0.976	0.9970
	LCV/minibuses	EFC = 0.0226 IRI + 0.976	0.9962
	SUV	EFC = 0.0154 IRI + 0.986	0.9918
	Small HV	EFC = 0.01 IRI + 0.99	1.000
	Large HV	EFC = 0.01 IRI + 0.99	1.000
112 km/h	PC	EFC = 0.0237 IRI + 0.9753	0.9958
	LCV/minibuses	EFC = 0.02 IRI + 0.98	1.000
	SUV	EFC = 0.0126 IRI + 0.986	0.9878
	Small HV	EFC = 0.0077 IRI + 0.9947	0.9613
	Large HV	EFC = 0.0074 IRI + 0.994	0.9657

Real vehicle speeds on intercity roads

One limitation of the American model is that we only have discrete three-speed consumption values: 56, 88, and 112 km/h, corresponding to the main speed limits in the USA. However, in France, the speed limits go up to 130 km/h (on highways) and, on the other hand, have more variability, even when restricting themselves to interurban roads. From 70 km/h on national or departmental roads in accident-prone areas to 110km/h on expressways, passing through 80 and 90km/h. On the other hand, the speeds practiced do not correspond to the speed limits, which is a limitation of Chatti and Zaabar's work. Therefore, we need to calculate fuel consumption and its evolution as a function of the IRI for speed values, if not continuous, at least discrete at the typical speeds practiced by type of vehicle on the categories of interurban roads that we are studying. Table S2 summarizes the actual speeds practiced by two main types of vehicles - LV and HV (more than 4 axles) - according to measurement campaigns carried out in France.

Table S2 Average speeds by day in France (Source: author; Data: ONISR (2015))

Network (Speed limitation LV/HV))	LV	Evolution	HV	Evolution
Highways (130/90)	118	Stable*	88	Stable
Expressways (110/80)	101	Stable*	84	Stable
National and country roads (90/80)	82	Stable*	79	Stable

Stable= relative stability, general decline but recent slight increase*

Note that these speeds change over time, and perhaps depending on the road geometry. Thus, SANEF - a French private highway operator - announced average speeds of LV close to 130 km/h (between 127 and 129 km/h) since 2012 (SANEF 2017).

Sensitivity of the excess fuel consumption to IRI: French equations

To calculate fuel consumption and its evolution as a function of the IRI for speed values, we need to know the trend curves of the sensitivity of the consumption of each type of vehicle as a function of the speed at the fixed IRI. However, it is not mathematically consistent to determine a trend curve from 3 points (= 3 speeds): a polynomial function of degree 2 gives an R^2 of 1. Therefore, we choose linear regressions although they have quite bad correlation coefficients for LVs (of the order of 0.6). These curves show the importance of speed in the sensitivity of consumption to IRI for each type of vehicle. The results are presented in Figure S3, Figure S4, Figure S5, and Figure S6 for the 4 different fleet types. The curves for large HVs show that the higher the driving speed, the less the vehicle's consumption will be sensitive to IRI. Physically, this could be explained by the preponderance of aerodynamic resistance at high speed (Chatti and Zaabar 2012). Surprisingly, no threshold appears according to the mass of the vehicle. Indeed, if large HGVs are less sensitive than other types of vehicles to the effect of IRI with the increase in speed from an IRI of 2, the speed has on the other hand no impact on the consumption sensitivity to IRI below an IRI of 3 m/km for PCs , between 4 and 5 m/km for LCVs, and below 3 to 4 m/km for small HVs.

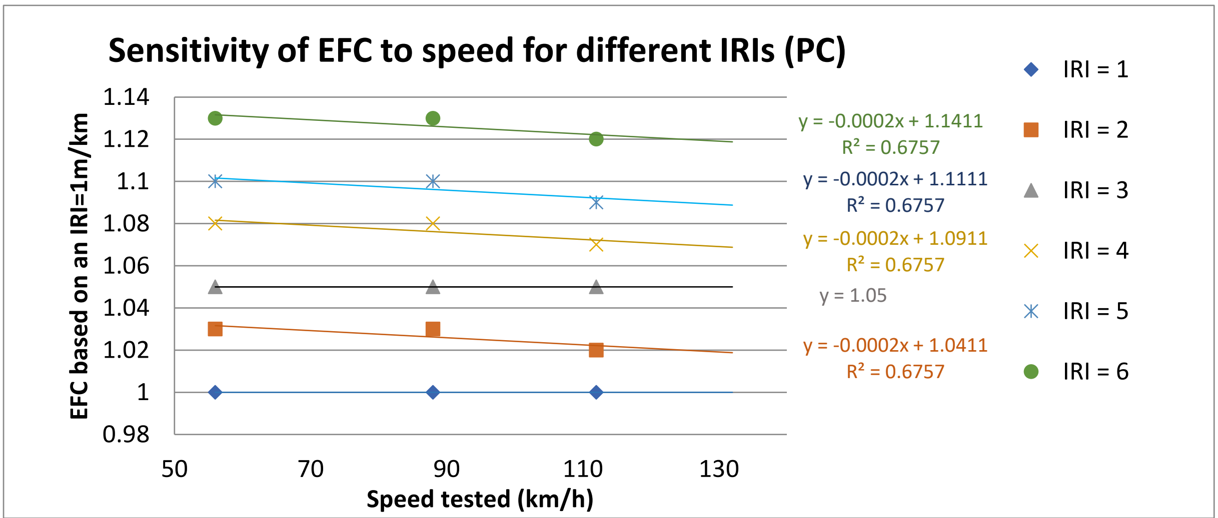

Figure S3 Sensitivity of the EFC to IRI for PCs depending on the speed (reference: 1 for IRI = 1 m/km)

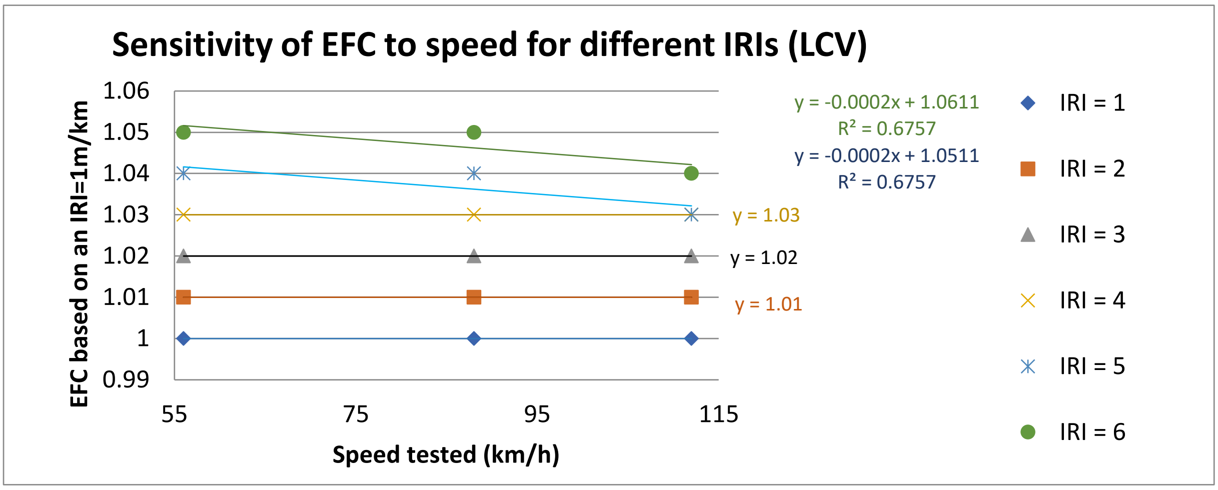

Figure S4 Sensitivity of EFC to IRI for LCVs depending on the speed (reference: 1 for IRI = 1 m/km)

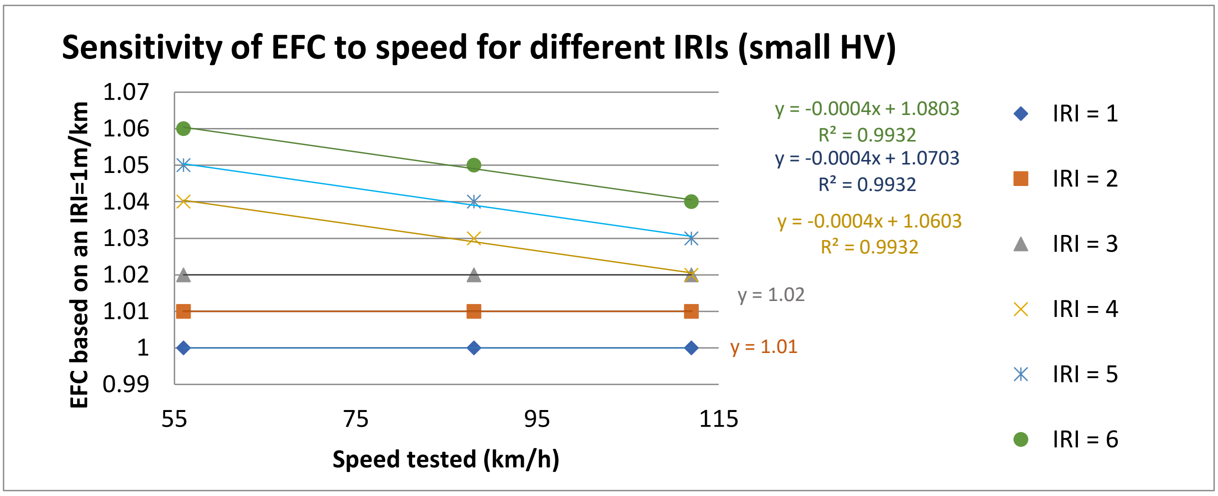

Figure S5 Sensitivity of EFC to IRI for small HVs depending on the speed (Reference: 1 for IRI = 1 m/km)

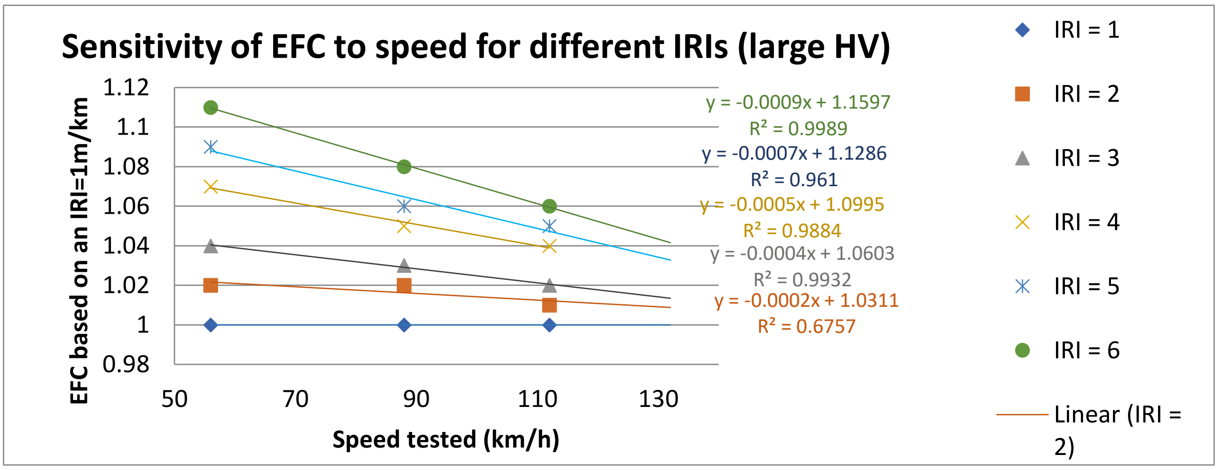

Figure S6 Sensitivity of EFC to IRI for large HVs depending on the speed (reference: 1 for IRI = 1 m/km)

These linear regressions, therefore, allow us to estimate the EFC ratio as a function of the IRI at the speeds practiced in France by our vehicles, by vehicle class, for their average speed on each kind of intercity roads. This gives us the sensitivities shown in Table S3.

Table S3 EFC ratios per type of vehicle and type of French road depending on IRI (Reference: 1 for IRI = 1m/km)

	IRI	1	2	3	4	5	6
PC	*Highways*	1	1.0175	1.05	1.0675	1.0875	1.1175
	expressways	1	1.0209	1.05	1.0709	1.0909	1.1209
	National/rural	1	1.0247	1.05	1.0747	1.0947	1.1247
LCV	*Highways*	1	1.01	1.02	1.03	1.0275	1.0375
	expressways	1	1.01	1.02	1.03	1.0309	1.0409
	National/rural	1	1.01	1.02	1.03	1.0347	1.0447
Small HV	*Highways*	1	1.01	1.02	1.0251	1.0351	1.0451
	expressways	1	1.01	1.02	1.0267	1.0367	1.0467
	National/rural	1	1.01	1.02	1.0287	1.0387	1.0487
Large HV	*Highways*	1	1.0135	1.0251	1.0555	1.067	1.0805
	expressways	1	1.0143	1.0267	1.0575	1.0698	1.0841
	National/rural	1	1.0153	1.0287	1.06	1.0733	1.0886

From these values, we want to obtain the EFC of each type of vehicle by type of road with continuous IRI values. As an example, the results are given for the highway network in Figure S7 and all of the EFC functions according to the IRI by type of network and vehicle calculated by our method are given in Table S4. Note that, due to lack of data in the annual observatory of the ONISR, we consider that LCVs circulate at the same average speeds as PCs, and that small HVs drive at the same speeds as large HVs.

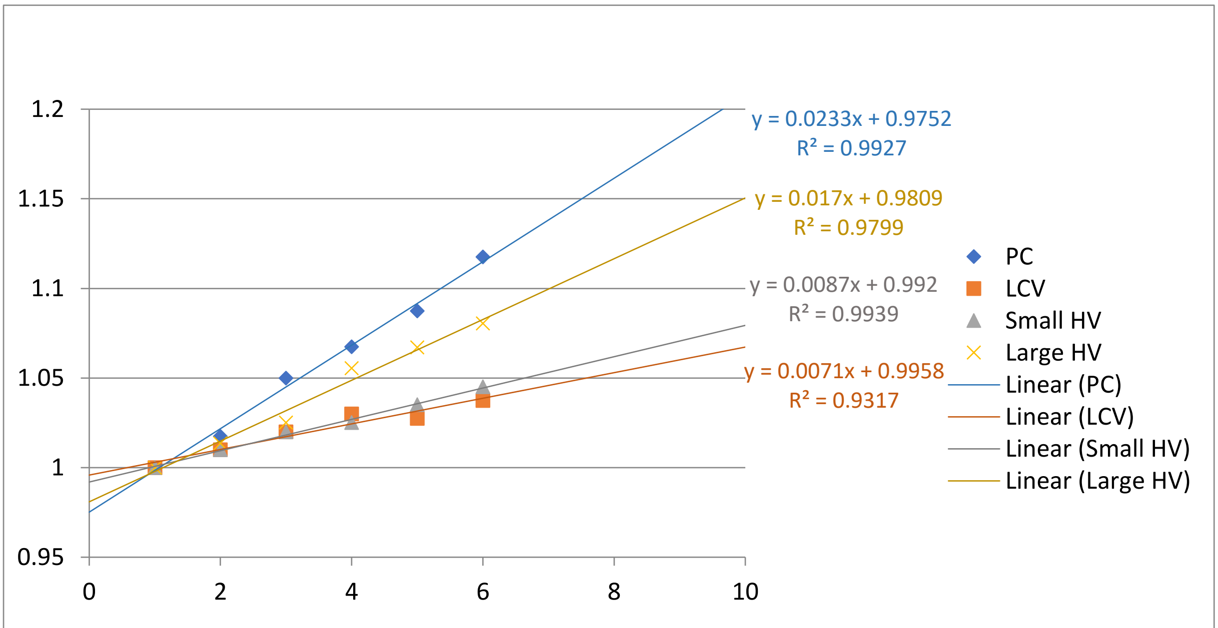

Figure S7 EFC depending on IRI on French highways for PCs, LCVs, small and large HVs (Reference: 1 for IRI = 1 m/km)

Table S4 EFC functions depending on IRI on French intercity roads

French HDM-4 model			
		EFC=f(IRI) function	R^2
Highways (118/88)	PC	EFC = 0.0233 IRI + 0.975	0,9927
	LCV	EFC = 0.00710 IRI + 0.996	0,9317
	Small HV	EFC = 0.00870 IRI + 0.992	0,9939
	Large HV	EFC = 0.0170 IRI + 0.981	0,9799
Express ways (101/84)	PC	EFC = 0.0239 IRI + 0.975	0,9966
	LCV	EFC = 0.0079 IRI + 0.994	0,9694
	Small HV	EFC = 0.0092 IRI + 0.991	0,9975
	Large HV	EFC = 0.0177 IRI + 0.980	0,9823
National/rural roads (82/70)	PC	EFC = 0.0245 IRI + 0.976	0,9983
	LCV	EFC = 0.0088 IRI + 0.993	0,9914
	Small HV	EFC = 0.0097 IRI + 0.991	0,9996
	Large HV	EFC = 0.0185 IRI + 0.980	0,9848

By way of comparison, Zhang et al. (2010) propose an equation for EFC depending on IRI roughly calculated from the extreme measurements (min/max) made during the WesTrack project on HVs (Epps 1999): EFC = 0.0397 ∗ IRI + 0.9524. The authorized speed for trucks in the USA is 55mph or about 80km/h. This, therefore, corresponds to our conditions on national and rural roads. Let's note that the EFC sensitivity attributed to IRI in this equation is approximately twice as large as the one we found in the equations we developed. Our model might thus be conservative in the differentiation between road maintenance plans.

4. French calibration of the relationship between IRI and vehicle consumptions tires and other R&M

Tire consumption

Tire wear models

To calculate the effect of road surface condition on the consumption of tires, we will also use the HDM-4 model calibrated by Chatti and Zaabar which we will adapt according to the same procedure as the one carried out to calculate the EFC equations. We will not consider the different wear rates between American tires and French tires, after discussion with experts from Michelin. For each vehicle type, after having determined by regressions the sensitivity of tire consumption to speed at constant IRI (from 1 to 6 m/km with a 1-m/km wide interval), rubber consumption adjustment factors are calculated depending on the IRI at the average speeds of each of our 3 types of French interurban networks, with wear at IRI = 1 m/km as a reference. We obtain the adjustment factors presented in Table S5.

Table S5 Tire consumption adjustment factors

	IRI	1	2	3	4	5	6
PC	*Highways*	1.00	1.01	1.04	1.05	1.06	1.08
	expressways	1.00	1.01	1.03	1.04	1.05	1.07
	Nationa/rural	1.00	1.01	1.02	1.03	1.04	1.05
LCV	*Highways*	1.00	1.01	1.02	1.04	1.05	1.05
	expressways	1.00	1.01	1.02	1.03	1.04	1.04
	Nationa/rural	1.00	1.01	1.02	1.02	1.03	1.03
Small HV	*Highways*	1.00	1.01	1.02	1.04	1.05	1.06
	expressways	1.00	1.01	1.02	1.04	1.05	1.06
	Nationa/rural	1.00	1.01	1.02	1.04	1.05	1.06
Large HV	*Highways*	1.00	1.01	1.02	1.03	1.04	1.04
	expressways	1.00	1.01	1.02	1.03	1.04	1.04
	Nationa/rural	1.00	1.01	1.02	1.03	1.03	1.04

From these factors, we plot the regressions by type of network and vehicle category to know the excess tire wear (ETW) depending on IRI. We obtain the equations in Table 6.

Table 6 ETW function

	Vehicle	ETW=f(IRI) function	R^2
Highways (118/88)	PC	ETW = 0.0168 IRI + 0.9812	0.9854
	LCV	ETW = 0.0102 IRI + 0.9927	0.9687
	Small HV	ETW = 0.0122 IRI + 0.9866	0.9907
	Large HV	ETW = 0.0089 IRI + 0.9917	0.9983
Express ways (101/84)	PC	ETW = 0.0136 IRI + 0.9856	0.9884
	LCV	ETW = 0.0088 IRI + 0.9929	0.9776
	Small HV	ETW = 0.0012 IRI + 0.987	0.9921
	Large HV	ETW = 0.0085 IRI + 0.9923	0.9972
National/rural roads (82/79)	PC	ETW = 0.0100 IRI + 0.9905	0.9865
	LCV	ETW = 0.0073 IRI + 0.9931	0.9839
	Small HV	ETW = 0.0117 IRI + 0.9874	0.9938
	Large HV	ETW = 0.008 IRI + 0.9931	0.9949

These ETW functions are to be applied to the reference tire wear rates considered at IRI = 1. To calculate these wear rates, we study the relationship between tire wear rate and speed determined in the USA by Chatti and Zaabar, considering that wear is the same in the US and France. We use the correlations determined in Figure S8 to calculate the wear rates at the average speeds practiced on French intercity networks.

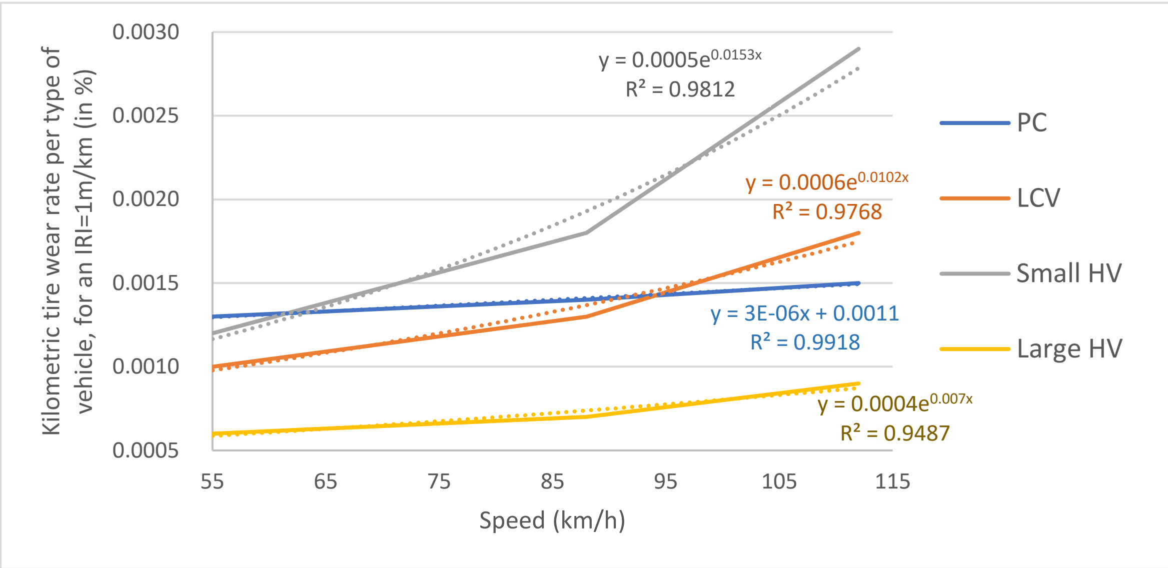

Figure S8 Study of the correlations between tire wear rate and speed determined in the USA by Chatti and Zaabar

By reversing this wear rate and converting a percentage to the tire part, the Typical Lifespans (TL) of the tires in the study of Chatti and Zaabar (C&Z) are calculated and given in Table S7.

Table S7 Typical lifespans of tires depending on the type of vehicle and road traveled (in kilometers)

US TIRES TYPICAL LIFESPANS (C&Z 2013)	HIGHWAYS	EXPRESSWAYS	NATIONAL/RURAL ROADS
PC	67 685	70 623	74 059
LCV	50 019	59 489	72 211
SMALL HV	52 035	55 319	59 717
LARGE HV	135 025	138 859	143 805

These TLs do not correspond to the figures found in the literature or among experts. We, therefore, decide to recalculate the wear rates that better correspond to driving conditions and tires in France. To recalculate consistent baselines for the French context, we consider that the average French road surface condition equal to IRI = 3 m/km rolling on national/rural roads (most of the French mileage). The TLs are estimated by French experts around 50,000 km for LV and 200,000 km for HGVs. We then calculate the corresponding wear rates on the different networks at IRI = 3 m/km (= inverse of the TL), which is corrected by the adjustment factors at IRI = 3m/km to obtain the rates at IRI = 1m/km by the
Table S9.
mean of a cross product with the American data. We obtain the rates indicated in Table S8, to which correspond the TLs in

Table S8 Corrected wear rate per kilometer

CORRECTED TIRE WEAR RATE AT IRI = 1 M/KM (PER KM)	HIGHWAYS	EXPRESSWAYS	NATIONAL/RURAL ROADS
PC	2.11E-05	2.04E-05	1.96E-05
LCV	2.82E-05	2.38E-05	1.97E-05
SMALL HV	5.63E-06	5.29E-06	4.90E-06
LARGE HV	5.23E-06	5.09E-06	4.92E-06

Table S9 Corrected tire lifespans

TL AT IRI=1M/KM IN FRANCE	HIGHWAYS	EXPRESS WAYS	NATIONAL/RURAL ROADS
PC	47383	49116	51125
LCV	35413	41978	50765
SMALL HV	177757	188976	204000
LARGE HV	191244	196520	203320

The ETW equations will then be applied to wear rate per kilometer depending on IRI and the type of vehicle and road traveled.

Vehicle wear

Consideration of the speed factor

According to Chatti and Zaabar, suspension maintenance costs increase with speed at set IRI, but wear sensitivity to IRI is not dependent on it. To take this into account, we consider that the average wear rate in France (=one suspension change every 80,000 km) corresponds to an average driving speed of 56 km/h and an IRI of between 1 and 3 m/km (Chatti and Zaabar's baseline, adapted to the conditions of French roads), and we calculate the additional cost adjustment factor according to US speeds (88 km/h, 112 km/h) in proportion to the costs found in the maintenance of the suspensions by Chatti and Zaabar depending on the speed in databases from Texas and Michigan. From these speed adjustment factors, we plot linear regressions by vehicle type for LCV and HVs, VP suspension costs behaving very similarly to LCVs according to Chatti and Zaabar's data. We obtain the equations in Figure S9 (HV in brown and LV in blue).

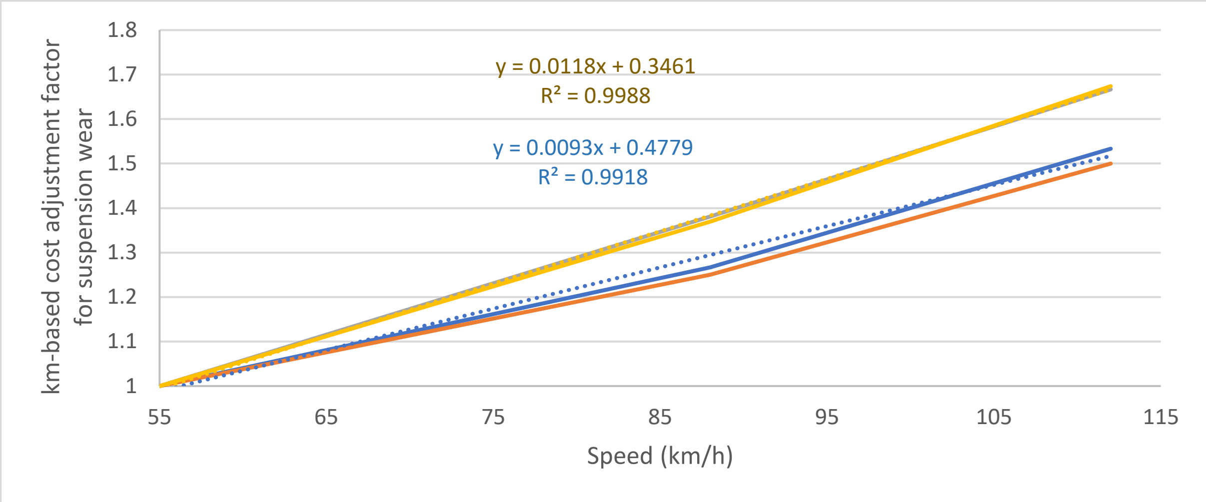

Figure S9 Relationship between wear/cost of vehicle suspensions and driving speed – PC in blue, LCV in orange, Small Heavy Vehicles in grey, and LHV in yellow

Wear and cost models for the shock absorbers

For our 4 categories of vehicles, we have calculated the average mileage costs in France in maintenance and repair (M&R) excluding tires. We assume that they correspond to the average wear rate in France – i.e. a change every 130,000 km of both LV's and HV's shock absorbers - at an average driving speed of 56 km/h[8]. We then calculate the ratios between the suspension costs and total R&M costs from Chatti and Zaabar's study (table 5.6). Depending on the type of vehicle, the maintenance of the suspensions represents 36 to 38% of the total M&R costs (excluding tires). We then calculate, based on our total average French M&R costs, the cost of maintaining the suspensions, assuming that the American ratio is valid in France. The kilometric costs calculated correspond to the year 2013 for PCs, 2016 for LCVs, and 2017 for trucks: we use the INSEE series of consumer price index in vehicle maintenance (INSEE 2018) to calculate the 2017 mileage costs and those according to the protocol already used for the tire wear model.

We assume that IRI rarely exceeds 3 m/km in France, based on the few surface condition data we were able to collect. Therefore, we deduce that vehicle maintenance costs do not vary with the condition of the road surface (Bennett and Greenwood 2003; Poelman and Weir 1992) in France. We consider that the variation that appears for IRIs greater than 3 m/km is only the result of premature wear of the shock absorbers and associated parts. We will therefore focus on the shock absorber replacement operation in terms of labor and spare parts required. We multiply the mileage costs considering inflation between 2013 and 2017 (INSEE 2018) calculated according to the average running speeds by network and vehicle type by the adjustment factors according to C&Z IRIs. We obtain the following costs in Table S10.

Table S10 2017-per km suspension maintenance costs – France (€TTC/km)

	Vehicle/IRI	1	2	3	4	5	6
Hig hw ays (1	PC	3.96E-02	3.96E-02	3.96E-02	4.36E-02	5.54E-02	6.73E-02

[8] Corresponding to Chatti and Zaabar's baseline, corresponding more or less to the average driving speeds considered in the European traffic emissions studies

	LCV	2.33E-02	2.33E-02	2.33E-02	2.56E-02	3.26E-02	3.95E-02
	Small HV	4.76E-02	4.76E-02	4.76E-02	5.71E-02	8.10E-02	1.05E-01
	Large HV	4.24E-02	4.24E-02	4.24E-02	4.66E-02	6.36E-02	7.63E-02
Express ways (101/84)	PC	3.56E-02	3.56E-02	3.56E-02	3.92E-02	4.99E-02	6.06E-02
	LCV	2.09E-02	2.09E-02	2.09E-02	2.30E-02	2.93E-02	3.56E-02
	Small HV	4.60E-02	4.60E-02	4.60E-02	5.52E-02	7.82E-02	1.01E-01
	Large HV	4.09E-02	4.09E-02	4.09E-02	4.50E-02	6.14E-02	7.37E-02
National/rural roads (82/79)	PC	3.12E-02	3.12E-02	3.12E-02	3.43E-02	4.37E-02	5.30E-02
	LCV	1.83E-02	1.83E-02	1.83E-02	2.01E-02	2.56E-02	3.11E-02
	Small HV	4.40E-02	4.40E-02	4.40E-02	5.28E-02	7.47E-02	9.67E-02
	Large HV	3.91E-02	3.91E-02	3.91E-02	4.30E-02	5.87E-02	7.04E-02

From these costs, we can calculate kilometric cost equations in R&M as a function of the IRI for an IRI greater than 3 m/km, indicated in Table S11.

Table S11 Per km cost equations in R&M according to the IRI for an IRI greater than 3 m / km in France

	Vehicle	Function COSTS_R&M=RM=f(IRI)	R^2
Highways (118/88)	PC	RM =0.0318.exp(0.1833*IRI)	0.9750
	LCV	RM =0.0318.exp(0.1833*IRI)	0.975
	Small HV	RM =0.0565.exp(0.2714*IRI)	0.9874
	Large HV	RM =0.059.exp(0.2074*IRI)	0.9651
Express ways (101/84)	PC	RM =0.0286.exp(0.1833*IRI)	0.9750
	LCV	RM =0.0286.exp(0.1833*IRI)	0.975
	Small HV	RM =0.0545.exp(0.2714*IRI)	0.9874
	Large HV	RM =0.057.exp(0.2074*IRI)	0.9651
National/rural roads	PC	RM =0.0025.exp(0.1833*IRI)	0.9750
	LCV	RM =0.025.exp(0.1833*IRI)	0.975
	Small HV	RM =0.0521.exp(0.2714*IRI)	0.9874
	Large HV	RM =0.0545.exp(0.2074*IRI)	0.9651

Considering that the average costs originally calculated correspond to a wear rate under the average conditions mentioned above (change every 100,000 km for LVs as well as HVs), we obtain correspondences between kilometer costs in suspension maintenance and the number of worn shock absorbers for each type of network and vehicle and according to IRI. We obtain Table S12, the corresponding number of total shock absorber sets worn per vehicle-kilometer traveled (vkt).

Table S12 Corresponding number of total shock absorber sets worn per vkt

	Vehicle/IRI	1	2	3	4	5	6
Hig hw ays (11	PC	1.50E-05	1.50E-05	1.50E-05	1.65E-05	2.10E-05	2.55E-05

	LCV	1.28E-05	1.28E-05	1.28E-05	1.41E-05	1.80E-05	2.18E-05
	Small HV	1.07E-05	1.07E-05	1.07E-05	1.28E-05	1.81E-05	2.34E-05
	Large HV	1.07E-05	1.07E-05	1.07E-05	1.17E-05	1.60E-05	1.92E-05
Express ways (101/84)	PC	1.35E-05	1.35E-05	1.35E-05	1.49E-05	1.89E-05	2.30E-05
	LCV	1.16E-05	1.16E-05	1.16E-05	1.27E-05	1.62E-05	1.96E-05
	Small HV	1.03E-05	1.03E-05	1.03E-05	1.23E-05	1.75E-05	2.26E-05
	Large HV	1.03E-05	1.03E-05	1.03E-05	1.13E-05	1.54E-05	1.85E-05
National/rural roads (82/79)	PC	1.18E-05	1.18E-05	1.18E-05	1.30E-05	1.66E-05	2.01E-05
	LCV	1.01E-05	1.01E-05	1.01E-05	1.11E-05	1.42E-05	1.72E-05
	Small HV	9.83E-06	9.83E-06	9.83E-06	1.18E-05	1.67E-05	2.16E-05
	Large HV	9.83E-06	9.83E-06	9.83E-06	1.08E-05	1.47E-05	1.77E-05

From this wearing rate per kilometer, we can easily calculate the typical mileage longevity of shock absorbers by vehicle category and network used depending on IRI (i.e. the inverse of the wearing rate per kilometer), shown in Table S13.

Table S13 Correspondence between IRI level and mileage longevity of the suspensions by type of vehicle and according to the network used

	Vehicle/IRI	1	2	3	4	5	6
Highways (118/88)	PC	66 552	66 552	66 552	60 501	47 537	39 148
	LCV	77 853	77 853	77 853	70 775	55 609	45 796
	Small HV	93 897	93 897	93 897	78 247	55 233	42 680
	Large HV	93 897	93 897	93 897	85 361	62 598	52 165
Express ways (101/84)	PC	73 976	73 976	73 976	67 251	52 840	43 515
	LCV	86 538	86 538	86 538	78 671	61 813	50 905
	Small HV	97 211	97 211	97 211	81 009	57 183	44 187
	Large HV	97 211	97 211	97 211	88 373	64 807	54 006
National/rural roads (82/79)	PC	84 513	84 513	84 513	76 830	60 367	49 714
	LCV	98 865	98 865	98 865	89 877	70 618	58 156
	Small HV	101 698	101 698	101 698	84 748	59 822	46 226
	Large HV	101 698	101 698	101 698	92 452	67 798	56 499

On national roads (NRs) and departmental roads (DRs), where most of the French mileage is traveled, we find the lifetime mileage of shock absorbers within the range of manufacturer recommendations. On the other hand, we see that at high speeds, IRI has very negative effects on the lifespan of the shock absorbers, which drops by half for an IRI of 6 m/km, regardless of the type of vehicle.

This series of data allows us, via an exponential regression (best R^2), to calculate the lifespan functions of shock absorbers according to the operating conditions at IRI higher than or equal to 3 m/km, indicated in Table S14. For IRI =<3 m / km, the typical lifespan of the shock absorbers is that shown in Table S13.

Table S14 Shock absorber lifespan functions according to operating conditions for IRI greater than or equal to 3 m / km in France

		Shock absorbers lifespan function SAL=f(IRI)	R^2
Highways (118/88)	PC	SAL =139 643.exp(-0.183*IRI)	0.9750
	LCV	SAL =139 643.exp(-0.183*IRI)	0.975
	Small HV	SAL =218 765.exp(-0.271*IRI)	0.9874
	Large HV	SAL =181 842.exp(-0.207*IRI)	0.9651
Express ways (101/84)	PC	SAL =155 221.exp(-0.183*IRI)	0.9750
	LCV	SAL =155 221.exp(-0.183*IRI)	0.975
	Small HV	SAL =226 487.exp(-0.271*IRI)	0.9874
	Large HV	SAL =188 260.exp(-0.207*IRI)	0.9651
National/rural roads (82/79)	PC	SAL =177 331.exp(-0.183*IRI)	0.9750
	LCV	SAL =177 331.exp(-0.183*IRI)	0.975
	Small HV	SAL =236 940.exp(-0.271*IRI)	0.9874
	Large HV	SAL =196 949.exp(-0.207*IRI)	0.9651

5. Road noise health impact indicators

Update of the statistical models of tire-pavement noise evolution from the European benchmark method

Acoustic categories of pavement surfaces

Three categories of rolling courses – R1, R2 et R3 – were determined by observing the LAmax sound levels on approximately 380 road sections according to the noise measurement process called “procedure IV” (isolated vehicles) at a temperature T = 20°C and a speed v = 90 km/h (Table S15). This categorization can easily be criticized because, within each technique, there is a strong dispersion of acoustic levels, e.g. up to a 5dB(A) standard deviation for type 2 very-thin asphalt overlay (VTAO) with 0 to 6 mm-large aggregates (=type 2 VTAO 0/6). Among these rolling courses, the most used in France on interurban roads are probably the VTAO 0/10 on the highways and the Semi-coarse asphaltic concrete (SCAC) 0/10 on the DRs. Surface dressing (SD) techniques are used on DRs depending on local cultures and budgets. Thus, the 3 classes are important for our method.

Table S15 Classification of road resurfacing techniques according to the Setra categorization (Sétra 2009)

R1	**R2**	**R3**
Porous asphalt 0/6	VTAO 0/10-T2	SCAC 0/14
UTAO 0/6	Porous asphalt 0/14	VTAO 0/14
UTAO 0/6-T2	TOA 0/10	SD 6/8
Porous asphalt 0/10	Micro surfacing	Concrete cement

VTAO 0/6-T1	SD 4/6	SD 6/10
	VTAO 0/10-T1	SD 10/14
	SCAC 0/10	
	UTAO 0/10	

The Sétra method and its limitations

The aging effect of the road wearing course was studied by Rx class for surfaces aged between 2 to 10 years in the NMPB volume 1 (Sétra 2009): this document represent the European benchmark method for road noise simulation. Beyond 10 years old, this study considers that road noise level remains stable, apart from specific road defects which are not considered. However, when these models were developed, noise measurements were taken from French road sections that were often less than 3 years old. In the NMPB, the noise level plots as a function of the age of the wearing course for each category of pavement were then plotted, as well as their trend curve, and two other curves: one considering LAmax stable with the age and anoter considering that LAmax increases by 1 dB (A) every 2 years. Among these last two curves, the line closest to the regression was considered the most probable trend. Slopes in the level of transmission power have been defined based on these statistical treatments: they are easily debatable (e.g. correlation coefficients not indicated), but largely used as a reference in France and Europe.
By using this model, we obtain the power levels indicated in Table S16, rounded to the nearest dB (A), and we recall the aging effects of the type of rolling course Rx, with x from 1 to 3, proposed by the NMPB.

Table S16 Noise power level data - motor component and tire-pavement component - per meter of source line on a 2-year surface and effects of aging, by application of the NMPB model to our French interurban roads, without a ramp, for the speeds indicated in Table 2

	Lw/m – engine component (dB(A))			**Lw/m – tire-pavement component (dB(A))**									**Aging effect from 2 to 10 years-old (dB(A)/year)**		
				R1			**R2**			**R3**					
	RD/RN	*RE*	*RA*	*RD/RN*	*RE*	*RA*	*RD/RN*	*RE*	*RA*	*RD/RN*	*RE*	*RA*	*R1*	*R2*	*R3*
1 HV	50	50	51	59	60	60	62	63	63	63	64	64	0.30	0.15	0.13
1 LV	42	43	43	49	50	52	53	54	56	55	57	58	0.50	0.25	0.20

The NMPB's model assumes a sudden stabilization of these power levels beyond 10 years of age seems unlikely to us. As we model the effects of maintenance programs with resurfacing periods consistently greater than 10 years in practice, we need to model this subsequent development. In addition, the functions retained are linear because the age intervals of the road surface considered are restricted. However, several authors rather suggest logarithmic or y = 1-exponential (-t) curve shapes over long times (Anfosso-Lédée and Toussaint 2015; Kragh, Andersen, and Pigasse 2013).

Development of new noise evolution models over times

Update of the database of the ex-LRPC of Strasbourg

To improve the aging model of the NMPB, we obtained the database of the ex-LRPC of Strasbourg containing additional measurements of LAmax (7.5m), called “acoustic level during passage”, in its updated version in the second half of 2017. The database presents level of noise measured for different kinds of rolling courses that we can separe under the Rx classification, at different ages. It has considerably grown since the NMPB’s calculations in 2009, and in particular to include measures of road surfaces older than 10 years old. However, the number of measurements at ages over 10 years, all kinds of rolling course combined, is around 15. The total sample size only contains 318 individuals. By type of surface, the size of the samples is also reduced: respectively 201, 13, and 98 individuals for R1, R2, and R3 categories. For those over 2 years (inclusive), we get 88, 9, and 57 measurements. Despite a still restricted database, we will try to find better equations to model the effect of age on the level of noise of rolling courses by analysing the database.

Statistical study of R1 rolling courses

We start by analysing the category R1 and present results in Figure S10.

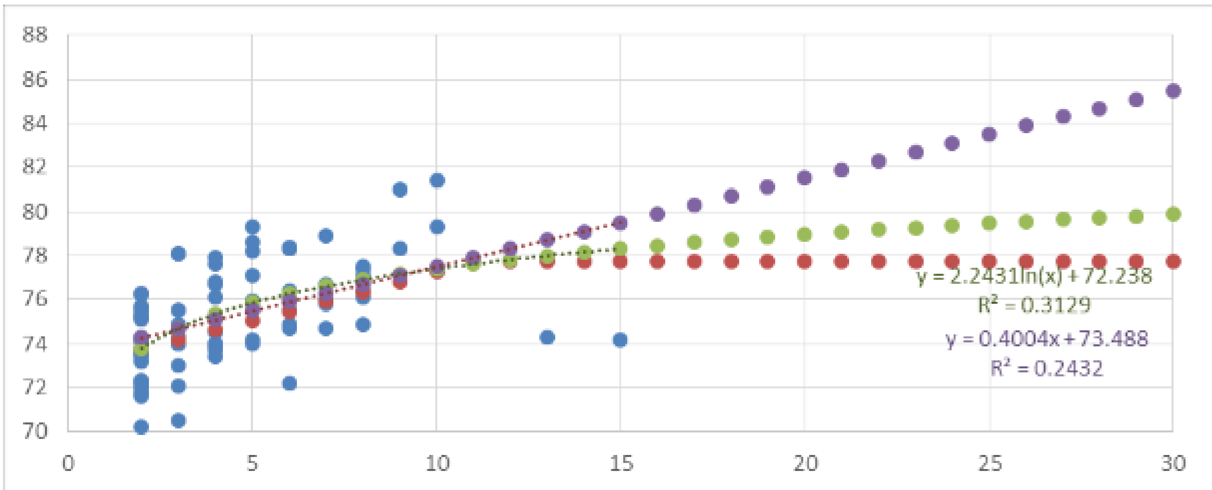

Figure S10 Sound level measurements of R1 rolling course from the acoustic database of the ex-LRPC Strasbourg (blue) and various evolution models (dotted regressions, and regression explorations up to t = 30 years with the other color dots): linear in purple, logarithmic in green, and NMPB (Sétra 2009) in red. On the y-axis: sound level (in dB (A)); on the x-axis: age of the rolling course (in years).

This dataset shows much better correlations when ignoring measurements on rolling course less than 2 years old (it doubles R^2). The correlation of logarithmic form is a little better than that of the linear form as seen in Figure S10. The absence of measurements after 10 years, apart from 2 measurements, does not allow quality work to evaluate the noise levels evolution beyond this surface age. However, we compare 3 trends: two models based on the two types of regression performed, and the NMPB model. To study this model, we calculated the effect, on the total sound level, of the linear acoustic increment over time of the pavement-tire and the motor components between 2 and 10 years on a total sound power level, for an LV and the R1 category. As the sound levels are not additive, a specific calculation to

add the two components is necessary. For example, while the annual increment on the power level is 0.5 dB (A) / year for the pavement-tire component of a LV, the increment on the total power level depends on speed and the age of the rolling course and is presented in Figure S11. The level of emitted power measured at the passage at 7.5m is calculated according to an affine relation to time according to Equation S1 andThe Setra guide proposes standard equations to calculate emission power levels per meter of source line - engine and tire-pavement components for an LV and an HV - as well as noise level evolutions of the tire-pavement component for rolling courses between 2 and 10 years old (Sétra 2009). We choose the equations for the "all-speed" and "zero gradient" HV, and the "stabilized speed, all-gradient" LV. Note that the slope greatly varies the transmission power level of an HV. The equations are to be applied at a given speed over certain speed intervals, which we choose in line with the average speeds practiced by category of vehicle and by type of road in Franc.
Equation S2.

Equation S1 Equation for switching between emission power level per meter of source line and maximum sound power level

$$L_{a,max} = L_{w/m}(t) + \log(Vmoy) + 30$$

Thus, we can add the same temporal increment to LAmax and Lw/m, but it is different from that of $L_{w/m,pavement-tire}$ as shown in Figure S11. We account for this computational non-linearity in the comparative approach presented in Figure S10, at reference speed of 90 km/h. We, therefore, applied the calculated increments for $L_{w/m,tot}$ for DRs and NRs.

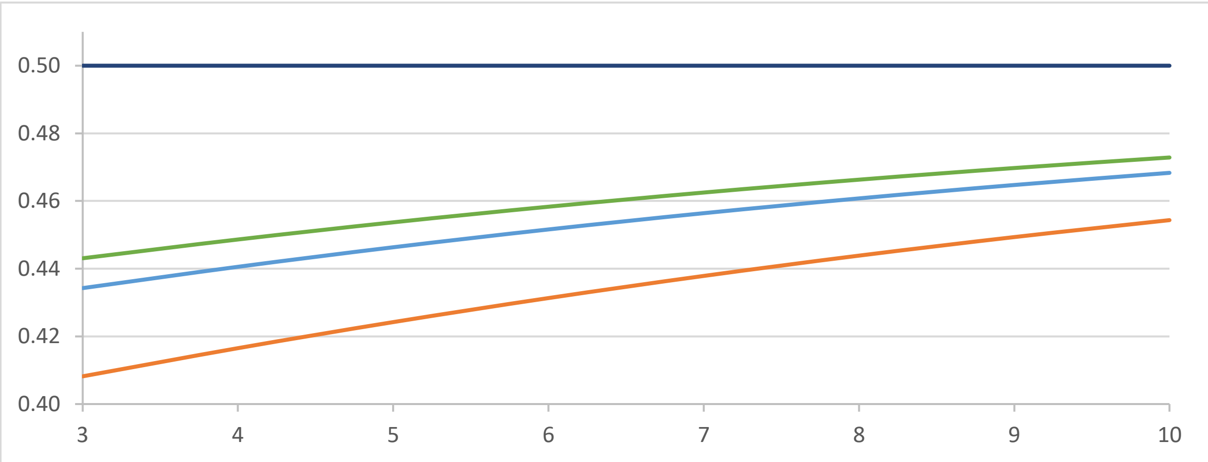

Figure S11 Annual power level increments for LV (in dB(A)) according to surface layer's age (in year) – increments for DRs and NRs in orange, ERs in light blue, HRs in green, with the tire-pavement component only in dark blue

This comparison analysis leads us to the following conclusion: the linear model gives values that are far too high for aged rolling courses, while the NMPB model is far from being convincing from the point of view of the physical sense. We propose, by default, to retain the logarithmic model shown on the sample below for R1 rolling courses, despite a coefficient of determination of 0.31. If the acoustic increment remains almost identical over the interval 2 to 15 years between the NMPB model and the logarithmic model, the trend appears physically more likely beyond with the logarithm model than with that of the NMPB. It would seem important to explore these questions on larger samples, which would have to be made with modern vehicles in France.

Statistical study of R2 and R3 rolling courses

We reproduce this approach for R2 and R3 rolling courses. For R2 rolling courses, as shown in Figure S12, the correlations are better on a sample restricted to measurements after 2 years. However, this can be explained first of all by the small size of the sample considered (9 individuals older than 2). These linear and logarithmic regressions, despite coefficients of determination higher than the usual results of this type of exercise (of the order of 0.5 here), remain unreliable. However, we have to choose between the linear model, the logarithmic model, and the NMPB model. Depending on the model used for R1 rolling courses, the average LAmax of these surfaces ranges from 75 to 80 dB (A) between 2 and 30 years old. The R2 rolling course being noisier than the R1 ones according to the NMPB - 75 dB (A) for a "young" VTAO with 0/10mm-large aggregates of type T2 against 78-79 dB (A) for "young" SCAO with 0/10mm- and 0/14mm-large aggregates -, it is normal that our model transcribes these trends. We do not want to choose the evolution model of the NMPB because it gives at all times lower sound levels than those of the R1 rolling course according to our model, that is plotted on real data. The linear model exhibits aberrant sound power levels. We choose again the logarithmic model by default, although the calculated power level is very high: about 4 dB (A) more than the R1 rolling course at T = 30 years, while an increase of 3 dB (A) already represents a doubling of the acoustic energy. We again draw attention to the need for field measurements on surfaces older than those reported in the existing French database.

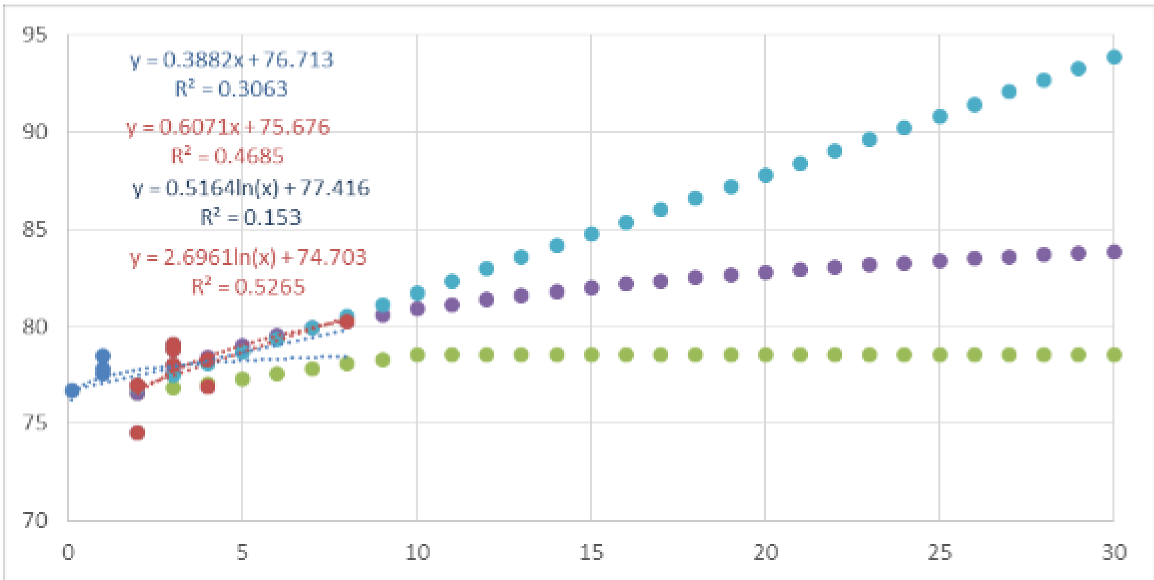

Figure S12 Noise level measurements of R2 surfaces from the acoustic database of the ex-LRPC Strasbourg - measurements before 2 years in dark blue and between 2 and 8 years in red. Regressions on measurements after 2 years in red and on all dots in blue. Different models of evolution (regressions and their extrapolation up to t = 30 years with colored dots): linear in light blue (equation of the regression on measures after 2 years), logarithmic in purple (idem), and NMPB in green. On the y-axis: noise level (in dB (A)); on the x-axis: age of the rolling course (in years)

The measurements of R3 surfaces seem to indicate a poor segmentation of these surfaces as shown in Figure S13: the measurements are very dispersed and no good regression between the level of emission power and the age of the surface are found.

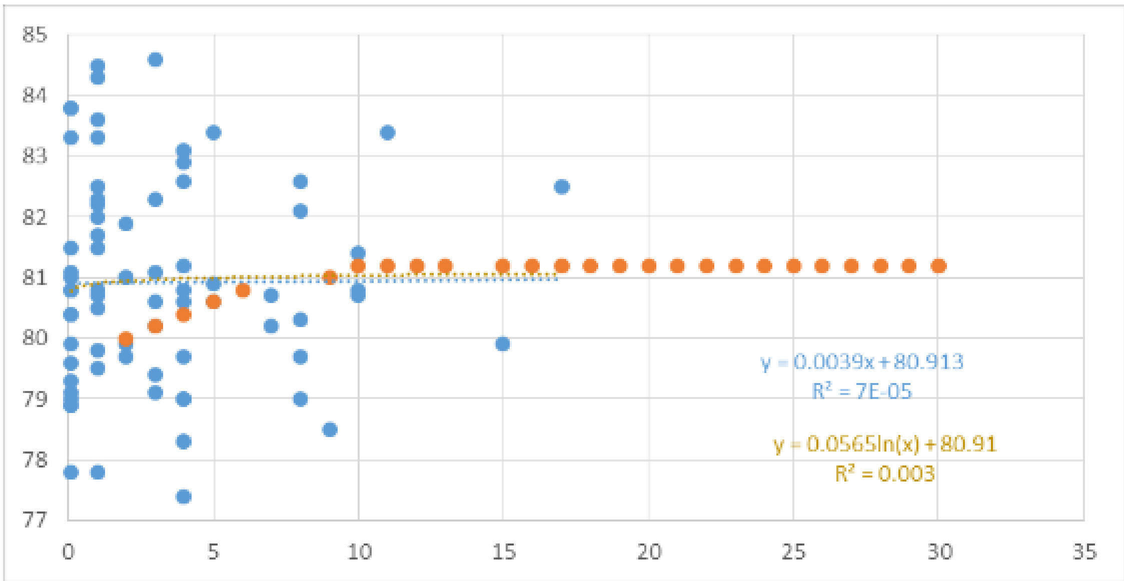

Figure S13 LAmax measures in blue on R3 surface layers from the ex-LRPC Strasbourg database. Tests of correlations to the age of the surface layer in light blue and yellow, and NMPB model in orange (forms of regression on measures (blue dots) in dotted lines, and their extrapolation up to t = 30 years in the orange dots). On the y-axis: sound level (in dB (A)); on the x-axis: age of the surface layer (in years).

We have tested various segmentations on these rolling courses. No segmentation, even by a single technique, makes it possible to highlight any satisfying correlation. We thus use the NMPB model: the noise level is much higher than the other surface classes at T = 2 years (80 dB (A)). On the other hand, the R2 surfaces become noisier than the R3 surfaces when reaching 7-8 years.

Synthesis of the developed LV equations and HV extrapolation

The previous comparison of models of changes in noise levels of the NMPB and those suggested by the updated French measurements only concerns the LVs. However, we must also consider the evolution of the HV noise levels. Unfortunately, we don't have any HV data. The NMPB offers an acoustic level aging increment that is almost two times lower than that of LVs, but the power levels are above T = 2 years by approximately 10 dB (A). To transcribe the "logarithmic effect" on the noise emitted by the vehicles highlighted on the LV measurements for surface categories R1 and R2, and to take into account the respective effects of aging between LV and HV presented in the NMPB, we propose a logarithmic coefficient increment respecting a rule of proportionality with the increments of the NMPB. For R3 coatings, the NMPB model is retained. The noise level calculation equations considered are synthesized in Table 16 of the article for surfaces older than 2 years; before that age, the tire-pavement noise component is considered as stable.

Equations from Sétra

Noise power levels per meter of source line - engine and tire-pavement components

The Setra guide proposes standard equations to calculate emission power levels per meter of source line - engine and tire-pavement components for an LV and an HV - as well as noise level evolutions of the tire-pavement component for rolling courses between 2 and 10 years old (Sétra 2009). We choose the equations for the "all-speed" and "zero gradient" HV, and the "stabilized speed, all-gradient" LV. Note that the slope greatly varies the transmission power level of an HV. The equations are to be applied at a given speed over certain speed intervals, which we choose in line with the average speeds practiced by category of vehicle and by type of road in Franc.

Equation S2 Generic equation for calculating the sound power level per meter of source line in dB (A) (Sétra 2009)

$$L_{w/m} = a + b.\log\left(\frac{Vmoy}{Vref}\right) + \Delta L$$

With $Vmoy$ the average speed practiced by the vehicle considered, $Vref$ the reference speed taken equal to 90 km/h for LVs and 80 km/h for HVs, and ΔL a correction term relating to the speed and the gradient.

To apply our equations, the Setra guide provides coefficient values according to the category of road surfaces R1, R2, or R3 (Table S15), which we recall for the "tire-pavement" component in Table S17 and for the engine component in Table S18 (Sétra 2009).

Table S17 Coefficients for calculating the level of emission power related to tire-pavement component depending on the vehicle and the category of the rolling course

Rolling course	LV		HV	
	a	b	a	b
R1	49.4	21	59.1	20
R2	53.4	20.1	61.1	20
R3	55.9	21.4	63.1	20

Table S18 Coefficients for calculating the level of emission power linked to the engine depending on the vehicle and speed

Vehicle	[Vinf ; Vsup]	a	b
LV	[30 ; 110]	42.4	2
LV	[110 ; 130]	40.7	21.3
HV	[70 ; 100]	50.4	3

We obtain the sound power levels shown in Table 6 in the article, rounded to the nearest dB (A).

6. References

Anfosso-Lédée, Fabienne, and Loïc Toussaint. 2015. “Long-Term Acoustical Performance of Low Noise Road Surfaces in Urban Areas in Switzerland.” In. Maastricht.

Arnsperger, Christian, and Philippe Van Parijs. 2007. *Éthique économique et sociale*. Paris: La Découverte.

Bennett, C.R, and I.D Greenwood. 2003. “Volume 7: Modeling Road User and Environmental Effects in HDM-4, Version 3.0, International Study of Highway Development and Management Tools (ISOHDM).” World Road Association (PIARC). http://www.lpcb.org/index.php/documents/papers-and-reports/reports-and-books/194-2003-modelling-road-user-and-environmental-effects-in-hdm-4/file.

Desportes, Marc, and Antoine Picon. 1997. *De l’espace Au Territoire: L’aménagement En France XVIe - XXe Siècles*. Paris: Presses de l’École Nationale des Ponts et Chaussées.

Easterlin, R. 2003. “Building a Better Theory of Well-Being.” In *Proceedings*. University of Milano-Bicocca. http://www-bcf.usc.edu/~easterl/papers/BetterTheory.pdf.

Epps, J. A. 1999. “The Road to Performance-Related Specifications.” Reno, Nevada: WesTrack Interim Rep.

Eriksson, Lina, James Mahmud Rice, and Robert E. Goodin. 2007. “Temporal Aspects of Life Satisfaction.” *Social Indicators Research* 80 (3): 511–33. https://doi.org/10.1007/s11205-006-0005-z.

Gagnepain. 2006. “La Climatisation Automobile - Impacts Consommation et Pollution.” Repères. ADEME. http://www2.ademe.fr/servlet/getDoc?cid=96&m=3&id=25236&p1=00&p2=12&ref=17597.

INSEE. 2018. “Series 001769682 Seasonally Adjusted Consumer Price Index - Base 2015 - All Households - France - All Items | Insee.” May 2018. https://www.insee.fr/en/statistiques/serie/001769682#Tableau.

Kragh, Jørgen, Bent Andersen, and Gilles Pigasse. 2013. “Acoustic Ageing of Pavement - Dvs-Drd Joint Research Programme – Super Silent Traffic.” n°460. Ministère des transports danois - Direction des routes (Vejdirektoratet). http://vejdirektoratet.dk/DA/viden_og_data/publikationer/Lists/Publikationer/Attachments/798/acoustic%20ageing%20of%20pavement.pdf.

Leclerc, Cédric. 2008. “Réduction de La Traînée d’un Véhicule Automobile Simplifié à l’aide Du Contrôle Actif Par Jet Synthétique.” Toulouse, France: Institut national polytechnique de Toulouse.

Poelman, M.A, and R.P. Weir. 1992. “Vehicle Damage Induced by Road Surface Roughness.” In *Vehicle, Tire, Pavement Interface*, p97-15. Philadelphia: ASTM International. https://doi.org/10.1520/STP15911S.

Rawls, John. 1999. *A Theory of Justice*. Rev. ed. Cambridge, Mass: Belknap Press of Harvard University Press.

SANEF. 2017. “Dossier de Presse - Résultats de l’Observatoire Sanef Des Comportements.” 6eme édition. http://www.sanefgroupe.com/var/sanef/storage/media/presse/DP-observatoire-des-comportements/files/docs/all.pdf.

Santé publique France. 2016. “Impacts Sanitaires de La Pollution de l’air En France : Nouvelles Données et Perspectives.” 2016. http://www.santepubliquefrance.fr/Accueil-Presse/Tous-les-communiques/Impacts-sanitaires-de-la-pollution-de-l-air-en-France-nouvelles-donnees-et-perspectives.

Sétra. 2009. “Prévision Du Bruit Routier 1 - Calcul Des Émissions Sonores Dues Au Trafic Routier.” Sétra. https://www.cerema.fr/fr/centre-ressources/boutique/prevision-du-bruit-routier-calcul-emissions-sonores-dues-au.

Young, Cristobal, and Chaeyoon Lim. 2014. “Time as a Network Good: Evidence from Unemployment and the Standard Workweek.” *Sociological Science*, 10–27. https://doi.org/10.15195/v1.a2.

Zhang, Han, Michael D. Lepech, Gregory A. Keoleian, Shunzhi Qian, and Victor C. Li. 2010. “Dynamic Life-Cycle Modeling of Pavement Overlay Systems: Capturing the Impacts of Users, Construction, and Roadway Deterioration.” *Journal of Infrastructure Systems* 16 (4): 299–309. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000017.