SUPPLEMENTARY MATERIAL

Towards road sustainability – Part II: methodological application to road maintenance and lessons learned from a French highway

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

1. Survey on road resurfacing in France

Faced with the lack of knowledge on the reality of interurban road resurfacing practices in France in all their plurality, we surveyed all the managers concerned in the country.

Questionnaire and survey protocol

Distributed online between May and November 2017 via GoogleForm, the questionnaire “The renewal of road surface layers in France” aimed to supplement national knowledge of actual resurfacing practices on interurban roads (see full questionnaire in Appendix 4). The announced objective was to help “the development of a holistic evaluation model of the impact of the frequency of renewal of surface layers (i.e. resurfacing) in France […] according to the input data currently available or potentially available within 10 years ”and“ constitute a first limited library of relevant maintenance practices by type of network (motorway, national/main department, secondary department/municipality) ”.

The questionnaire consists of 23 questions organized into 5 sections. The first section concerns essential information on the manager: type of manager (“SCA” for the private concessionaires of governmental roads, “DIR” for national roads operated by regions, “CD” for county roads, Municipality, Company, Other), network maintained (type, linear), maintenance budget and distribution (resurfacing and others). The second section provides information on the resurfacing techniques used: parts of the resurfacing techniques used, thicknesses used, the composition of the materials and granulometry of the aggregates, choice of technique. The third section deals with the cost of techniques: parameters, ranges, and average prices by technique and cost breakdown (raw materials, labor). The fourth section discusses the manager's knowledge of his road assets: frequency of maintenance, factors triggering resurfacing operations, postponement of work practices, mechanical equivalences of techniques, smoothness and adhesion records, as well as the existence and accessibility of heritage data.

Respondents

The questionnaire required about fifteen minutes to be completed, provided that the respondent was technically and quantitatively aware of the practices of his service. Often, due to the lack of a single point of contact with all this data, the responses required additional research on the part of managers to provide a comprehensive response.

Out of a total of 100 departments, 11 DIR and 6 SCA, the 37 responses obtained in 7 months count 27 departments, 6 DIR, and 4 SCA, for a French representation of 24% of DR, 67% of NR, and 73% of highways, i.e. 92,000 km of DR, 7,800 km of NR, and 6,300 km of highways (Table 1).

Table 1 Representativeness of the survey's sample

Network	Respondents	Representativeness (% of mileage)	Represented mileage (km)
NR	4	73%	6300
HR	6	67%	7800
DR	27	24%	92 000

Type of resurfacing techniques used by network - Response analysis

In France, the surface layers are reconstructed approximately every fifteen years. The less expensive Surface dressings (ESU) can be done every 5 to 8 years, and remain widely used on moderately to lightly trafficked roads. They are particularly used in the context of tight budgets (small cities or departmental roads). The types of techniques depend mainly on the materials used (diameter of the aggregates and type of asphalt binder), the mixing temperature, and the thickness of the layer. Asphalt Concrete (AC, "BB" in French) is a mixture of aggregates coated with an asphalt binder. There are several types: Semi-coarse AC (BBSG in French), Thin AC (BBM), Very Thin AC (BBTM), Ultra-Thin AC (BBUM), porous AC (BBDr), High Modulus AC (BBME), emulsion AC (BBE). Depending on the material, the thickness of the layer to be applied will be adapted, but generally goes from 1.5cm (BBUM) to 6-7cm (BBSG 0/10) or even 7-9cm (BBSG 0/14) of material, going through 2.5 cm for BBTM and 3 to 4cm for BBM. More recently, micro-surfacing (ECF) has also been developed for its low cost and environmental impact. The properties of the resurfacing techniques vary and depend on the choice of the type of resurfacing, by type of network. For interurban roads, these choices are shown in Figure 1. To resurface a roadway, we usually plan a few centimeters in the surface area of the roadway, before depositing a bonding layer that will ensure the mechanical link between the old ones. materials and the new asphalt layer that is placed on the road. Surface dressing consists, after pavement preparation, of applying one or more layers of bitumen emulsion and aggregate alternately. They are suitable for municipal and departmental roads with low traffic, because they treat both impermeability and skid resistance, at a low cost.

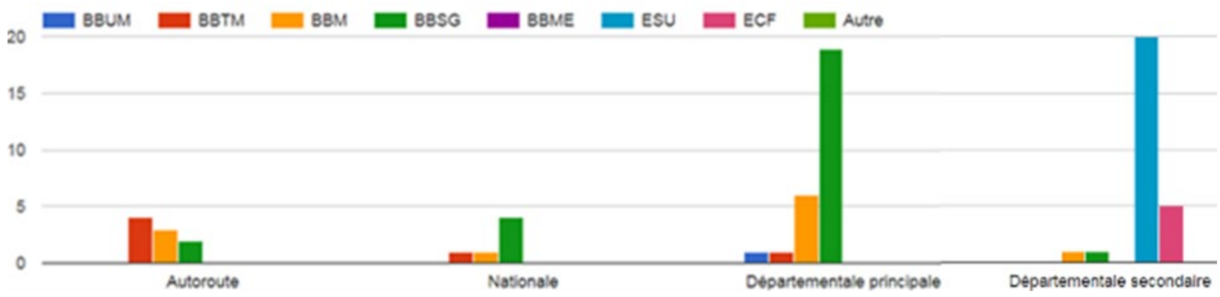


Figure 1 Resurfacing techniques by type of network maintained according to our resurfacing survey (in number of responding managers) – Autoroute = highways; Nationale = national roads; Départementale principale = highly-trafficked departmental roads; Départementale secondaire = lower-trafficked departmental roads.

Cost of resurfacing techniques - Response analysis

summarizes the data collected for the major resurfacing techniques mentioned by the road managers who answered our survey. Some respondents mention outright confidentiality of the data (1 occurrence) or indicate "not applicable" (1 occurrence).

Table 2 Summary of cost data for resurfacing techniques from the survey

COST	SCAC	TAC	VTAC	MICROSURFACING	SURFACE DRESSING
AVERAGE (€TTC/M2)	17.5	14.2	9.56	4.66	3.10
OCCURRENCES	12	6	8	7	13
STANDARD DEVIATION	7.71	3.92	4.95	0.87	1.07
AVERAGE (€HT /T)	62.0	63.5	62.0	5.18	4.85
OCCURRENCES	7	7	3	2	2
STANDARD DEVIATION	4.05	3.15	2.00	3.29	3.75

Additional data, at low occurrences (1 to 3), and corresponding to a technique within a family are available in our database (e.g. single layer micro-surfacing, double layer micro-surfacing, single layer surface dressing, double layer surface dressing, cold cast AC, UTAC, porous AC).

2. IRI parametrization

Our sample shows fairly low IRI levels, which remain consistent with the highway's frequent resurfacing (on average every 13-14 years). In Figure 2, we have placed two points: the average IRI of the highway section at the beginning and end of its life (stards). The IRI reaches an average of 0.7-0.8 m / km at the end of its surface life (uniform blue star on the figure) and drops again after resurfacing to 0.4 m / km (blue star with a dark outline).

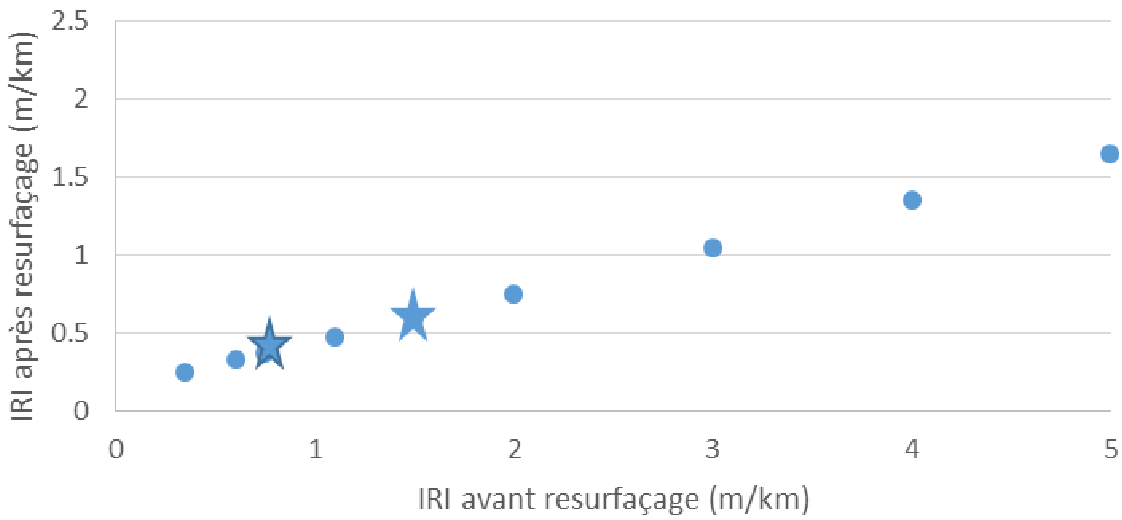


Figure 2 Effect of resurfacing work on the highway surface condition with the selected calibrated parameters (X-axis: IRI before resurfacing operation; Y-axis: IRI after resurfacing operation)

Our surface condition degradation model behaves as shown in Figure 3. We see that the model tends to erase the variations of the IRI on the highway section: annual minima and maxima get close after each resurfacing. This phenomenon is not realistic: the average standard deviation of the IRI data on the operator's data set is 0.47 (left trace) and 0.49 (right trace) on the highway. After simulation, this mean standard deviation drops to 0.07 after the original reconstruction (2017), to 0.02 after the first resurfacing (2030), and 0.006 after the second and last resurfacing (2043). However, the excess-fuel consumption and excess-wear equations being linear (or behaving almost linearly) on the IRI levels considered, and the "natural" standard deviation being low (<0.5 m / km), only considering the average (since the standard deviation becomes extremely low) should only generate a negligible error on the results. On the other hand, the IRI level increases during the iteration of the cycles, excluding maximum values, which is quite relevant. We remain at an average end-of-life IRI of around 1.2 m/km, this value being consistent although higher than what is shown by field data.

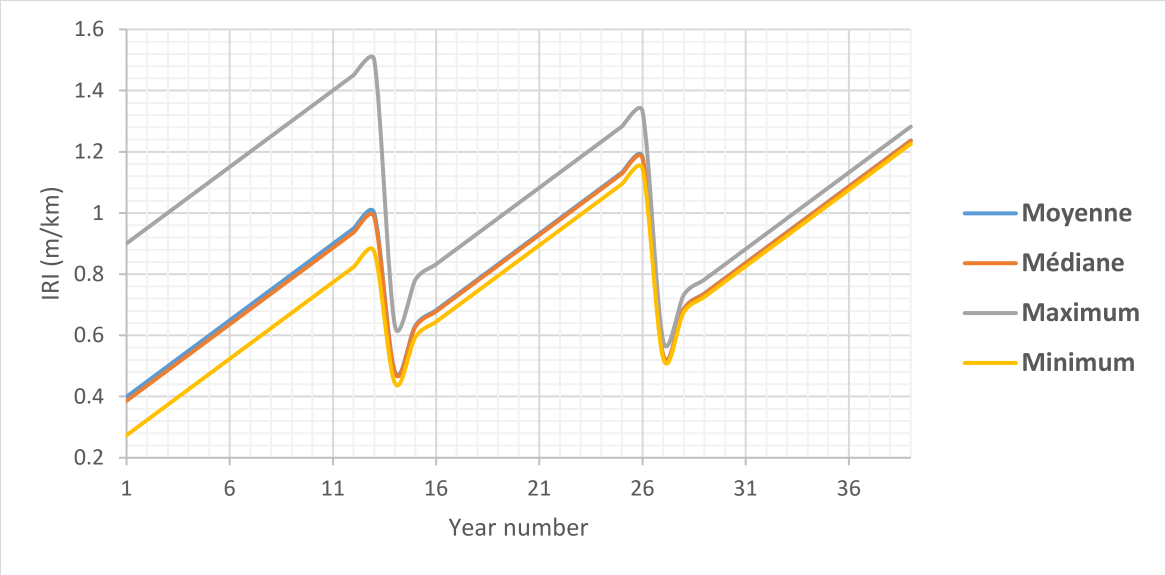


Figure 3 Average (in blue), median (in orange), maximum (in grey), and minimum (in yellow) values of the IRI of the studied highway sub-sections, simulated over the lifetime (in years) for standard maintenance on highways in France

3. Road resurfacing techniques LCIs

LCIS of the 8 most frequent resurfacing techniques in France

Table 3 Processes created relating to the resurfacing technique

Created process	Description
Imported European bitumen, FR	1t of bitumen, produced in Europe, at asphalt plant
Bitumen production, FR	1t of bitumen, produced in France, at asphalt plant
Market, bitumen, FR	1t of bitumen, consumed in France, at asphalt plant
Market, virgin aggregate, FR	1t of French average aggregate, at asphalt plant
Market, polymer, FR	1t de polymer, at asphalt binder plant
Market, modified bitumen, FR	1t de modified bitumen, at asphalt binder plant
Market, emulsion binder, FR	1t of emulsion binder, at asphalt binder plant
Asphalt mixing, FR	Mixing of 1t of asphalt mixture (materials excluded)
Average asphalt mixture, on-site, FR	1t of average hot mix asphalt (4.8% bitumen, 3% aggregate loss), on construction site
Cold asphalt mixture, on-site FR	1t of cold mix asphalt, (7% émulsion), on construction site

Table 4 synthesis of the LCIs developed per resurfacing technique

TECHNIQUE	STEP	SUBSTEP	PROCESS (in French)	QUANTITY	UNITS
Semi-coarse AC	Tack coat		*Accrochage 1m2*	1.00E+00	sm
	Asphalt mixture		*Béton Bitumineux moyen, FR*	1.41E-01	t/sm
	Construction	PAH emissions	*Fumées bitume HAP*	6.01E-02	unit/sm
		Finisher	*Finissage 1 jour*	1.43E-04	d/sm
		Roller V1	*Compactage vibrant 1 jour*	2.86E-04	d/sm
Thin AC	Tack coat		*Accrochage 1m2*	1.00E+00	sm
	Asphalt mixture		*Béton Bitumineux moyen, FR*	9.41E-02	t/sm

	Construction	PAH emissions	*Fumées bitume HAP*	4.00E-02	unit/sm
		Finisher	*Finissage 1 jour*	1.43E-04	d/sm
		Roller V1	*Compactage vibrant 1 jour*	2.86E-04	d/sm
Very Thin AC	Tack coat		*Accrochage 1m2*	1.00E+00	sm
	Asphalt mixture		*Béton Bitumineux moyen, FR*	5.89E-02	t/sm
	Construction	PAH emissions	*Fumées bitume HAP*	2.50E-02	unit/sm
		Finisher	*Finissage 1 jour*	2.50E-02	d/sm
		Roller V1	*Compactage vibrant 1 jour*	2.86E-04	d/sm
Ultra-Thin AC	Tack coat		*Accrochage 1m2*	1.00E+00	sm
	Asphalt mixture		*Béton Bitumineux moyen, FR*	3.53E-02	t/sm
	Construction	PAH emissions	*Fumées bitume HAP*	1.50E-02	unit/sm
		Finisher	*Finissage 1 jour*	1.43E-04	d/sm
		Roller V1	*Compactage vibrant 1 jour*	2.86E-04	d/sm
Monolayer micro-surfacing, on-site	Materials		*Enrobe a froid FR*	1.50E-02	t/m²
	Construction	Cold mixture machine	*Coulage enrobe froid 1 jour*	1.43E-04	d/sm
		Small loader (<10t)	*Chargement 1 jour*	1.43E-04	d/sm
		Vacuum sweeper	*RAS*		d/sm
		Roller V1	*Compactage vibrant 1 jour*	1.43E-04	d/sm
Double-layer micro-surfacing, from plan	Materials		*Enrobe a froid FR*	3.00E-02	kg/m²
			Enrobage a froid	3.15E-01	t/m²
	Construction	Finisher	*Finissage 1 jour*	1.43E-04	d/sm
		Small loader (<10t)	*Chargement 1 jour*	1.43E-04	d/sm
		Vacuum sweeper	RAS		d/sm
		Roller V1	*Compactage vibrant 1 jour*	1.43E-04	d/sm
Double layer dressing					
	Materials	Aggregates	*Market granulats vierge FR*	2.00E+01	kg/sm
		Emulsion	*Market emulsion FR*	2.50E+00	kg/sm
	Transportation	Truck	*transport, freight, lorry 16-32 metric ton, EURO4*	6.75E-01	t.km/sm
	Construction	Sprayer	*Epandage 1 jour*	1.43E-04	d/sm
		Gravel spreader	*Gravillonnage 1 jour*	4.29E-04	d/sm
		Roller on tires P1	*Compactage pneu 1 jour*	1.43E-04	d/sm
Double prechipped surface dressing					
	Materials	Aggregates	*Market granulats vierge FR*	3.00E+01	kg/sm
		Emulsion	*Market emulsion FR*	3.50E+00	kg/sm
	Transportation	Truck	*transport, freight, lorry 16-32 metric ton, EURO4*	1.01E+00	t.km/sm
	Construction	Sprayer	*Epandage 1 jour*	1.43E-04	d/sm
		Gravel spreader	*Gravillonnage 1 jour*	4.29E-04	d/sm
		Roller on tires P1	*Compactage pneu 1 jour*	1.43E-04	d/sm

Sm=square meter

Table 5 LCI of a process relating to coating one squared meter of road

STEP	SUBSTEP	PROCESS	QUANTITY	UNITS
Materials	Emulsion	*Market emulsion FR*	5.00E+02	g/sm
Transportation	Truck, from binder plant to asphalt plant	*Market for transport, freight, lorry 16-32 metric ton, EURO4*	4.00E-02	tkm/sm
Construction	Spraying	*Epandage 1 jour*	2.82E-05	d/sm

Building machines LCIs

Table 6 Processes to use different construction machines over one working day involved in resurfacing

OPERATION	PROCESS (IN FRENCH)	QUANTITY	UNIT
MILLING	*Engin de chantier, RER*	5.32E-01	unit/d
FINISHING	*Engin de chantier, RER*	1.93E-01	unit/d
VIBRATING COMPACTING	*Engin de chantier, RER*	5.41E-02	unit/d
COMPACTING, ON TIRES	*Engin de chantier, RER*	8.87E-02	unit/d
COLD IN-PLACE RECYCLING	*Engin de chantier, RER*	9.51E-01	unit/d
BINDER SPRAYING	*Engin de chantier, RER*	1.98E-01	unit/d
GRAVEL SPREADING	*Engin de chantier, RER*	1.98E-01	unit/d
COLD ASPHALT MIXTURE PLACING	*Engin de chantier, RER*	2.58E-01	unit/d
LOADING	*Engin de chantier, RER*	1.18E+00	unit/d

Table 7 LCI relating to the combustion of 1 ton of diesel (low sulfur content) in a construction machine

FLOW	NATURE	PROCESS	QUANTITY	UNITS
INPUT	Diesel	*diesel production, low-sulfur, Europe without Switzerland*	1.00E+00	t
	Lubricant	*lubricating oil, RER*	2.16E+01	kg
	Machine	*building machine, RER*	5.63E-03	unit
	Lub Incineration	*treatment of waste mineral oil, hazardous waste incineration, Europe without Switzerland*	2.16E+01	kg
OUTPUT	CB	*Carbon black, elementary flows/air/unspecified*	1.31E+03	g
	CH_4	*Methane, elementary flows/air/low pop density*	8.30E+01	g
	CO	*Carbon monoxide, fossil, elementary flows/air/low pop density*	1.08E+04	g
	CO_2	*Carbon dioxide, fossil, elementary flows/air/low pop density*	3.16E+03	kg
	N_2O	*Dinitrogen monoxide, elementary flows/air/low pop density*	1.35E+02	g
	NH_3	*Ammonia, elementary flows/air/low pop density*	8.00E+00	g
	NMVOC	*NMVOC, non-methane volatile organic compounds, unspecified origin, elementary flows/air/low pop density*	3.38E+03	g
	NOx	*Nitrogen oxides, elementary flows/air/low pop density*	3.26E+04	g
	PM_{10}	*Particulates, < 10 um, elementary flows/air/low pop density*	2.10E+03	g
	$PM_{2.5}$	*Particulates, < 2.5 um, elementary flows/air/low pop density*	2.10E+03	g
	TSP	*Particulates, > 2.5 um, and < 10um, elementary flows/air/low pop density*	2.10E+03	g
	Cadmium	*Cadmium, elementary flows/air/low pop density, long-term*	1.00E-02	mg
	Copper	*Copper , elementary flows/air/low pop density*	1.70E+00	mg
	Chromium	*Chromium, elementary flows/air/low pop density*	5.00E-02	mg
	Nickel	*Nickel, elementary flows/air/low pop density*	7.00E-02	mg
	Selenium	*Selenium, elementary flows/air/low pop density*	1.00E-02	mg
	Zinc	*Zinc, elementary flows/air/low pop density*	1.00E+00	mg

Benz(a)-anthracene	*Benz(a)anthracene, elementary flows/air/unspecified*	8.00E+01	µg
Benzo(b)-fluoranthene	*Benzo(b)fluoranthene, elementary flows/air/unspecified*	5.00E+01	µg
Dibenzo(a,h)-anthracene	*Dibenz(a,h)anthracene, elementary flows/air/low pop density*	1.00E+01	µg
Benzo(a)pyrene	*Benzo(a)pyrene, elementary flows/air/unspecified*	3.00E+01	µg
Chrysene	*Chrysene, elementary flows/air/unspecified*	2.00E+02	µg
Fluoranthene	*Fluoranthene, elementary flows/air/low-pop density*	4.50E+02	µg
Phénanthrene	*Phenanthrene, elementary flows/air/low-pop density*	2.50E+03	µg

Table 8 Estimated consumptions and yields of construction machines needed for resurfacing

OPERATION	DETAIL	CONSOMMATION	YIELD
		l/d	sm/d
Milling	Miller, 2-2.2m wide	6.30E+02	8.40E+02
Finishing	Finisher, 15-20 t	2.28E+02	7.00E+03
Compacting, vibrant	Roller, vibrant, V1	6.40E+01	3.50E+03
Compacting, tire	Roller, tire, P1	1.05E+02	7.00E+03
Cold in-place recycling	Cold in-place recycler	1.13E+03	4.28E+04
Spraying	Binder sprayer	2.34E+02	7.00E+03
Gravel spreading	Gravel spreader	2.34E+02	4.67E+03
CAM spreading	CAM spreader	3.05E+02	7.00E+03
Loading	Small loader <10t	1.40E+03	7.00E+03

Asphalt mixture, mixing, and materials LCIs

Table 9 Process "Cold asphalt mixture, FR": on-site supply of 1 ton of cold-poured asphalt mixture on the French market

STAGE	Detail	PROCESS	QUANTITY	UNITS
Materials	Emulsion	*Market emulsion bitume FR*	1.03E+02	kg
	Aggregates	*Market granulat vierge FR*	9.24E+02	kg
	Mixing	*market for electricity, medium voltage, FR*	5.00E+00	kWh
Transportation	Truck, asphalt plant to site	*market for transport, freight, lorry 16-32 metric ton, EURO4*	3.59E+01	tkm

Table 10 Process «Average asphalt mixture, FR»: on-site supply of 1 ton of hot asphalt mixture on the French market

STAGE	Detail	PROCESS (in French when created)	QUANTITY	UNITS
INPUT				
Materials	Bitumen	*Market bitume FR*	4.80E+01	kg
	Aggregates	*Market granulat vierge FR*	9.52E+02	kg
Manufacturing		*Manufacture d'une tonne d'enrobé en centrale, FR*	1	Unit
Transportation	Truck, asphalt plant to site	*market for transport, freight, lorry 16-32 metric ton, EURO4*	3.09E+01	t.km
OUTPUT *(loading PAH emissions)*		*Fumées bitume HAP*	4.26E-01	Unit

Table 11 Process « PAH emissions »: emissions LCIs relating to the loading of 1t of HMA of binder (calculation: author; emission data: CIMAROUT (USIRF 2016))

Emitted substance	Flow to air	Quantity (kg/t of asphalt mixture)	Quantity (kg/t of binder)
Fluoranthene	*Fluoranthene*	3.21E-12	7.42E-12

Pyrene	*Pyrene*	2.15E-12	4.97E-12
Benzo(a)anthracene	*Benzo(a)anthracene*	1.02E-13	2.36E-13
Chrysene	*Chrysene*	4.68E-13	1.08E-12
Benzo(b)fluoranthene	*Benzo(b)fluoranthene*	2.51E-13	5.79E-13
Benzo(j)fluoranthene	*PAH, polycyclic aromatic hydrocarbons*	9.34E-14	2.16E-13
Benzo(k)fluoranthene	*Benzo(k)fluoranthene*	1.06E-13	2.45E-13
Benzo(a)pyrene	*Benzo(a)pyrene*	1.49E-13	3.43E-13
Benzo(e)pyrene	*PAH, polycyclic aromatic hydrocarbons*	3.57E-13	8.23E-13
Dibenzo(a,h)fluoranthene	*PAH, polycyclic aromatic hydrocarbons*	5.95E-14	1.37E-13
Benzo(ghi)perylene	*Benzo(g,h,i)perylene*	1.91E-13	4.40E-13
Indeno(1,2,3,cd)pyrene	*Indeno(1,2,3-cd)pyrene*	7.64E-14	1.76E-13
Naphtalene	*Naphtalene*	3.97E-07	9.17E-07
Acénaphtene	*Acenaphtene*	8.44E-08	1.95E-07
Fluorene	*Fluorene*	4.66E-08	1.08E-07
Phénanthrene	*Phenanthrene*	8.33E-08	1.92E-07
Anthracene	*Anthracene*	3.88E-09	8.96E-09
Fluoranthene	*Fluoranthene*	5.19E-09	1.20E-08
Pyrene	*Pyrene*	3.14E-09	7.25E-09
Benzene	*Benzene*	7.43E-09	1.72E-08
Cyclopentane	*Hydrocarbons, unspecified*	8.49E-09	1.96E-08
n-Hexane	*Hexane*	2.12E-08	4.89E-08
Toluene	*Toluene*	5.95E-08	1.37E-07
Stirene	*Stirene*	4.25E-09	9.82E-09
Xylenes	*Xylene*	1.57E-06	3.62E-06
Ethylbenzene	*Benzene, ethyl-*	1.49E-06	3.44E-06
Formaldehyde	*Formaldehyde*	4.25E-09	9.82E-09

Table 12 Manufacturing process for 1t of asphalt mixture

	Procédé Ecoinvent	Chauffage	Séchage	Mélange	Total	Unité
INPUT						
Electricity	*market for electricity, medium voltage, FR*	2.25E+00		5.00E+00	**7.25E+00**	**kWh**
Natural gas (+LNG)	*heat production, natural gas, at industrial furnace low-NOx >100kW, Europe without Switzerland*	1.38E+00	4.62E+01	0.00E+00	**4.76E+01**	**kWh**
HEAVY FUEL	*heavy fuel oil, burned in refinery furnace, Europe without Switzerland*	0.00E+00	2.10E+01	0.00E+00	**2.10E+01**	**kWh**
LPG	*heat, district or industrial, other than natural gas, heat production, light fuel oil, at industrial furnace 1MW, RER without CH*	0.00E+00	1.40E+00	0.00E+00	**1.40E+00**	**kWh**
LIGHT FUEL OIL	*heat, central or small-scale, other than natural gas, heat production, light fuel oil, at boiler 100 kW, non-modulating, RER without CH*	1.38E+00	7.00E-01	0.00E+00	**2.08E+00**	**kWh**
Lignite	*heat, central or small-scale, other than natural gas, lignite briquette, at stove 5-15 kW – RER without CH*	0.00E+00	7.00E-01	0.00E+00	**7.00E-01**	**kWh**
Tap water	*market for tap water, Europe without Switzerland*				**7.00E+02**	**kg**
Water	*Elementary flow "water, well, in-ground"*				**9.53E-05**	**m3**
OUTPUT						

Wastewater, average, GLO	**2.32E-03**	**m3**
« Nitrate » in water	**3.57E-06**	**kg**
COD, « Chemical Oxygen Demand" in water	**8.26E-04**	**kg**
« Biologic Oxygen Demand » in water	**4.84E-05**	**kg**
« Suspended solids, unspecified » in water	**7.49E-04**	**kg**
« Hydrocarbons, unspecified » in water	**5.82E-06**	**kg**

Table 13 Summary of energy consumptions for French asphalt plants by manufacturing process and by ton of asphalt mixture

Process	**Energy source (%)**							**Share (%)**	**Energie (kWh/t)**
	Electricity	NG	FL	LNG	LPG	FD	Lignite		
Binder heating	45	27.5	0	0	0	28	0	6.25	5
Drying (burners)	0	65	30	1	2	1	1	87.5	70
Other - plant	100	0	0	0	0	0	0	6.25	5

Table 14 LCI to supply one ton of aggregates to a French asphalt plant

STAGE	**Process (in French when created)**	**Quantity**	**Unit**
Production	*Granulat, roche massive, FR (UNPG)*	0.764	t
	Granulat, roche meuble, FR (UNPG)	0.236	t
Transportation	*transport, freight, lorry 16-32 metric ton, EURO4, RER*	2.88E+01	t.km
	transport, freight train, FR	4.38E+01	t.km
	transport, freight, inland waterways, barge tanker, RER	4.47E+00	t.km

Table 15 Water heating inventory for one ton of emulsion, at plant

Energy source	**Ecoinvent process**	**Quantity (MJ/t)**
Natural gas	*heat production, natural gas, at industrial furnace low-NOx >100kW, Europe without Switzerland*	3.87E+01
Heavy fuel	*heavy fuel oil, burned in refinery furnace, Europe without Switzerland*	9.30E+00

Table 16 Emulsion manufacturing inventory (mixture) for one ton of emulsion

Energy	**Process**	**Quantity (MJ/t)**
Electricity	*market for electricity, medium voltage, FR*	72,0

Table 17 Inventory of raw materials for the production of 1t of bitumen emulsion and choice of EcoInvent sub-processes

Materials	**Process (in French when created)**	**Quantity (kg/t)**
Bitumen	*marché, bitume, FR*	6.50E+02
Emulsifier	*market for chemicals, inorganic, GLO*	3.00E+00
Chlorhydric acid (28%m)	*market for hydrochloric acid, without water, in 30% solution state, RER*	3.00E+00
Water	*market for tap water, Europe without Switzerland*	3.44E+02

Table 18 LCI of one ton of modified bitumen, at binder plant

Stage	**Process**	**Quantity**	**Unity**

Bitumen	*market, bitumen, FR*	9.65E+02	kg/t
Polymer	*acrylonitrile-butadiene-stirene copolymer production, RER*	3.50E+01	kg/t
Transportation, polymer	*market for transport, freight, lorry 16-32 metric ton, EURO4*	1.75E+01	t.km/t
Mixing bitumen/polymer	*market for electricity, medium voltage, FR*	2.52E+00	MJ/t

French market bitumen model and LCIs

Table 19 Assumptions of bitumen transport from the refinery to the French binder plant

TRANSPORT	DISTANCE (KM)	ROAD (%)	SEA (%)	RIVER (%)	RAIL (%)
BITUMEN, EUROPEAN OR FRENCH	460	80	0	10	10

We, therefore, obtain the transport inventory for one tonne of bitumen from Europe to the following French processing plants (asphalt plants or binder plants):

- Truck: 205 km, "*transport, freight, lorry 16-32 metric ton, EURO4, RER*"
- Tanker: 250 km, « *Transport, freight, sea, transoceanic tanker, GLO*"

Table 20 LCI to store 1 ton of bitumen in France

ECOINVENT PROCESS (V2.2)	QUANTITY	UNIT
market for electricity, medium voltage, FR	9.7	MJ
heat production, natural gas, at industrial furnace low-NOx >100kW, Europe without Switzerland	72.8	MJ
heavy fuel oil, burned in refinery furnace, Europe without Switzerland	17.5	MJ

Table 21 LCI for refining 1 ton of bitumen in France

ECOINVENT V3 PROCESS	QUANTITY	UNIT
market for electricity, medium voltage, FR	8.7	MJ
heat production, natural gas, at industrial furnace low-NOx >100kW, Europe without Switzerland	404	MJ
heavy fuel oil, burned in refinery furnace, Europe without Switzerland	97	MJ

Table 22 LCI of extractions and transport of crude oil to French refineries to obtain 1 ton of bitumen - ratios calculated from the graph of crude oil imports into France from the Ministry of the Environment for 2015 (Ministry of the Environment 2017)

STAGE	PROCESS	QUANTITY	UNIT
Extraction	*crude oil, at production onshore, RU*	0.40	t
	crude oil, at production onshore, RME	0.60	t
Transportation	*Transport, pipeline, onshore, petroleum*	1214	t.km
	Transport, freight, sea, transoceanic tanker, GLO	7105	t.km

We estimated that 50% of the bitumen consumed in France was produced in France, and the rest was produced elsewhere in Europe. The European bitumen is modeled using Eurobitume LCIs while we will build a process for French bitumen production. We assume that 60% of the crude oil arrives from the Middle East, and 40% from the ex-URSS. Respectively 59%, 10%, and 31% of the crude oil are assumed to arrive in France at the Havre's harbor, Fos' harbor, and Lorient's harbor.

Table 23 Ratios of the average French bitumen and estimated transport distances between the various points of supply of crude oils to bitumen

Share	Origin	Destination	Mode	Distance (km)
40%	Samara	Port of St Petersburg	Pipeline	1800
40%	Port of St Petersburg	Port of Havre	Tanker	2760
60%	Well, Saudi Arabia	Port Ju'aymah	Pipeline	660
31%	Port, Ju'aymah	Port of Lavera	Tanker	8675
10%	Port, Ju'aymah	Port of Donges	Tanker	11180
19%	Port, Ju'aymah	Port of Havre	Tanker	11540
16%	Port of Lavera	Refinery of Lavera	Pipeline	1
14%	Port of Lavera	Refinery of Feyzin	Pipeline	310
10%	Port of Donges	Refinery of Donges	Pipeline	10
20%	Port of Havre	Refinery of Gonfreville	Pipeline	10
24%	Port of Havre	Refinery of Gravenchon	Pipeline	40
15%	Port of Havre	Refinery of Grandpuits	Pipeline	270

4. LCIs for the use of internal combustion engine vehicles per kilometer traveled

Emission and fleet model

We use the CopCete software for its consideration of the French context (park) as well as for its better updating of COPERT (although a V version now exists). It considers 26 substances emitted: carbon monoxide and dioxide, nitrogen oxides, volatile organic compounds (VOC), benzene, fine particles (PM), sulfur dioxide, lead, cadmium, methane, non-methane VOC, nitrous oxide, ammonia, polycyclic aromatic hydrocarbon, copper, chromium, nickel, selenium, zinc, barium, arsenic, acrolein, formaldehyde, butadiene, acetaldehyde, and benzo(a)pyrene. We neglect the penetration of LPG vehicles in the fleet, which according to our simulations with CopCete implies an error of less than 1% on average consumption and emissions. On the other hand, we take into account the penetration of hybrid gasoline and diesel vehicles, with a stable distribution of 2/3 gasoline and 1/3 diesel over time according to the forecasts of the 2013 IFSTTAR fleet. We can consider that the average consumption in France and emissions by type of road and vehicle thus obtained correspond to an average French IRI by type of network.

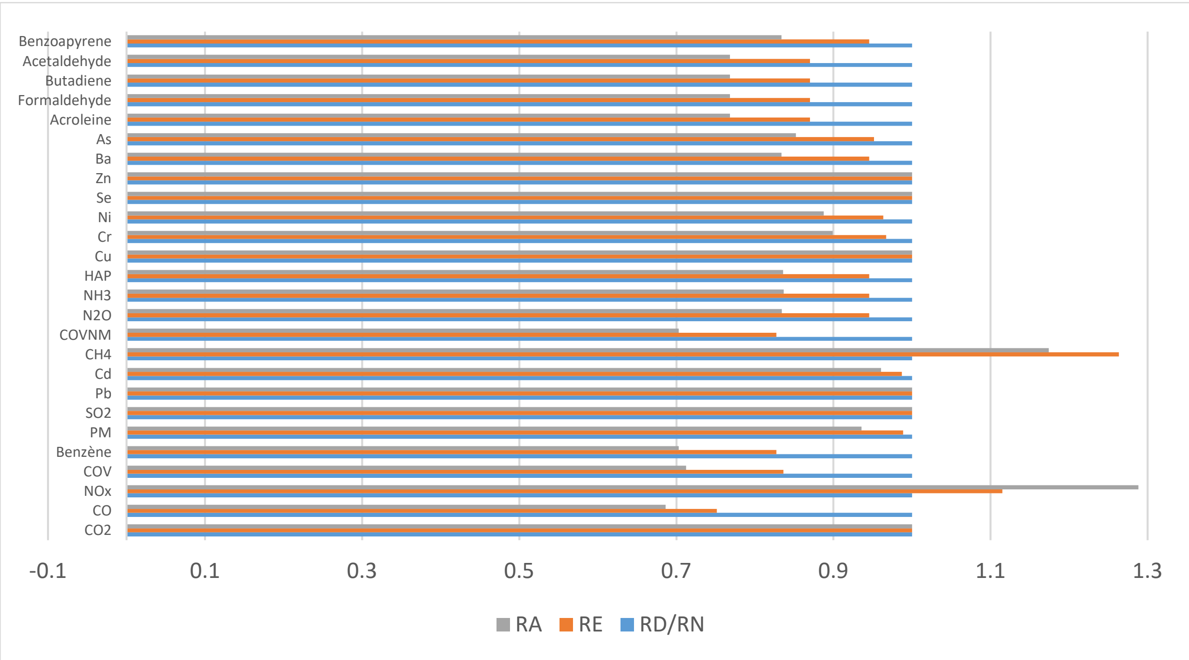
Link between EFC and excess emissions

If it is now possible for us to calculate an over-consumption relating to a deterioration of the state of road surface, nothing indicates that these laws are applicable to calculate excess emissions, since that would mean linearity between consumption and all the emissions. If Simons (2016) classifies emissions into 3 groups, one presenting linearity – for CO_2, SO_2, heavy metals, N_2O, ammonia, and PAHs – and the other two not (CO, NO_x, PM, CH_4, COVNM), the study of emissions from two average passenger cars in the French fleet in 2017, one running on diesel and the other on petrol, according to the network (RD/RN, RE, RA) does not seem to support this fact. In fact, the following figure shows the ratio of the quantity of each type of emission to the quantity of fuel consumed, normalized with respect to the ratio on RD/NR. Thus, if for a type of emission the 3 bars of the histogram in Appendix 1 are worth 1, this means that the linearity of the emission to consumption is perfect. The higher the

ratio with the speed (stronger on RE than on RD/RN, even stronger on RA), the more the emission increases with the speed (this is the case for NOx), and vice versa (this is the case for PM). Thus, not only do the emission linearity groups proposed by Simons not correspond to what can be calculated according to COPERT IV V11.4, but in addition, the links between consumption and emissions seem to depend on the type of fuel used, since we can see increasing monotony for diesel and decreasing monotony for gasoline on the same emission, for example on CO, or even non-monotonicity at speed as for the CH4 emissions of diesel passenger cars.
Thus, the link between consumption and emissions of road vehicles is more complex than that announced by Simons. However, the non-linearities that appear may be due to the dependence of emissions on engine temperature, for example (case of NOx), which increases with speed.

Thus, if we consider that the driving speed does not depend on the modification of the road surface condition, we could make the hypothesis of linearity of all consumption emissions for a given network and vehicle. This is the hypothesis that we will retain, in the absence of a finer-grained emissions simulation model. The consumption and emissions of our various vehicles – VP, VUL, HGV – will be calculated with the CopCete software configured to correspond to our typical networks. The evolution of the fleets retained will be that of the IFSTTAR, version March 2013. Note that all the average speeds observed on our networks could be respected in the configuration except HGVs on RA, which we will consider to be driving on average at 86 km/h instead of 88 km/h.

(1)



(2)

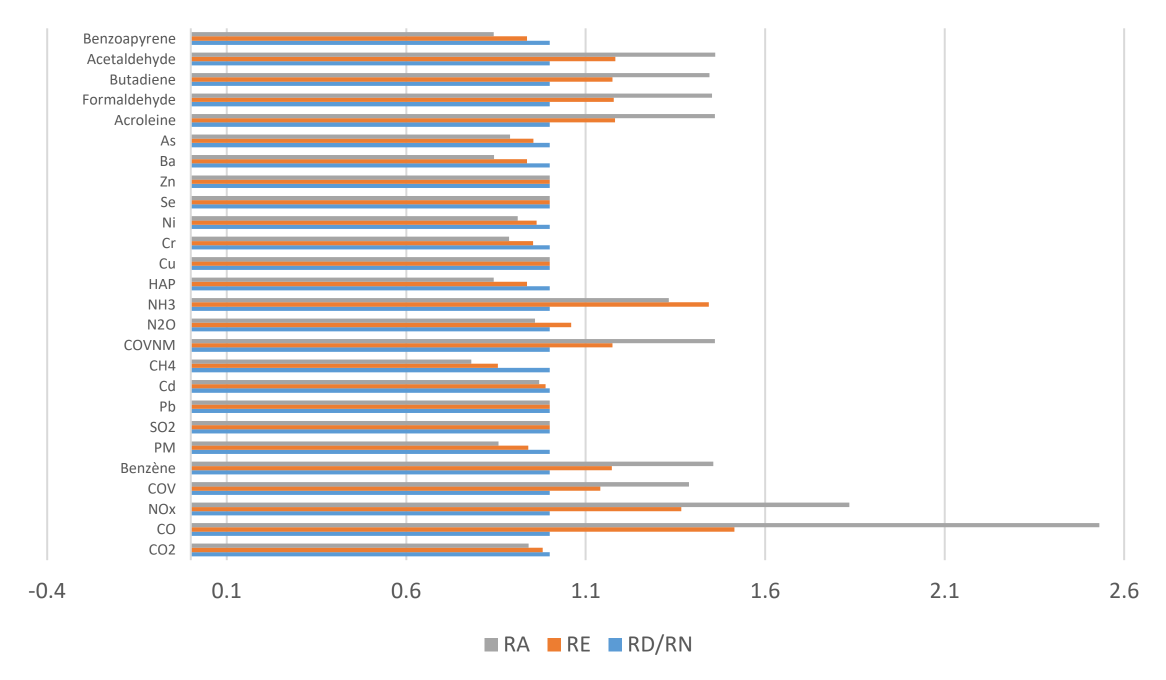


Figure 4 Linearity test of emissions to consumption for a diesel passenger car (1) and a gasoline passenger car (2) average in 2017 in France according to the type of network traveled (therefore the speed and the driving cycle) – RA=highway network; RE=Expressway ; RD/RN=national/county roads - Emissions of 26 types of substance, using the Environment Department's CopCETE software

5. LCI for vehicle maintenance

LCIs for using a maintenance shop

Table 24 LCI for using a garage, per euro charged, excluding taxes

FLOW	ECOINVENT PROCESS	QUANTITY	UNIT
	INPUT		
ELECTRICITY	*market for electricity, low voltage, FR*	6.05E-04	kWh
NATURAL GAZ	*heat production, central or small scale, natural gas, at boiler condensing modulating <100kW*	1.97E-04	kWh
LIGHT FUEL OIL	*heat production, central or small scale, light fuel oil, at boiler 10kW, non-modulating, Europe without Switzerland*	8.39E-05	kWh
PROPANE	*heat production, district or industrial, propane, at industrial furnace >100kW, Europe without Switzerland*	5.67E-04	kWh
TAP WATER	*market for tap water, RER without CH*	5.72E-06	m3
	OUTPUT		
WASTEWATER TREATMENT	*market for wastewater, average, GLO*[1]	5.72E-06	m3

LCIs for shock absorber kits

Table 25 Synthesis of LCIs of shock absorber kit change for the 4 different categories of vehicles

ECOINVENT PROCESS	1 PC	1 LCV	1 SHV	1 LHV	UNIT
inert waste, for final disposal, GLO	9.60E-01	1.01E+00	2.40E+00	1.14E+01	kg
lubricating oil production, RER	8.64E-04	2.52E-03	4.32E-03	1.58E-02	kg
polypropylene production, granulate, GLO	4.00E-01	8.50E-01	1.00E+00	2.65E+00	kg

[1] This flow is to be positioned as input with a "-" sign in OpenLCA, otherwise its impacts are not taken into account

steel production, electric, low-alloyed, GLO	-8.24E+00	-1.75E+01	-2.06E+01	-5.96E+01	kg
steel, low-alloyed, hot rolled, GLO	8.24E+00	1.75E+01	2.06E+01	5.96E+01	kg
synthetic rubber production, GLO	5.60E-01	1.19E+00	1.40E+00	6.51E+00	kg
thermoforming production, with calendering, GLO	4.00E-01	8.50E-01	1.00E+00	2.65E+00	kg

LCIs of tires

Table 26 Tire weight assumption per category of vehicle

category of vehicle	PC	LCV	SHV	LHV
Average weight (kg)	9.50	26.5	40.0	70.0

Table 27 LCIs of the production of one tire per vehicle category

				« pneu X » (in English : “tire X”)			
STAGE	**Flow**	**Process**	**Unit**	**PC**	**LCV**	**SHV**	**LHV**
Materials	Natural rubber	*Natural rubber*	kg	1.85E+00	4.73E+00	1.50E+01	2.63E+01
	synthetic rubber	*synthetic rubber, GLO*	kg	2.24E+00	5.96E+00	4.00E+00	7.00E+00
	carbon black	*carbon black production, GLO*	kg	2.09E+00	7.33E+00	8.40E+00	1.47E+01
	Silica	*sodium silicate production, spray powder, 80%, GLO*	kg	3.22E-01	1.77E-01	8.00E-01	1.40E+00
	Steel wires	*steel, low-alloyed*	kg	1.20E+00	4.86E+00	9.00E+00	1.58E+01
		wire drawing, steel, GLO	kg	1.20E+00	4.86E+00	9.00E+00	1.58E+01
	Nylon 6-6	*nylon 6-6, GLO*	kg	9.10E-02	3.18E-01	0.00E+00	0.00E+00
	Polyester fibers	*fleece, polyethylene, GLO*	kg	3.64E-01	1.27E+00	0.00E+00	0.00E+00
	zinc oxide	*zinc oxide, GLO*	kg	1.43E-01	3.98E-01	8.00E-01	0.00E+00
	sulfur	*Market for sulfur, GLO*	kg	1.09E-01	3.05E-01	6.00E-01	1.05E+00
	Stearic acid	*fatty acid, GLO*	kg	6.65E-02	1.86E-01	0.00E+00	0.00E+00
	Plastifier	*paraffin production, GLO*	kg	6.65E-01	0.00E+00	0.00E+00	0.00E+00
	Other	*chemical organic GLO*	kg	5.70E-01	1.06E+00	1.16E+00	2.03E+00
	Silane	*silicone product production, GLO*	kg	0	0	1.60E-01	2.80E-01
	Resin	*polyester resin, unsaturated, GLO*	kg	0	0	8.00E-02	1.40E-01
Manufacturing	Consumption	*Consommations de manufacture pneumatique*	Unit	9.50E+00	2.65E+01	4.00E+01	7.00E+01
	Emissions	*Emissions de manufacture pneumatique*	Unit	9.50E+00	2.65E+01	4.00E+01	7.00E+01
Solid waste	Waste	*market for municipal solid waste, RoW*	kg	1.20E-01	3.34E-01	5.04E-01	8.82E-01

Table 28 EoL inventories for one kilogram of tire recycled as material, for all categories of vehicles

	Flow	**EcoInvent process**	**Quantity**	**Unit**
Input	Electricity	*market for electricity, high voltage, FR*	770.5	Wh
	Water	*tap water, Europe without Switzerland*	7.1	kg
	Diesel	*diesel production, low-sulfur, RER without CH*	0.01	kg
	Transportation	*market for transport, freight, lorry 16-32 metric ton, EURO4, RER*	0.125	t.km

Output	Recycled rubber *(avoided impact)*	*synthetic rubber, GLO*	0.67	kg
	Steed *(avoided impact)*	*steel production, electric, low-alloyed, GLO*	0.07	kg
	SO2	*Sulfur dioxide, air, unspecified*	0.72	g
	NOx	*Nitrogen oxides, unspecified*	0.38	g
	H2S	*hydrogen sulfide, air, unspecified*	0.18	g
	Dust	*Particulates, unspecified*	0.19	g
	NMVOC	*NMVOC, non-methane volatile organic compounds, unspecified origin*	0.76	g

Table 29 EoL inventories for one kilogram of tire burned as energy, for all categories of vehicles

		"Fin de vie, valorisation énergétique, pneumatique VL" – LV tire EoL		
	Flow	**EcoInvent process**	**Quantity**	**Unit**
INPUT	Transportation	*market for transport, freight, lorry 16-32 metric ton, EURO4, RER*	1.25E-01	t.km
OUTPUT	petroleum coke *(avoided impact)*	*petroleum coke, GLO*	7.14E-01	kg
	coal *(avoided impact)*	*hard coal mine operation, RoW*	1.65E-01	kg
	natural gas *(avoided impact)*	*natural gas, high pressure, RU*	3.10E-02	m3
	fly ash for clinker *(avoided impact)*	*hard coal ash - RER without CH*	0.25	kg

		"Fin de vie, valorisation énergétique, pneumatique PL" – HV tire EoL		
	Flow	**EcoInvent process**	**Quantity**	**Unit**
INPUT	Transportation	*market for transport, freight, lorry 16-32 metric ton, EURO4, RER*	1.25E-01	t.km
OUTPUT	petroleum coke *(avoided impact)*	*petroleum coke, GLO*	6.31E-01	kg
	coal *(avoided impact)*	*hard coal mine operation, RoW*	1.46E-01	kg
	natural gas *(avoided impact)*	*natural gas, high pressure, RU*	2.74E-02	m3
	fly ash for clinker *(avoided impact)*	*hard coal ash - RER without CH*	0.25	kg

6. Time spending calculation for R&M

There are no statistics on typical times spent on vehicle maintenance or time spent refueling. We propose rough estimates per vehicle consumption unit and per category, which we can multiply by the number of units consumed by the assessed infrastructure to estimate the time spent by users. We will consider different times for vehicle operation maintenance, summarized in the article. The trip to the garage will take 30’. The tire change operation time will be set at 45' for 2 passenger car tires[2], 1 hour for 2 LCV or SHV tires, 1 hour 30 minutes for 2 LHV tires[3]. The times considered for changing the suspensions will be (1+4[4])/2= approximately 2.5 hours per pair (LV). Finally, the typical tank volumes and the time taken to fill them with fuel will be 10' for light vehicles and 0' for LHVs for moving to the

[2] That is twice the average maximum time guaranteed for 2 tires at Norauto and green lights (resp. 1 hour and 30 minutes), two main maintenance companies in France

[3] The dismantling/fitting package for a tire being 2/3 of that for the 2 tires of a passenger car or LCV according to this site: http://fntv-services.com/document/Profil_Prestations.pdf we multiply the time for 2 penus VP by 2/3, we divide by 10/2 tires, and we subtract 1h corresponding to economies of scale

[4] https://conseils.oscaro.com/diagnostic_amortisseur.html

pump, 10' for light vehicles, 6' for SHV, 9' for LHV[5] for waiting, filling the tank and paying, and the volumes of the tanks considered are as follows: PC = 50L, LCV = 80L[6], SHV = 315L, LHV = 800L[7].

7. Analyses of the inflation rates from INSEE time series

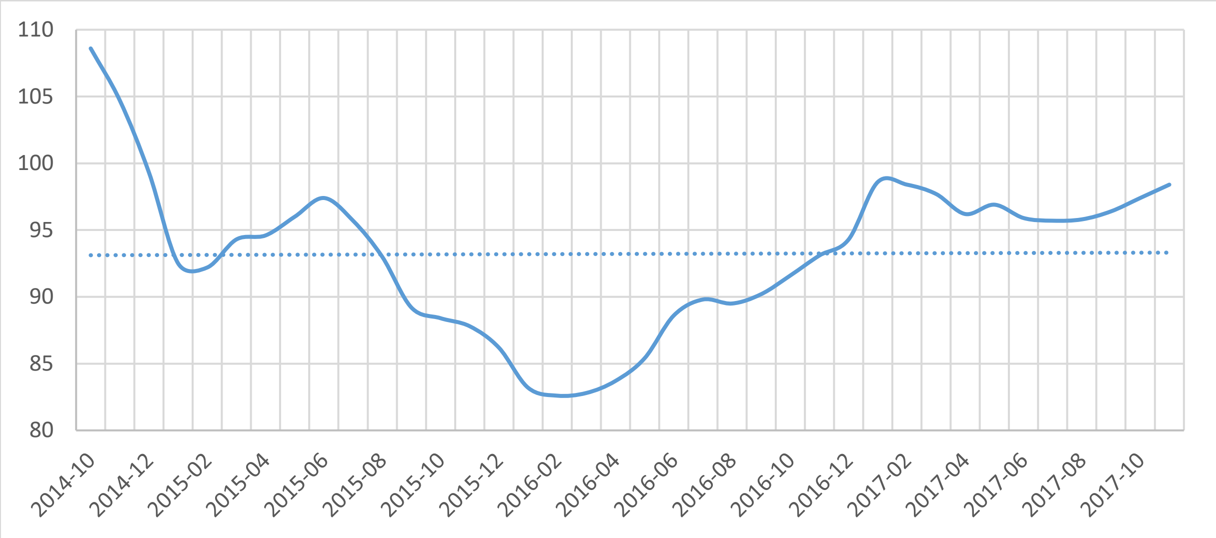


Figure 5 Fluctuation of the TP09 Index relating to the road asphalt works market between 2014 and 2017 (Source: author; figures: INSEE, base 2010)

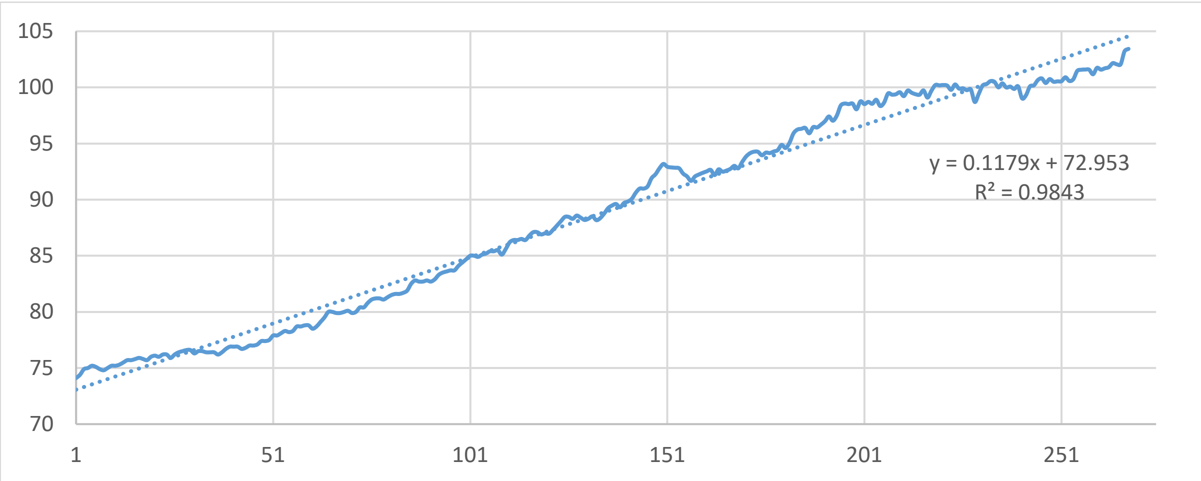


Figure 6 Consumer Price Index between January 1996 and April 2018 and linear regression in dotted line over months (source: author; INSEE data)

[5] Flow of 150L/min (https://www.pitpoint.be/fr/faire-le-plein-lng/) and payment and wait of 3'

[6] Compromise between the small LCV and the large LCV: https://www.lacentrale.fr/fiche-technique-voiture-peugeot-expert-ii+(2)+fourgon+tole+confort+227+l1h1+2.0+hdi+fap +130-2013.html

[7] https://fr.answers.yahoo.com/question/index?qid=20130123054541AASek0z

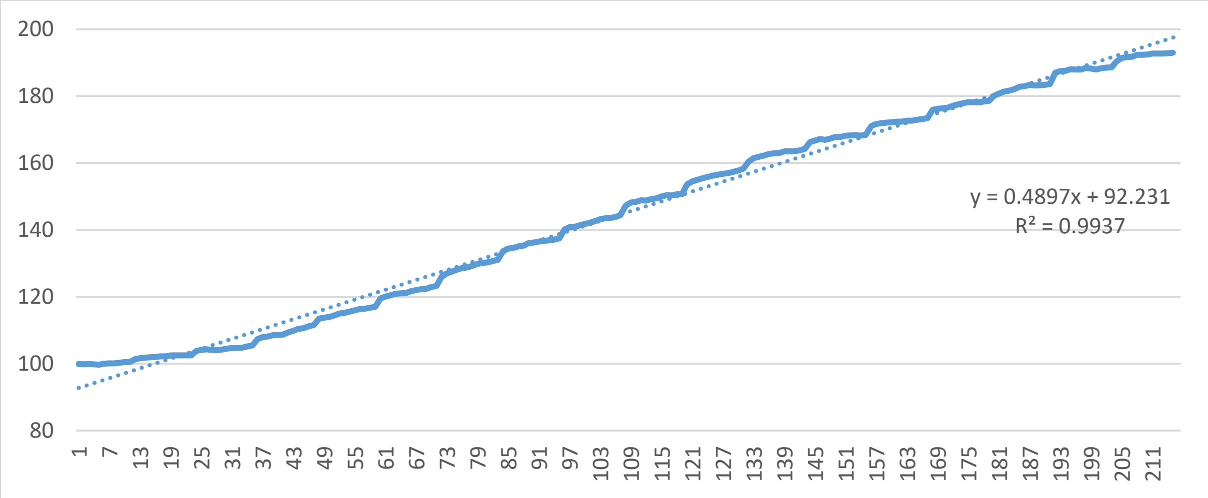


Figure 7 Evolution over time of prices for the repair of personal vehicles in France per month (from 1998 to 2015)

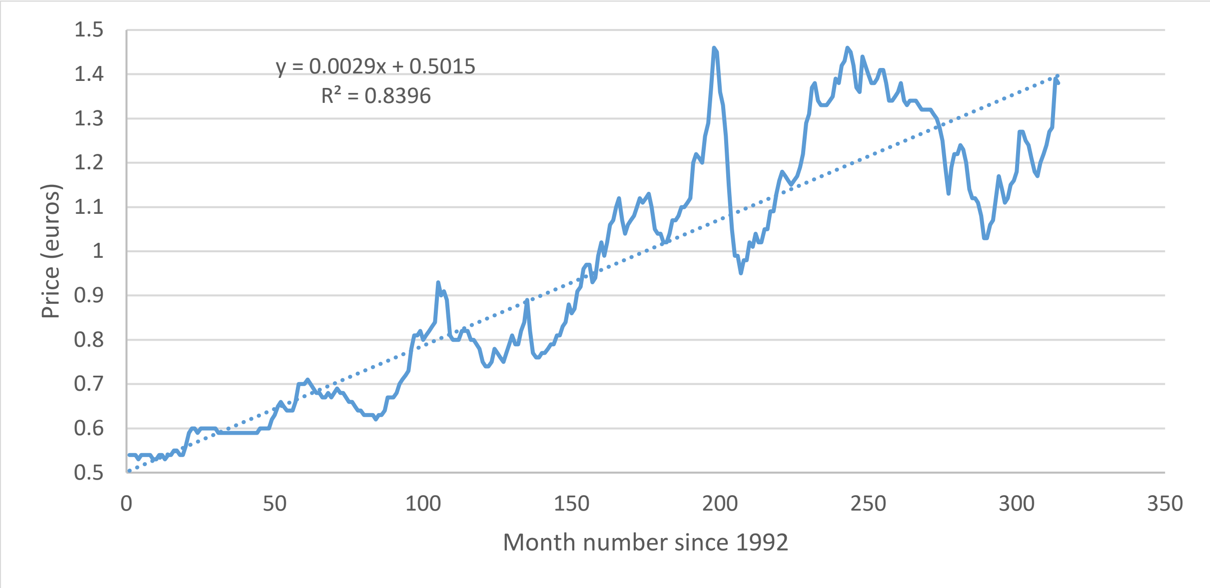


Figure 8 Average monthly diesel retail prices in mainland France in current euros (INSEE data – 1992-2018)

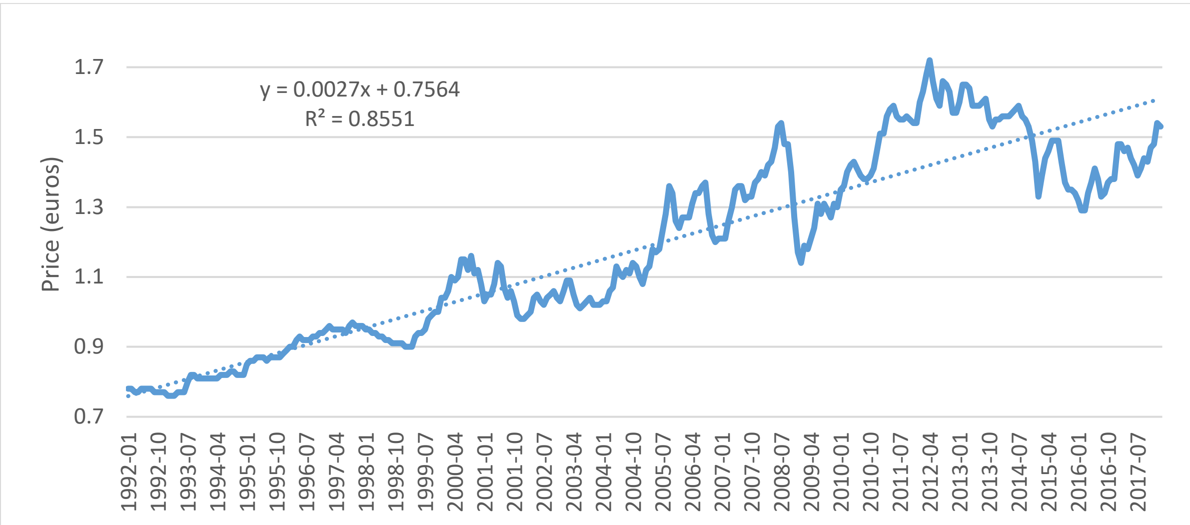


Figure 9 Average monthly retail prices in mainland France – Unleaded premium fuel, 98 octane (1 litre)

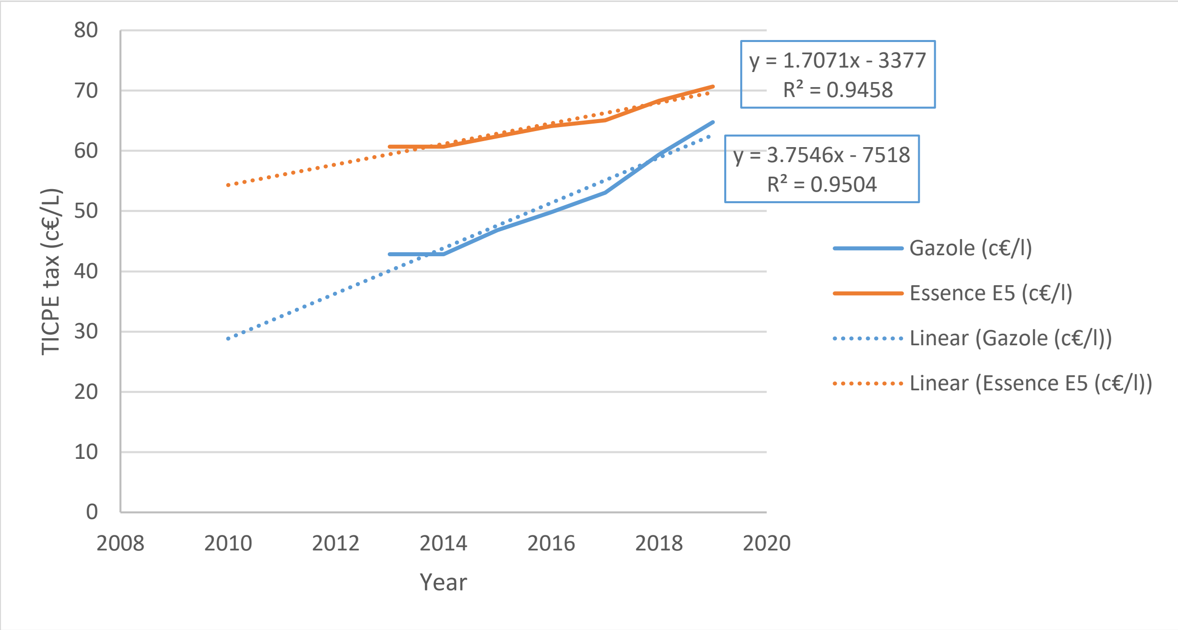


Figure 10 Evolution of the TICPE tax on diesel and gasoline in France between 2012 and 2022 (figures: Ministry for Ecological and Solidarity Transition 2018)

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