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ENVIRONMENTAL SUSTAINABILITY AS A PERFORMANCE MEASURE FOR ASSESSING PREVENTIVE MAINTENANCE POLICIES

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PRESENTATION OUTLINE

- Introduction
- Preventive Maintenance
- Environmental assessment
- Performance assessment
- Costs assessment
- Multi-attribute analysis
- Conclusions

State-of-the-Art

Environmental Certifications for buildings and products are well-established worldwide

→ Sustainability assessment of road pavements still has to be clearly defined and developed

Roads: "green" rating systems and tools are becoming popular

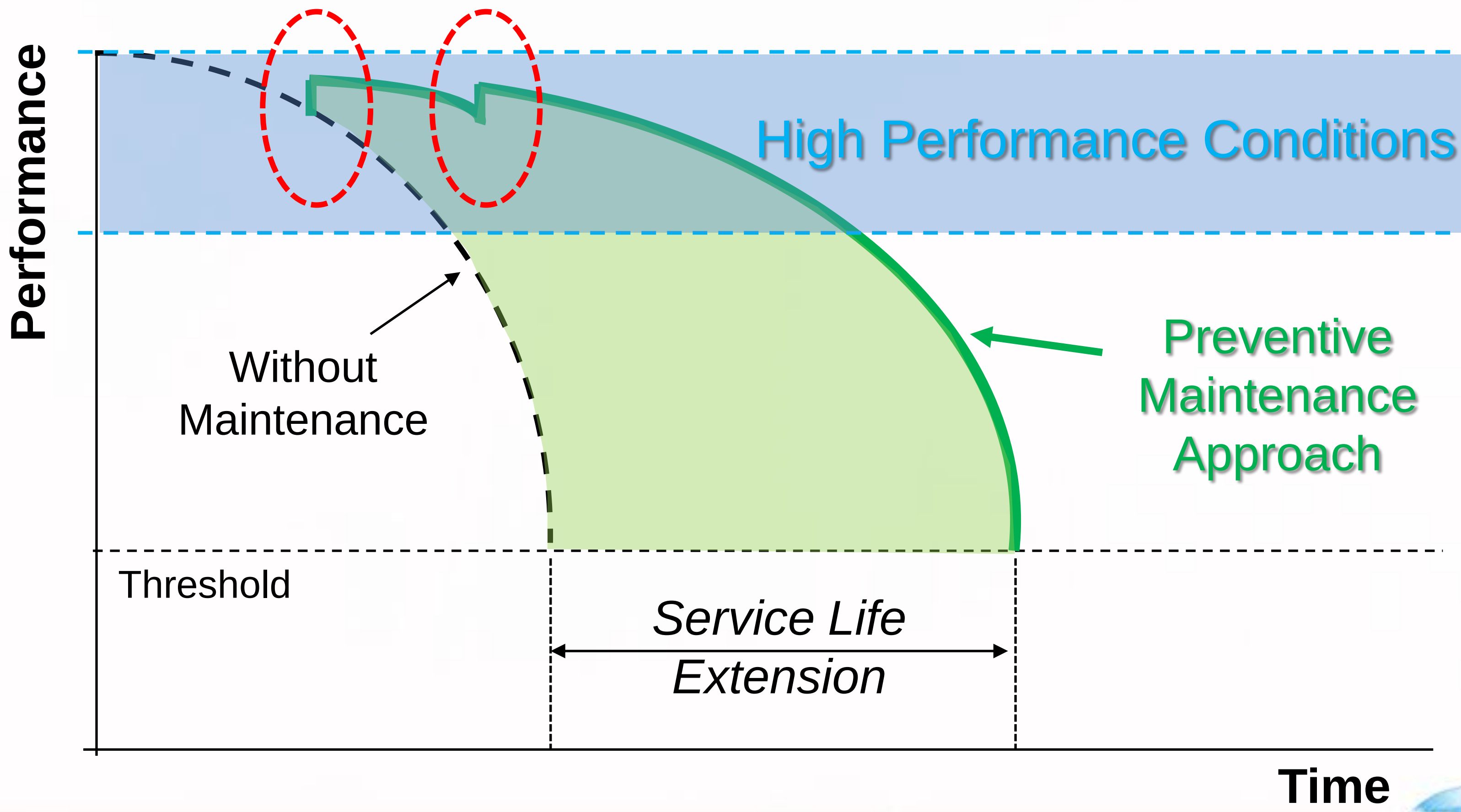
→ Sustainability analyses are still considered as a stand-alone evaluation of a project

Decision Support Systems only focus on costs and performance of strategies

→ Pavement Management Systems do not consider environmental impacts

OBJECTIVES

Comparing Preventive Maintenance Strategies

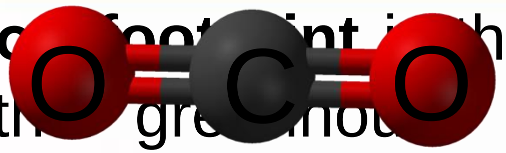


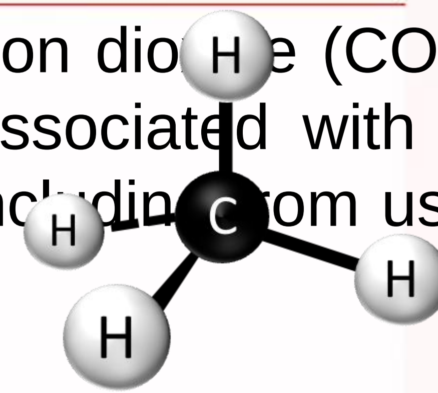
OBJECTIVES

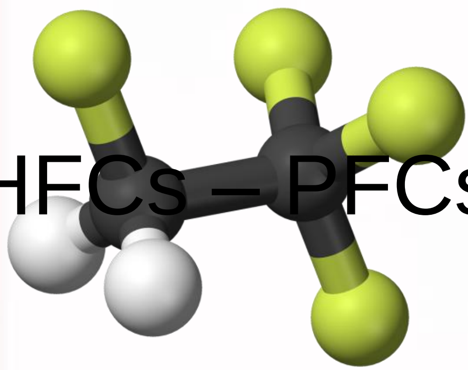
Comparing Preventive Maintenance Strategies

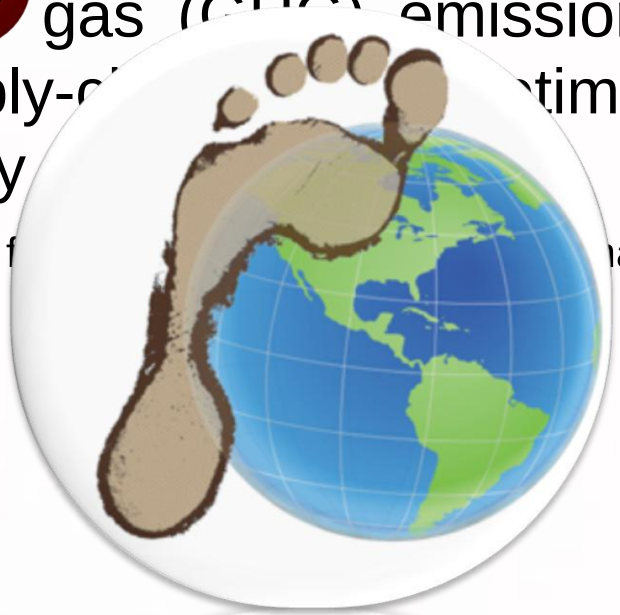
“**Carbo[illegible] foot[illegible]int** [illegible] he overall amount of carbon dio[illegible]e (CO_2) and oth[illegible] gr[illegible] gas ([illegible]) emissions associated with a product, along its supply-c[illegible]times including from use and end-of-life recovery [illegible]

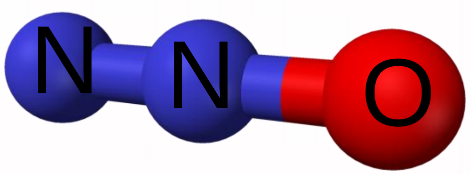
[European Commission – Institute f[illegible]ability]

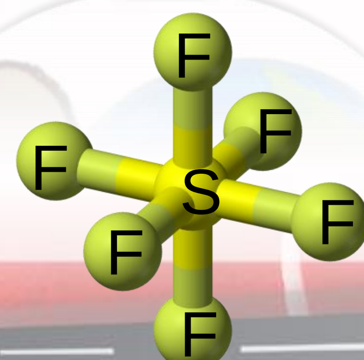












equivalent carbon dioxide = **CO_2e**

How to convert a certain GHG into a unit of equivalent carbon dioxide?

Global Warming Potential (GWP)

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency ($W\ m^{-2}\ ppb^{-1}$)	Global Warming Potential for Given Time Horizon			
				SAR‡ (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b]1.4×10^{-5}	1	1	1	1
Methane[c]	CH_4	12[c]	3.7×10^{-4}	21	72	25	7.6
Nitrous oxide	N_2O	114	3.03×10^{-3}	310	289	298	153
Substances controlled by the Montreal Protocol							
CFC-11	CCl_3F	45	0.25	3,800	6,730	4,750	1,620
CFC-12	CCl_2F_2	100	0.32	8,100	11,000	10,900	5,200
CFC-13	$CClF_3$	640	0.25		10,800	14,400	16,400
CFC-113	CCl_2FCClF_2	85	0.3	4,800	6,540	6,130	2,700
CFC-114	$CClF_2CClF_2$	300	0.31		8,040	10,000	8,730
CFC-115	$CClF_2CF_3$	1,700	0.18		5,310	7,370	9,990
Halon-1301	$CBrF_3$	65	0.32	5,400	8,480	7,140	2,760
Halon-1211	$CBrClF_2$	16	0.3		4,750	1,890	575
Halon-2402	$CBrF_2CBrF_2$	20	0.33		3,680	1,640	503
Carbon tetrachloride	CCl_4	26	0.13	1,400	2,700	1,400	435

ENVIRONMENTAL ASSESSMENT

Life Cycle Carbon and Energy Assessment

"Embodied energy: the amount of energy consumed to produce a product. This includes the energy needed to mine or harvest natural resources and raw materials, and manufacture and transport finished materials." [U.S. Environmental Protection Agency]

Consumption Facts
Mass: 1,828.4 kg
Expected Lifespan: 20 years

Embodied Energy	
Total 1,828.4 kg	**118,284,466,000 Joules**
Steel 738.9 kg	32,289,930,000 Joules
Aluminium 142.9 kg	26,426,497,000 Joules
Plastic 155.6 kg	15,560,000,000 Joules
Alloy steel 237.2 kg	15,180,800,000 Joules
[illegible]	7,170,933,000 Joules
[illegible]	4,130,000,000 Joules
[illegible]	3,165,460,000 Joules
[illegible]	2,830,110,000 Joules
[illegible]	2,457,000,000 Joules
Polyester 21.8 kg	2,132,040,000 Joules
Magnesium 5.0 kg	1,970,000,000 Joules
Stainless steel 34.0 kg	1,485,800,000 Joules
Glass 48.1 kg	1,058,200,000 Joules
Metal 19.5 kg	780,000,000 Joules
Paint 12.7 kg	659,130,000 Joules
Lead 20.4 kg	589,560,000 Joules
Zinc 4.5 kg	234,450,000 Joules
Transportation 13,904 km	6,355,654,730 Joules
Disposal (Landfill)	164,556,000 Joules

Diesel = 36.4 MJ/liter or 42.8 GJ/t energy content (heating value)

Cradle-to-Grave approach

full Life Cycle Assessment from resource extraction ('cradle') to use and disposal phase ('grave').

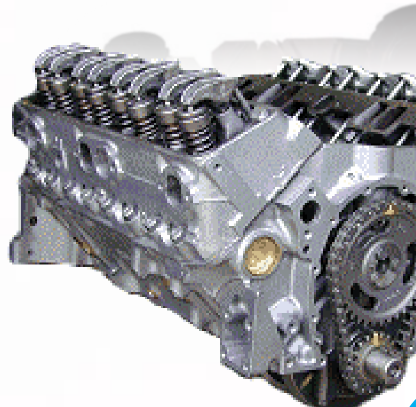
Cradle-to-Gate approach

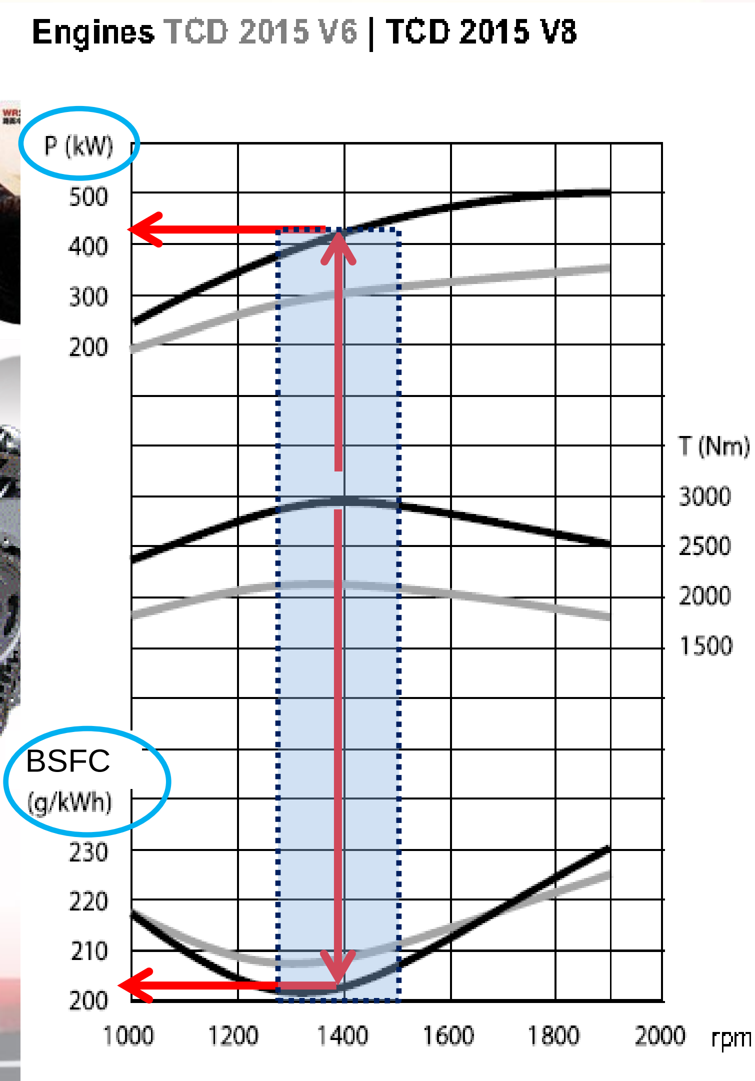
__Need to have a unique inventory of carbon & energy for road materials__

	Emission – CO_2 [illegible]	[illegible]	Embodied energy [illegible]	[illegible]ard Dev.
Bitumen	[illegible]	[illegible]	[illegible]	226.0
Bitumen e[illegible]	[illegible]	[illegible]	[illegible]	28.8
Crushed a[illegible]	[illegible]	[illegible]	[illegible]	9.9
Pit-run ag[illegible]	[illegible]	[illegible]	[illegible]	1.4
Cement	1079.6	311.5	5900	847.1
Quicklime	2500	-	9240	-
Water	0.29	-	10	-
Polymers – elastomers	3000	543.4	91440	36753.5
Polymers – plastomers	1400	424.3	44667.3	51087.7
Emulsifiers	600	52.4	63250	6010.4

ENVIRONMENTAL ASSESSMENT

Impacts related to equipment





$$F\,[l] = BSFC\left[\frac{g}{kW\cdot h}\right]\cdot P[kW]\cdot T[h]\cdot 1/\gamma\left[\frac{l}{g}\right]$$

Where:

F = fuel consumed,

T = time

Models	Prod. [m^2/h]	P_engine [KW]		F [l/h]	F_{sqm} [l/m^2]	CO_2e [g/m^2]	Energy [MJ/m^2]
MILLERS							
PL2000S	2448.98	447		105	0.043	113.62	1.544
PL2100S	4320.00	447		105	0.024	64.41	0.875
W120F	1020.41	227		61	0.060	158.42	2.152
W200	2040.82	380		62	0.030	80.51	1.094
PAVERS							
AP1000D	4082	166		41.0	0.010	26.63	0.362
AP600D	2449	122		31.3	0.013	33.91	0.461
DF145C	3673	153		38.2	0.010	27.53	0.374
F121C	2449	120		30.9	0.013	33.44	0.454
Super1603	2449	100		26.5	0.011	28.68	0.390
Super1803	2857	130		33.1	0.012	30.70	0.417
SLURRY MACHINERIES		**mixer engine** [KW]	**truck engine** [KW]				
M206	3600	74	186	41.7	0.0116	30.70	0.417
M210	3600	74	224	42.4	0.0118	31.25	0.424

$$CO_2\ emissions\,[g] = F[l]\cdot \alpha\left[\frac{g}{l}\right]$$

$$\alpha = 2778g\cdot 0.99\cdot\frac{44}{12} = 10084\,\frac{g}{gallon} = 2.6639\,\frac{kg}{l}$$

[EPA report 420-F-05-001]

Where:

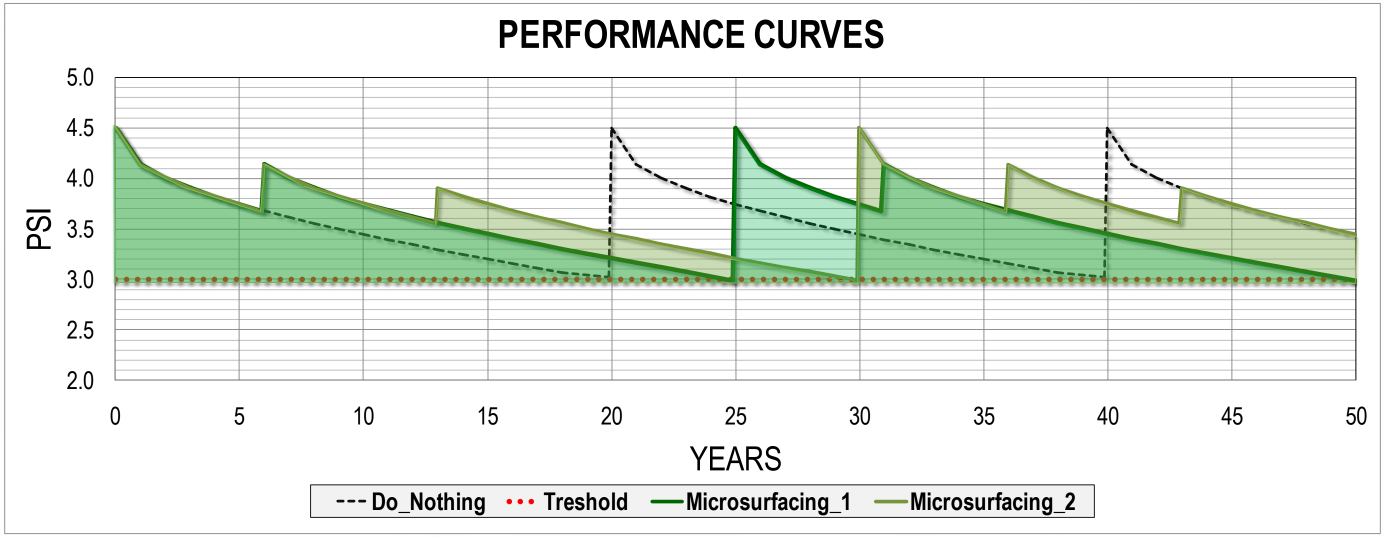
α = specific amount of CO_2 emitted during the combustion of a liter of diesel

2778 g = carbon content per gallon of diesel fuel [U.S. EPA]

0.99 = oxidation factor

44/12 = ratio of the molecular weight of CO_2 to the molecular weight of carbon

PERFORMANCE ASSESSMENT
Area-Under-Curve



Maintenance strategy	AuC *Area Under Curve*	Performance increase
ONLY_MAJOR_REHABILITATION	29.83	
OVERLAY (1)*_[@year 8]*	37.31	+ 25.08 %
OVERLAY (2) *_[@years 8 and 16]*	42.45	+ 43.65 %
MICROSURFACING (1) *_[@year 6]*	33.03	+ 10.73 %
MICROSURFACING (2) *_[@years 6 and 13]*	40.74	+ 36.57 %
SLURRY (1) *_[@year 5]*	32.91	+ 10.33 %
SLURRY (2) *_[@years 5 and 12]*	38.51	+ 29.10 %

COSTS ASSESSMENT

Life Cycle Cost Analysis

PRICE LIST	VDOT
ANALYSIS PERIOD	50 years
DISCOUNT RATE	4 %
METHODS	PWC, EUAC

Maintenance strategy	**PWC** [$/m^2]	**EUAC** [$/m^2]
ONLY_MAJOR_REHABILITATION	107.87	5.02
OVERLAY (1)_ *[@year 8]*	87.80	4.09
OVERLAY (2) _ *[@years 8 and 16]*	88.05	4.10
MICROSURFACING (1) _ *[@year 6]*	87.90	4.09
MICROSURFACING (2) _ *[@years 6 and 13]*	88.89	4.14
SLURRY (1) _ *[@year 5]*	87.10	4.05
SLURRY (2) _ *[@years 5 and 12]*	87.44	4.07

OUTCOMES

Life Cycle Analysis

PM_different strategies		Costs		Performance	Environment	
		PWC [$/m2]	*EUAC [$/m2]*	*AuC*	*energy [MJ/ m2]*	*CO_2e [g/m2]*
Microsurfacing	*(1 intervention per cycle) – yr. 6*	87.90	4.09	33.03	808.78	58.45

HOW TO COMBINE THEM?

Multi-Attribute Approach Analysis

Only_Major_Rehab.	Costs		Performance	Environment	
	PWC [$/m2]	*EUAC [$/m2]*	*AuC*	*energy [MJ/ m2]*	*CO_2e [g/m2]*
	107.87	5.02	29.83	1154.84	86.21

Parameters Rescaling

COSTS

Since the "*Only_Major_Rehabilitations*" alternative was the most expensive, a maximum value of 1 was assigned to it. All the other strategies were scaled using a simple direct proportion.

$$x_i = \frac{(PM\_strategy_{i\_cost} \cdot 1)}{Do\_Nothing_{cost}}$$

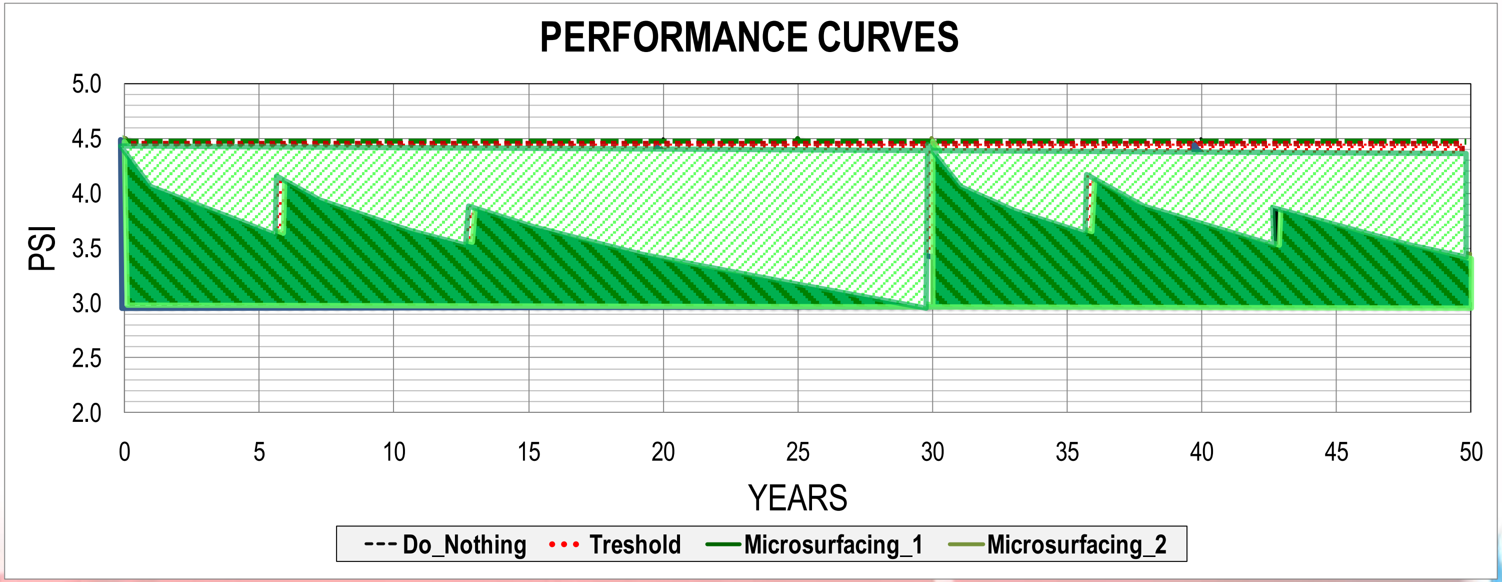
ENVIRONMENT

Since the "*Only_Major_Rehabilitations*" strategy was the most polluting, a maximum value of 1 was assigned to it. All the other strategies were scaled using a simple direct proportion.

Parameters Rescaling

PERFORMANCE

Since the "*Only_Major_Rehabilitations*" strategy has the maximum difference from an ideal performance trend (e.g., horizontal decay curve), a maximum value of 1 was assigned to it.



MULTI-ATTRIBUTE APPROACH ANALYSIS

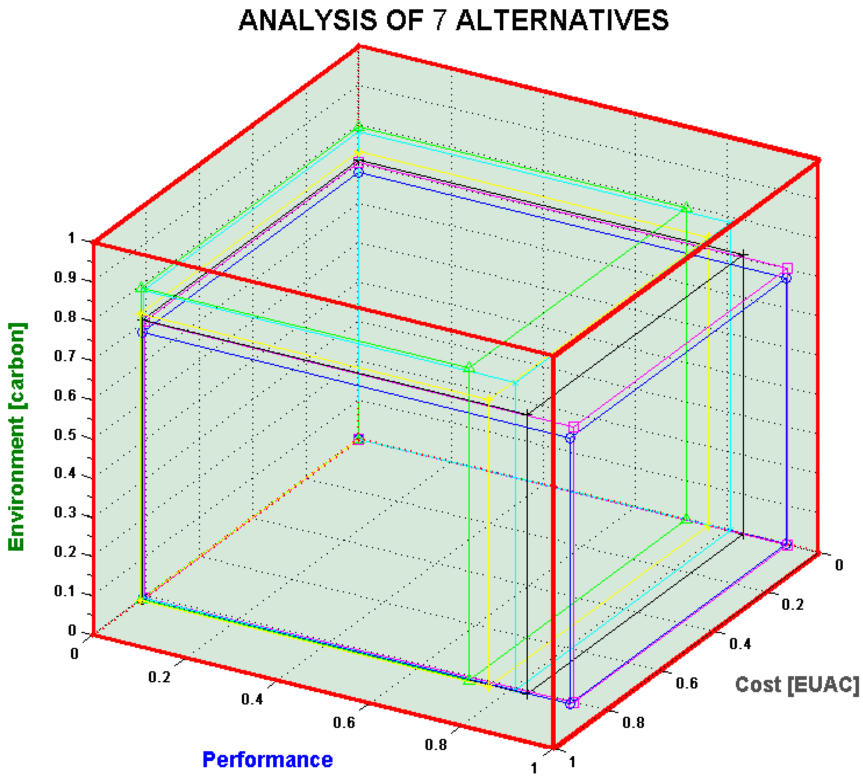
Cost + Performance + Environment

Parameters Rescaling

		Costs		Performance	Environment	
		PWC	*EUAC*	*AuC*	*Energy*	*Carbon*
Microsurfacing	*(1 intervention per cycle) - 6*	0.815	0.815	0.929	0.700	0.678
Microsurfacing	*(2 interventions per cycle) - 6 & 13*	0.824	0.825	0.758	0.776	0.732
Thin overlay	*(1 intervention per cycle) – 8*	0.814	0.815	0.834	0.710	0.710
Thin overlay	*(2 interventions per cycle) - 8 & 16*	0.816	0.817	0.712	0.796	0.794
Slurry seal	*(1 intervention per cycle) – 5*	0.807	0.807	0.932	0.662	0.703
Slurry seal	*(2 interventions per cycle) - 5 & 12*	0.811	0.811	0.808	0.700	0.783
ONLY_MAJOR_REHABILITATION		1	1	1	1	1

MULTI-ATTRIBUTE APPROACH ANALYSIS

Representation & Automatization

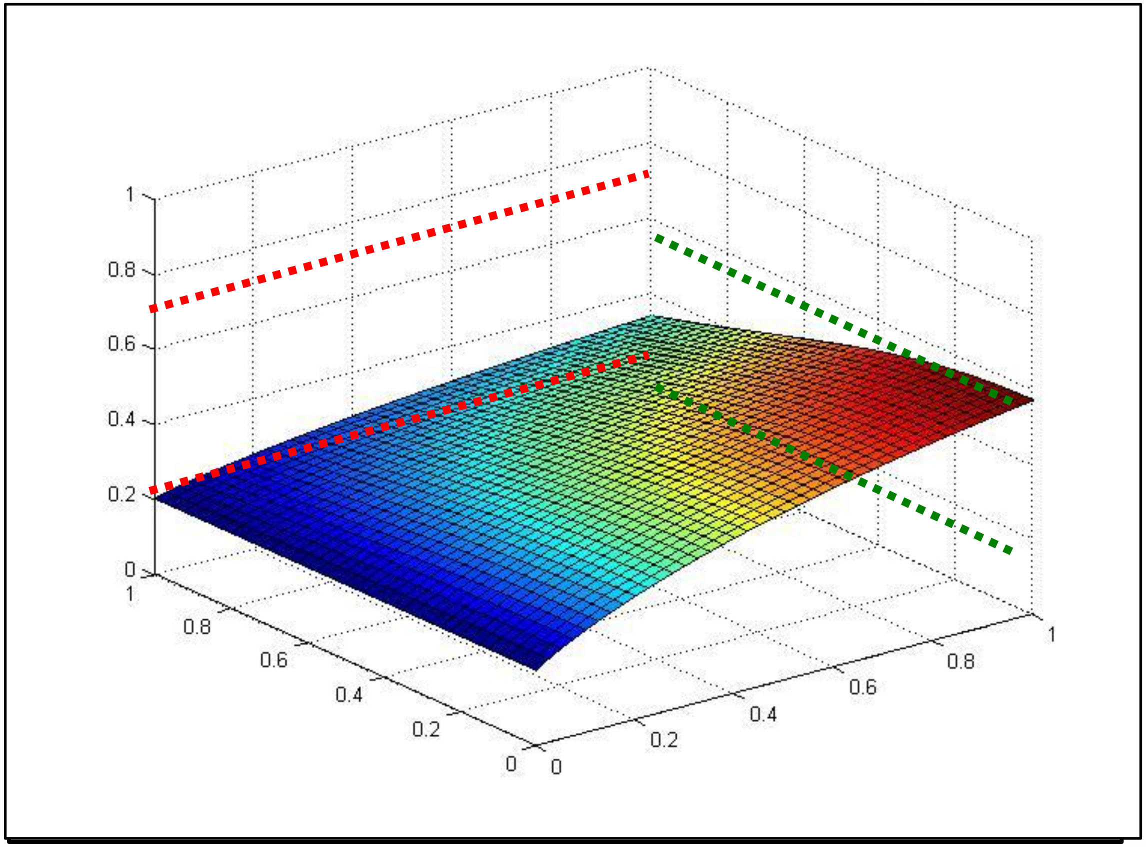


		Volume (EUAC * AuC * Carbon)
Microsurfacing	(1 intervention every cycle) - 6	0,513
Microsurfacing	(2 intervention every cycle) - 6 e 13	0,458
Thin overlay	(1 intervention every cycle) - 8	0,482
Thin overlay	(2 intervention every cycle) - 8 e 16	0,462
Slurry seal	(1 intervention every cycle) - 5	0,529
Slurry seal	(2 intervention every cycle) - 5 e 12	0,513
Do_Nothing		1

$$Multi\_Approach\_Index = w_1 \cdot X + w_2 \cdot Y + w_3 \cdot Z + \ldots + w_n \cdot N$$

MULTI-ATTRIBUTE APPROACH ANALYSIS

Optimization and Future Developments



CONCLUSIONS

- PM strategies were shown to be eco-effective, with a higher performance and lower costs over the life cycle.

- A large amount of emissions and energy could be saved by applying preventive maintenance plans on road pavements.

- The methodology provided is useful to compare strategies and alternatives considering multiple decision variables.

- PMS should be implemented in order to consider environmental impacts besides costs and performance

Thank you for your attention