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Study on Tyre Pressure Monitoring Systems (TPMS) as a means to reduce Light-Commercial and Heavy-Duty Vehicles fuel consumption and CO_2 emissions

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Executive Summary

In a project for the European Commission's DG CLIMA[1], TNO and TU Graz have performed a study on "Tyre Pressure Monitoring (TPMS) as a means to reduce Light-Commercial Vehicles (LCVs) and Heavy-Duty Vehicles (HDVs) fuel consumption and CO_2 emissions".

While TPMS has been made mandatory for M1 vehicles in 2012 for new types of cars and from 2014 for all new cars (Regulation (EC) 661/2009), LCVs and HDVs are not subject to such mandatory requirements even though TPMS could potentially contribute to curbing LCV and HDV fuel consumption and CO_2 emissions.

Goal and scope of this study

This report has assessed the feasibility, potential and cost-effectiveness of applying tyre pressure monitoring systems (TPMS) in light commercial vehicles (LCVs) and heavy-duty vehicles (HDVs) for the purpose of reducing fuel consumption and CO_2 emissions. In addition, also potential safety benefits have been estimated as well as a range of other impacts that may affect cost-effectiveness from the end-user as well as the societal perspective.

Below, results of the following topics are summarized:

1. The potential of TPMS for fuel saving and CO_2 reduction
2. State-of-the-art of TPMS technologies
3. Current and projected market penetration of TPMS for LCVs and HDVs
4. Costs of TPMS for LCVs and HDVs
5. Potential safety benefits of TPMS for LCVs and HDVs
6. Cost-effectiveness of TPMS for LCVs and HDVs
7. Options and rationale for policy intervention

The results show that TPMS can be cost-effective for the considered LCV and HDV applications. Yet in an autonomous growth scenario, suppliers expect that market shares to remain small in the coming years. This may be a motivation for the European Commission to implement policy measures to promote the uptake of TPMS.

The potential of TPMS for fuel saving and CO_2 reduction

To assess the potential impact of TPMS on the fuel consumption and CO_2 emissions of the European LCV and HDV fleet, first of all information has been collected on:

- the impact of tyre pressure on rolling resistance;
- the tyre pressure distribution "in the field"

Based on assumptions on how TPMS affects the tyre pressure distribution "in the field", the fuel consumption and CO_2 emissions in the situation without and with

[1] Service Request No 0712/2012/635955/ETU/CLIMA.C.2 under the Framework Contract on ENTR/F1/2009/030 - Lot 5

TPMS have been calculated using the Passenger car and Heavy duty vehicle Emission Model (PHEM) for a wide range of LCV and HDV vehicle configurations and mission profiles. The impact on fuel consumption and CO_2 emissions of more aggregated vehicle categories and the EU-27 LCV and HDV fleet as a whole has been determined by weighted averaging of the results for detailed vehicle configurations and mission profiles. For this determination available information on the contribution of the vehicle categories to the overall CO_2 emissions of the EU-27 LCV and HDV fleet is used.

Results have been determined for two scenarios:

- In the “high savings potential” scenario it is assumed that users of vehicles with TPMS always act on TPMS warnings, so that TPMS is able to fully prevent under-inflation by more than 10% (with the exception of N1 vehicles, where it has been assumed that under-inflation by more than 20% is fully prevented while under-inflation by 10-20% is reduced by 50%). It has furthermore been assumed that over-inflation is not affected (reduced) by TPMS system. This scenario is further differentiated to a case with TPMS installed on vehicles (trucks, tractors) and trailers, and another case where TPMS is not installed on trailers.
- In the “low savings potential” scenario it is assumed that only half the effect of the “best case scenario” is achieved due to factors such as reduction of over-inflated tyres due to TPMS monitoring, system malfunctions and/or imperfections, lack of user response to TPMS warnings or tampering with the systems by drivers and fleet owners due to non-acceptance of frequent warnings.

The scenario with “high savings potential” requires a high response of the driver / user to TPMS warnings. This can be considered to be the case when TPMS is applied on a voluntary basis, for example because the end-user identifies an economic (or safety or environmental) benefit for his vehicle/fleet. Also in case of mandatory fitment this scenario is conceivable, provided that TPMS signals cannot easily be ignored and systems are not tampered with.

A “low savings potential” is less likely to occur in case of voluntary adoption of TPMS, but might result from TPMS signals being ignored or systems being tampered with on a significant scale. This might happen in a scenario where TPMS fitment is mandatory while the benefits are not sufficiently perceived by the vehicle users.

The assessment has shown that widespread application of TPMS can reduce GHG emissions and fuel consumption in the LCV and HDV fleet by about 0.2% to 0.3% (see Table 1). Results vary strongly depending on the vehicle class and mission profile. The highest CO_2 saving potential is found for N2 and N3 vehicles in long haul operation. For city buses TPMS has the lowest impact.

The relative reduction, even in the transport application with the highest effect, is found to be low. Reductions of the order of magnitude as indicated in Table 1 are difficult to prove in real operation, as the effect is much smaller than variations in fuel consumption that are seen to occur between different trips, drivers and vehicles of the same model. Whether TPMS in LCV and HDV application can be cost effective, based on the presented figures for the fuel savings, is depending on the costs of TPMS and is discussed further on.

Table 1: Summary of TPMS impact on CO_2 emissions per vehicle category

vehicle category		kt/year EU27 baseline	relative CO_2 effect within vehicle category		delta kt/year EU27 relative to baseline	
			"low savings potential" scenario	"high savings potential" scenario	"low savings potential" scenario	"high savings potential" scenario
N1		96 700	-0.12%	-0.24%	-114	-228
N2		23 506	-0.22%	-0.43%	-51	-101
N3	TPMS on truck & trailer	201 912	-0.21%	-0.42%	-424	-848
	no TPMS on trailer		-0.12%	-0.24%	-240	-480
M2		1 500	-0.17%	-0.34%	-3	-5
M3		22 726	-0.08%	-0.15%	-17	-35
total LCV and HDV	TPMS on truck & trailer	346 344	**-0.18%**	**-0.35%**	**-609**	**-1 217**
	no TPMS on trailer		**-0.12%**	**-0.25%**	**-425**	**-849**

State-of-the-art of TPMS technologies

Direct TPMS systems measure the pressure in individual tyres, using sensors mounted on the wheel rim, on the inside of the tyre, or on the tyre valve, and can be applied to all types of LCVs and HDVs. Indirect TPMS systems measure pressure difference between tyres by comparing rotational speeds. Advanced indirect TPMS systems can detect under-inflation in individual tyres by monitoring tyre vibrations.

While direct TPMS has the advantage of determining absolute pressure values, low risk of (un)intentional misuse and high accuracy, indirect TPMS has the advantage of potentially low costs, and a lifetime not limited by sensor batteries. Yet both systems fulfil homologation regulations as set by UNECE R64.

Based on an review of current products and suppliers it can be concluded that TPMS for application in LCVs and HDVs are a technically and economically mature product. Expected future developments are mainly directed at improved performance, battery-less systems in the case of direct TPMS, and increased functionality by connecting vehicle TPMS information to fleet management systems.

Current and projected market penetration of TPMS for LCVs and HDVs

TPMS suppliers have been consulted to gain insight in the current market shares of TPMS for LCVs and HDVs as well as in expected trends for future market penetration in the absence of policy measures stimulating or mandating the uptake of TPMS.

The share of LCVs and HDVs currently equipped with TPMS systems is only 1% in M2 and N1 vehicles up to around 2.5% in N3 vehicles. The majority of systems is OEM-fitted. Retrofit systems take up at least 10% up to maybe 40% of the current market volume (this number is uncertain due to the limited amount of information available).

In an autonomous market development scenario, the market penetration of TPMS is expected to remain low in the future (2 to 6 years). However, the expected future shares show large variations for LCVs and HDVs. For LCVs, this depends on:

- Technology choice: Two different technologies are competing for the LCV market, indirect and direct TPMS. Suppliers of direct TPMS expect market shares to remain low (on average 3% in 2018), while indirect TPMS suppliers have a more optimistic view on future market penetration (30% in 2018).
- Spill-over effect: The LCV market benefits from TPMS applications on passenger cars. The mandatory fitments of TPMS on M1 vehicles has led to standardized solutions which can be adapted for application in LCVs.

For HDVs the market penetration is currently low and expected to remain low in the future (on average 3 to 8% in 2018), although suppliers do expect significant autonomous growth in N3 and M3 vehicles as in those segments the highest fuel savings can be achieved.

It must be noted that these market shares, current and projected, are solely based on a limited amount of questionnaire responses and are therefore quite uncertain.

Costs of TPMS for LCVs and HDVs

By means of a detailed questionnaire TPMS suppliers and other stakeholders have been asked to provide their estimates of the costs of TPMS for LCVs and HDVs. Based on responses and taking account of information available on the bill of components for TPMS and typical vehicle configurations, estimates of TPMS costs for different LCV and HDV applications have been derived. Costs have been estimated for OEM-fitted and retrofit systems, as well as for applications where both truck / tractor and trailer are fitted with TPMS or only the truck / tractor.

Table 2: Costs for TPMS per vehicle segment (excl. VAT), truck-only (TO) and truck-trailer (TT) configuration in the **“current cost”** scenario

		OEM-fitted		Retrofitted	
Vehicle segment		**TO [€]**	**TT [€]**	**TO [€]**	**TT [€]**
Service/delivery	**indirect**	8	n/a	n/a	n/a
	direct	44	n/a	88	n/a
Urban (delivery/collection)		164	n/a	348	n/a
Municipal utility		195	n/a	374	n/a
Regional (delivery/collection)		173	314	355	610
Long haul		185	338	365	651
Construction		234	395	422	731
Bus		174	n/a	327	n/a
Coach		209	n/a	378	n/a

The results for a “current cost” scenario are based on the average of the responses and are listed in Table 2. Based on the lowest cost estimates among the questionnaire responses also a “prospective cost” scenario (Table 3) has been derived which is considered representative for a near future situation with high sales volumes (consistent e.g. with the case of a regulated market). The costs per vehicle segment have been calculated as a weighted average of the appropriate share of vehicle classes in EU.

Table 3: Costs for TPMS per vehicle segment (excl. VAT), truck-only (TO) and truck-trailer (TT) configuration in the **"prospective cost"** scenario

		OEM-fitted		Retrofitted	
Vehicle segment		**TO [€]**	**TT [€]**	**TO [€]**	**TT [€]**
Service/delivery	**indirect**	5	n/a	n/a	n/a
	direct	20	n/a	40	n/a
Urban (delivery/collection)		54	n/a	108	n/a
Municipal utility		68	n/a	132	n/a
Regional (delivery/collection)		65	127	120	218
Long haul		70	136	129	240
Construction		78	146	144	264
Bus		50	n/a	80	n/a
Coach		52	n/a	80	n/a

Potential safety benefits of TPMS for LCVs and HDVs

Severe tyre under-inflation contributes to accident causation of LCVs and HDVs. A pressure deviation of more than 15% results in noticeable change of tyre properties (more than 10%) which affects the wear rate of the tyre and the braking and handling performance of the vehicle. The increased heat generation due to tyre under-inflation further reduces the maximum lateral tyre force. The trend among different tyre types is more or less the same, but significant quantitative deviations exist. Furthermore, the impact of tyre pressure on the stability of the vehicle depends on its configuration (number of axles, number of tyres, trailer, existence of ESP). Thus, in order to perform a complete analysis of the road safety benefit a more detailed analysis is necessary.

Tyre under-inflation does not affect the braking performance of all types of tyres and for all road surface conditions similarly. Tyre condition and tread depth are more significant factors on wet rather than on dry surfaces. Calculations show that improper tyre inflation can decrease the stability of a LCV by approximately 5 km/h (relative to the speed at which certain types of accidents happen in case of nominally inflated tyres). However, this depends also on the inclination of the road, the type of vehicle and the number of underinflated tyres.

Based on various studies, speed related accidents are found to account for almost 20% of HDV accidents. In accidents that involve deaths or severe injuries of truck occupants this share is in the range of 7.5 to 10%. A reduction in the number of speed and tyre related accidents due to proper tyre pressure conditioning should be expected. An indicative assessment of the safety benefits of TPMS has been made, both in terms of the avoided number of accidents as in terms of avoided external costs. More precise calculations can be made in case a more detailed analysis per vehicle configuration is performed.

It is estimated that properly maintaining the tyre inflation pressure can reduce the number of speed and tyre related accidents by 4% to 20%, and the total number of accidents by 0.8% up to 4%. For widespread application of TPMS a societal cost reduction of 11 to 58 M€ per year is estimated in the EU as a consequence of avoided fatalities resulting from single vehicle accidents by HDVs. This may be considered a lower bound for the possible monetised safety benefits of applying TPMS to LCVs and HDVs.

Cost-effectiveness of TPMS for LCVs and HDVs

A cost-benefit analysis has been carried out from a societal perspective as well as an end-user perspective.

In the cost-benefit analysis from the **societal perspective** the following costs and cost savings are taken into account:

- TPMS costs:
  - additional investment costs for TPMS (price excl. applicable taxes),
- Changes in usage costs:
  - fuel cost savings (based on fuel price excl. applicable taxes)
  - costs / savings associated with a change in the amount of maintenance:
    - extended lifetime of tyres
    - optimized inflation frequency
  - cost savings associated with less service disruptions due to reduced roadside tyre breakdown
  - cost savings associated with a reduction of external costs:
    - reduced amount of accidents (fatalities, injuries, congestion)
    - reduced amount of pollutant emissions

A societal discount rate of 4% is used. Results for the societal perspective are expressed as marginal GHG abatement costs in Euros per tonne of avoided CO_2-equivalents [€/tCO_2].

In the cost-benefit analysis from the **end-user perspective**, the following costs and cost savings are taken into account:

- TPMS costs:
  - additional investment costs for TPMS (price incl. applicable taxes),
- Changes in usage costs:
  - fuel cost savings (based on fuel price incl. applicable taxes)
  - costs / savings associated with a change in the amount of maintenance:
    - extended lifetime of tyres
    - optimized inflation frequency
  - cost savings associated with less service disruptions due to reduced roadside tyre breakdown

An end user discount rate of 8% is used. Results for the end-user perspective are be presented as a change in the total cost of ownership (ΔTCO) of the vehicle, as well as in the payback period for the investment in TPMS.

In the assessment of cost-effectiveness the investment costs, fuel cost savings and reduced accident costs are based on the assessments made in this study. For the other cost factors more indicative estimates have been derived.

Cost-effectiveness has been estimated for OEM-fitted and retrofit systems and for different LCV and HDV applications separately. Results have been calculated as function of the oil price (through a direct relation between oil price and diesel price). A sensitivity analysis has been carried out by assessing cost-effectiveness for different combinations of scenarios for the costs of TPMS and the potential fuel savings. Furthermore cost-effectiveness has been assessed taking account of all the above-listed cost factors as well as on the basis of TPMS investment costs and fuel cost savings only.

TPMS is considered cost-effective from an end-user perspective when the payback time is shorter than the average TPMS lifetime of 7 years, determined from supplier responses to the questionnaire.

If CO_2 abatement costs are negative, TPMS is definitively cost-effective from a societal point of view. But TPMS can also be considered cost-effective from a societal point of view if the abatement costs are positive. This depends on the level of CO_2 abatement costs that is considered acceptable in view of a CO_2 reduction target to be achieved or in comparison with other CO_2 reduction options.

Cost-effectiveness of OEM-fitted TPMS in the "current cost / high savings potential" scenario

As a starting point for the assessment of cost effectiveness the **"current cost / high savings potential"** scenario is taken, which represents the current situation in terms of TPMS production volumes and voluntary adoption.

For OEM-fitted TPMS in a "current cost / high savings potential" scenario, Table 4 shows all costs and cost savings from the societal perspective for a fuel price corresponding with an oil price of 100 $/barrel. This table illustrates the contribution of different cost factors to the total cost assessment. When summing up all costs and cost savings, the total is in all cases below zero, which indicates that in this scenario the implementation of TPMS leads to a net cost saving for society. From an end-user perspective, the result is not much different (Table 5). The total of the sum of investment minus cost savings remains negative.

The influence of the fuel price on these results is depicted in Figure 1 and Figure 2. Under these assumptions and taking account of all relevant cost factors OEM-fitted TPMS is cost-effective for all considered applications from a societal as well an end-user perspective irrespective of assumptions regarding the price of fuel.

In both cases, from a societal as well as from an end-user perspective, the most cost-effective application for TPMS is in a long-haul truck + trailer vehicle.

The overviews in Table 4 and Table 5 also clearly show that cost savings due to extended tyre lifetime are a determining factor in the cost effectiveness of TPMS. They are of the same order of magnitude as the fuel cost savings, and largely explain why an assessment of cost-effectiveness on the basis of investments and fuel cost savings only would lead to a significantly less favourable result. The effect of including cost savings due to extended tyre lifetime is somewhat dampened by the extra costs due to increased check frequency.

Table 4: Changes in annual costs per vehicle for OEM-fitted TPMS from a **societal perspective**, with cost assumptions according to the **"current cost / high savings potential"** scenario, assuming an oil price of 100 $/barrel

Societal perspective	Invest. costs		Operational costs				External costs		
	OEM investment cost (ex VAT)	Annuity	Fuel savings (ex VAT)	Extended lifetime of tyres	Change in check frequency	Reduced break-down	Reduced accidents	Reduced emissions	TOTAL costs
Vehicle segment	[€]	[€]	[€]	[€]	[€]	[€]	[€]	[€]	[€]
Service/delivery (indirect TPMS)	8	1	-11	-20	+12	-12	-4	-1.8	-36
Service/delivery (direct TPMS)	44	7	-11	-20	+12	-12	-4	-1.8	-30
Urban	164	27	-22	-29	+12	-12	-4	-2.8	-31
Municipal utility	195	32	-23	-18	+12	-12	-3	-2.2	-14
Regional TO	173	29	-30	-44	+12	-12	-6	-3.2	-54
Regional TT	314	52	-43	-88	+24	-12	-6	-4.6	-78
Long haul TO	185	31	-85	-95	+12	-12	-14	-4.2	-168
Long haul TT	338	56	-156	-191	+24	-12	-14	-7.6	-301
Construction TO	234	39	-28	-37	+12	-12	-5	-3.1	-35
Construction TT	395	66	-35	-73	+24	-12	-5	-3.9	-40
Bus	174	29	-19	-37	+12	-12	-5	-1.3	-33
Coach	209	35	-28	-38	+12	-12	-6	-0.9	-38

Table 5: Changes in annual costs per vehicle for OEM-fitted TPMS from an **end-user perspective**, with cost assumptions according to the **"current cost / high savings potential"** scenario, assuming an oil price of 100 $/barrel

End-user perspective	Invest. costs		Operational costs				External costs		
	OEM investment cost (ex VAT)	Annuity	Fuel savings (ex VAT)	Extended lifetime of tyres	Change in check frequency	Reduced break-down	Reduced accidents	Reduced emissions	TOTAL costs
Vehicle segment	[€]	[€]	[€]	[€]	[€]	[€]	[€]	[€]	[€]
Service/delivery (indirect TPMS)	8	1	-17	-20	+12	-12	n/a	n/a	-36
Service/delivery (direct TPMS)	44	8	-17	-20	+12	-12	n/a	n/a	-29
Urban	164	31	-34	-29	+12	-12	n/a	n/a	-32
Municipal utility	195	37	-35	-18	+12	-12	n/a	n/a	-17
Regional TO	173	33	-46	-44	+12	-12	n/a	n/a	-57
Regional TT	314	60	-67	-88	+24	-12	n/a	n/a	-83
Long haul TO	185	36	-131	-95	+12	-12	n/a	n/a	-191
Long haul TT	338	65	-240	-191	+24	-12	n/a	n/a	-354
Construction TO	234	45	-44	-37	+12	-12	n/a	n/a	-35
Construction TT	395	76	-54	-73	+24	-12	n/a	n/a	-39
Bus	174	33	-28	-37	+12	-12	n/a	n/a	-32
Coach	209	43	-43	-38	+12	-12	n/a	n/a	-38

Other costs have a limited impact on the cost-effectiveness. Especially the external costs savings related to reduced accidents and pollutant emissions turn out to be negligible.

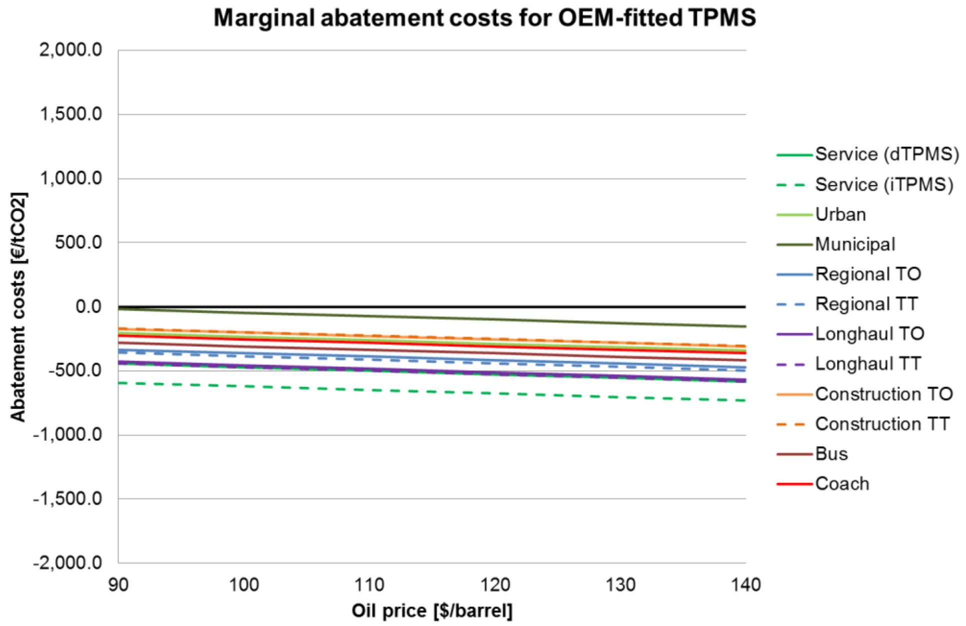

Figure 1: Marginal abatement costs from a **societal perspective** for an investment in OEM-fitted TPMS, with cost assumptions according to the **"current cost / high savings potential"** scenario and taking account of all relevant cost changes (investment costs, fuel cost savings, changes in other operation costs and reduced external costs).

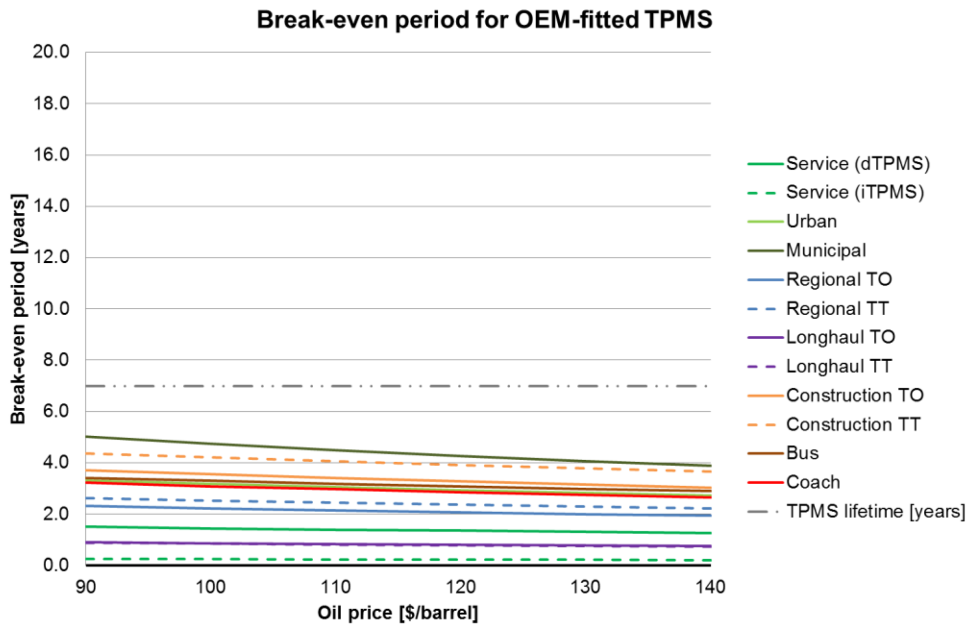

Figure 2: Break-even period for an investment in OEM-fitted TPMS from an **end-user perspective**, with cost assumptions according to the **"current cost / high savings potential"** scenario and taking account of all relevant cost changes (investment costs, fuel cost savings, and changes in other operation costs).

Robustness of the cost-effectiveness of OEM-fitted TPMS to scenario variations

Besides a **“current cost / high savings potential”** scenario, additional scenarios have been evaluated to provide insight into the impact of a lower cost scenario and of scenarios with lower savings potential:

- **“Prospective costs / high savings potential”**: This scenario can be thought to e.g. represent a situation in which TPMS application is mandated (leading to high production volumes and therefore low investment costs) and user response to TPMS signals is high.
- **“Current costs / low savings potential”**: This scenario is used as a worst case scenario. It may represent a future situation in which investment cost remain high while TPMS only results in low savings potential. But it also can be considered representative for a current situation in which TPMS application leads to a reduction of tyre over-inflation, which partly counteracts the estimated savings due to full prevention of under-inflation.
- **“Prospective costs / low savings potential”**: This scenario could e.g. occur in a situation in which TPMS application is mandated (leading to high production volumes and therefore low investment costs) but where user response to TPMS signals is low and/or systems are tampered with. It also caters for the possibility that TPMS application leads to a reduction of tyre over-inflation, which partly counteracts the estimated savings due to full prevention of under-inflation.

For all scenarios cost-effectiveness has also been evaluated on the basis of investment costs and fuel cost savings only, in addition to the above described case in which a range of cost impacts is taken into account.

<u>Taking all cost factors into account</u> the following conclusions can be drawn from the scenario analyses:

- In the **“prospective costs / high savings potential”** scenario, the cost-effectiveness of OEM-fitted TPMS is better than in the ”current cost / high savings potential” scenario. Payback times are generally 2 years or less, and abatement costs are even more negative (order of magnitude -500 €/tonne).
- In the **“current costs / low savings potential”**, with 50% lower fuel savings potential, OEM-fitted TPMS is only cost-effective from an end-user point of view for application in service/delivery vans, regional trucks and long haul trucks. Abatement costs are negative for these applications too, with the exception that for regional trucks with TPMS on truck and trailer this is only the case for oil prices above 115 €/barrel.
- In the **“prospective costs / low savings potential”** scenario, payback times for OEM-fitted systems are generally 3.5 years or less. Abatement costs are negative (order of magnitude -200 €/tonne or less).

When cost-effectiveness is based on <u>TPMS investment costs and fuel cost savings only</u>, payback times are significantly longer and abatement costs higher.

- In the **“prospective costs / high savings potential”** scenario payback times are still below 7 years (lifetime direct TPMS) for all applications, while abatement costs are negative for almost all vehicle categories.
- In the **”current cost / high savings potential”** scenario payback times are above 7 years for construction vehicles (TPMS on truck and trailer) and, in case of low oil prices, also for buses and municipal utility trucks.

- In the **“current costs / low savings potential”** abatement costs are below zero only for long haul trucks and for service/delivery vans with indirect TPMS. Payback times are only below 7 years for long haul applications and for service/delivery vans with indirect and direct TPMS.
- In **“prospective costs / low savings potential”** scenario payback times are below 7 years in most applications and abatement costs are negative. Exceptions are construction vehicles with truck-trailer configuration, for which abatement costs and break-even period are only favourable for higher oil prices.

Cost-effectiveness of retrofit TPMS

Due to the higher investment costs the cost-effectiveness of retrofit TPMS systems is worse than that of OEM-fitted systems.

<u>Taking all cost factors into account</u> retrofit TPMS is cost-effective for:

- all applications in the **“prospective costs / high savings potential”** scenario;
- most applications in the **“current costs / high savings potential”** scenario, with the exception of e.g. service/delivery vans, municipal trucks and construction vehicles with TPMS on truck and trailer. Abatement costs are always below zero only for long haul applications, regional trucks and truck & trailers and service / delivery vans and around zero for a few other applications;
- long haul applications only in the **“current costs / low savings potential”** scenario.
- most applications in the **“prospective costs / low savings potential”** scenario, except for construction TT and municipal vehicles, for which cost-effectiveness depends on the oil price. Above 110 $/barrel, both societal and end-user costs are favourable.

When cost-effectiveness is based on <u>TPMS investment costs and fuel cost savings only</u>, retrofit TPMS is only cost-effective for:

- all applications in the **“prospective costs / high savings potential”** scenario;
- long haul applications, regional truck & trailers and service / delivery vans in the **“current costs / high savings potential”** scenario, with abatement costs below zero only for long haul trucks;
- long haul trucks in the **“current costs / low savings potential”** scenario, when viewed from an end-user perspective. Abatement costs are above zero for all applications.
- long haul trucks, coaches and service delivery vehicles in the **“prospective costs / low savings potential”** scenario, when viewed from an en-user perspective. Abatement costs are below zero only for long haul trucks and coaches for all oil prices.

The results of the cost-effectiveness assessment of TPMS for HDVs and LCVs with all the different cost and fuel saving scenarios is summarized in Table 6.

Table 6: Overview of different cost and fuel saving scenarios for OEM and retro-fitted TPMS on HDV and LCV.

	Fuel cost savings only		**Considering all cost savings**	
Scenario	**OEM-fitted TPMS**	**Retro-fitted TPMS**	**OEM-fitted TPMS**	**Retro-fitted TPMS**
Current costs / high savings potential	Payback times are above 7 years for construction vehicles (TPMS on truck and trailer) and, in case of low oil prices, also for buses and municipal utility trucks.	Cost effective for long haul applications, regional truck & trailers and service / delivery vans. Abatement costs below zero only for long haul trucks.	TPMS is cost-effective for all considered applications from a societal as well an end-user perspective irrespective of assumptions regarding the price of fuel.	Cost effective for most applications (Abatement costs are always below zero and for a few applications around zero.
Prospective costs / high savings potential	Payback times are below 7 years (lifetime direct TPMS) for all applications, while abatement costs are negative for almost all vehicle categories	All applications	Cost-effectiveness is even better than in the ”current cost / high savings potential” scenario.	Cost-effective for all applications.
Current costs / low savings potential	Cost effective (from societal perspective) for long haul trucks and for service/delivery vans with indirect TPMS; and direct TPMS (from end user perspective).	Cost-effective for long haul trucks when viewed from an end-user perspective. Abatement costs are above zero for all applications.	TPMS is only definitive cost-effective from an end-user point of view for application in service/delivery vans, regional trucks and long haul trucks.	Cost effective for long haul applications
Prospective costs / low savings potential	Payback times are below 7 years in most applications and abatement costs are negative (Exceptions: construction vehicles with truck-trailer configuration)	Cost effective for long haul trucks, coaches and service delivery vehicles when viewed from an en-user perspective. Abatement costs are below zero only for long haul trucks and coaches at	Payback times for OEM-fitted systems are generally 3.5 years or less and abatement costs are negative.	Cost effective for most applications (Exceptions: construction TT and municipal vehicles).

		all oil prices.		

Options and rationale for policy intervention

In the **"current costs / low savings potential"** scenario, and taking into account all considered impacts on operational and external costs, OEM-fitted TPMS is cost-effective for all considered LCV and HDV applications. Nevertheless suppliers expect that autonomous adoption of TPMS will be slow and that market shares will remain small in the coming years. This may be a motivation for implementing policy measures to promote the uptake of TPMS. Possible policy measures, that could be considered, can be grouped into five policy categories:

Baseline solution
- Do nothing and allow the market to take the initiative.

Stimulation measures - information
- TPMS performance standard
- Labelling
  - Presence of TPMS visible in tyre labelling scheme
  - In the case of introduction of an HDV CO_2 labelling, the effect of TPMS influences the vehicle's CO_2 score or could be made explicit in the label
  - Information campaigns to better disseminate insights in end-user benefits to dealers and / or fleet managers

Stimulation measures - financial
- Dedicated fiscal incentives or subsidies (generally at Member State level)
  - Purchase incentive aimed at end users / fleet managers
  - Incentives aimed at vehicle manufacturers or tyre manufacturers
- Broader economic instruments promoting fuel saving and CO_2 reduction
  - E.g. CO_2 tax on fuels or inclusion of HDVs in the EU-ETS

Voluntary agreements with sector
- TPMS-specific voluntary agreement with OEMs and/or the transport sector
  - Stakeholders may agree to implement one or more of the above-mentioned information-related stimulation measures
  - Stakeholders may agree to achieve certain levels of TPMS penetration in targets years
- Broader / generic voluntary agreement with OEMs and/or the transport sector
  - Stakeholders may agree to achieve a certain CO_2 emission reduction in target years, with increased use of TPMS as one of the reduction measures

Regulation (mandatory fitment)
- Regulation for mandatory fitment
  - Regulation may be aimed at vehicle OEMs or tyre manufacturers
  - TPMS performance standard necessary to define minimum requirements for operation, malfunction, warning and pressure range
- Classify TPMS as "eco-innovation" in a possible future CO_2 regulation for HD vehicles

For the various options pros and cons and potential impacts have been analysed in a qualitative assessment.

Not taking any policy action is an option to be considered, as the relative CO_2 emission reduction potential TPMS is estimated to be less than 0.5%. Other technical options and improvements in the logistics system offer far greater reduction potentials.

Information campaigns seem a no regret option. The focus should in that case not only be on fuel cost savings but also on the benefits of increased tyre life and reduced costs due to tyre blow-outs and other tyre-related incidents. Including TPMS in tyre labelling schemes or in the context of introduction of an HDV CO_2 labelling are feasible and attractive options.

Financial stimulation measures are not an obvious candidate, as it is very likely that TPMS is cost-effective for many or all applications. The financial business case at the end-user level does not seem the main barrier for widespread uptake of TPMS. Due to the relatively small investment costs and savings involved, financial stimulation measures also run the risk of having administrative costs outweighing the potential benefits.

Promotion by the sector of the application of TPMS could be part of a voluntary agreement between the European Commission or a Member State government and the European or national logistics sector. Voluntary agreements are usually the result of negotiations between government and sectoral stakeholders in which it is agreed that the sector takes certain actions in return for a promise by the government not to implement possible government interventions, that are considered undesirable by the sector. Given the relatively small reduction potential of TPMS, care should be taken not to trade in potentially more effective options for voluntary TPMS application.

Regulation for mandatory fitment could be justified if OEM-fitted TPMS is cost effective for most or all applications in the scenarios that could occur in the case of mandatory fitment. When TPMS application is made mandatory through regulation, production volumes will increase significantly, what might lead to lower prices as in the “prospective cost” scenario. Analysis for the combination of the “prospective cost” scenario with scenarios for high resp. low fuel savings potential show that OEM-fitted TPMS could be cost effective for cases in the “prospective cost / high savings potential” scenario and in some of the “prospective cost / low savings potential” scenario. Therefore mandatory fitment of TPMS on new vehicles could lead in the described cost-effective scenarios to benefits for users as well as society. Given the current low market penetration of TPMS for HDVs, a regulation could accelerate mass production and reduce TPMS costs, and thereby could contribute to the materialization of appropriate cost benefits.

Mandatory fitment for LCVs only could be considered as cost-effectiveness for this application is robust to all considered scenario variations. The latter is also true for long haul applications, but as this application is difficult to define from a vehicle regulations point of view, mandating TPMS for long haul HDVs seems not feasible.

Classification of TPMS as “eco-innovation” in a possible future CO_2 regulation for HD vehicles has the advantage that it promotes OEMs to implement this option only in applications where the business case is considered profitable.

Given the uncertainties in the assessment of cost-effectiveness no recommendations are formulated for preferable policy options.

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1 Introduction

This report presents the results of a study by TNO and TU Graz on Tyre Pressure Monitoring Systems (TPMS) as a means to reduce Light-Commercial Vehicles (LCVs) and Heavy-Duty Vehicles (HDVs) fuel consumption and CO_2 emissions. This project has been performed by order of the European Commission DG CLIMA under “Service Request No 0712/2012/635955/ETU/CLIMA.C.2 under the Framework Contract on ENTR/F1/2009/030 - Lot 5”.

1.1 Definition

The term Tyre Pressure Monitoring System (TPMS) is defined as in Regulation 661/2009: ‘tyre pressure monitoring system’ means a system fitted on a vehicle which can evaluate the pressure of the tyres or the variation of pressure over time and transmit corresponding information to the user while the vehicle is running [Reg661, 2009].

Central Tyre Inflation Systems (CTIS) is a system which provides air pressure control in each tire of a vehicle as a way to improve performance on different surfaces, for example by lowering or increasing the air pressure. CTIS are not included in this review as they fall outside the definition of TPMS. Neither are any “external” tyre pressure monitoring systems included, which monitor the tyre pressure based on a measurement of the tyre contact area.

1.2 Background

“Tank-to-wheel” emissions of road transport contribute nearly 20% to the EU’s total emissions of carbon dioxide (CO_2), the main greenhouse gas. Producing the fuel consumed by road transport adds about a 14% to these emissions (“well-to-tank emissions”). While emissions from other sectors are generally falling, those from road transport have continued to increase since 1990.

Cars (M1) and light commercial vehicle (LCVs) regulations. In order to tackle road transport emissions, the European Commission has implemented a strategy on Light-Duty Vehicles (LDVs) with an objective of limiting average CO_2 emissions. Regulation (EC) 443/2009 and Regulation (EU) 510/2011 set out mandatory CO_2 emission standards for the new passenger car and light commercial vehicle fleets respectively.

Heavy-Duty Vehicle (HDV) CO_2 emissions, that represent about one quarter of road transport CO_2 emissions, are currently not regulated. As a result of continuously increasing freight volumes in the EU (except in 2009 due to the economic crisis), these emissions have been rising in spite of some improvements in vehicle fuel consumption and CO_2 performance. In June 2007 the Council invited the Commission "to develop and implement policy instruments and measures to reduce greenhouse gas emissions from those vehicles". The Commission, in its April 2010 Communication on "A European strategy on clean and energy efficient vehicles", announced that it would propose a strategy targeting fuel consumption and CO_2 emissions from heavy-duty vehicles.

Absence of TPMS regulation so far for LCVs and HDVs. While TPMS has been made mandatory for M1 vehicles in 2012 for new types of cars and from 2014 for all cars (Regulation (EC) 661/2009), LCVs and HDVs are not subject to such mandatory requirements even though TPMS could potentially contribute to curbing LCV and HDV fuel consumption and CO_2 emissions.

In general, TPMS has several potential benefits:
- Environmental benefits (evaluation in chapter 2);
- Safety benefits (evaluation in chapter 5);
- Economic benefits (evaluation in chapter 6).

The evaluation of these potential benefits is part of this study.

Environmental benefits
Under-inflated tyres have a higher rolling resistance compared to tyres inflated with the advised tyre pressure. This results in an increase in fuel consumption, which effectively means more CO_2 and other pollutants are emitted. The use of TPMS can prevent under-inflated tyres and therefore have an environmental benefit due to reduced emissions.

Safety benefits
The dynamic behaviour of a tyre (i.e. braking distance and lateral stability) is closely connected to its inflation pressure. Under-inflation can lead to a reduction of vehicle stability in safety critical situations (e.g. fast steering response, cornering, braking while cornering) which increases the chance of an accident. Extreme under-inflation can lead to thermal and mechanical overload and subsequent, sudden destruction of the tyre itself. The use of TPMS can prevent under-inflated tyres and therefore have a safety benefit due to maintaining vehicle stability.

Economic benefits
TPMS can lead to reductions in operating costs and societal costs for several reasons:
- fuel cost savings due to improved rolling resistance
- reduced amount of maintenance
  - extended lifetime of tyres
  - optimized inflation frequency
- decrease in service disruptions
  - reduced roadside tyre breakdown
- reduction of external costs
  - reduced amount of accidents (fatalities, injuries and congestion)
  - reduced amount of emissions

1.3 Aim and approach

The aim of this study is to provide information on the following topics related to TPMS applications in LCVs and HDVs:
1. Savings potential for fuel consumption & CO_2 emissions
2. Technology state-of-the-art
3. Current market penetration and uptake, as well as
4. Potential for improving safety

In addition the study assesses cost effectiveness and possible policy measures that the European Commission could implement to promote the application of TPMS in LCVs and HDVs in the EU. The structure of the report is aligned to these topics - as is explained in section 1.4.

The approach of each topic varies and will be further discussed in the various chapters. However, one overall approach to collect information on the topics 1 to 4 (see aim of the study) was to send out a questionnaire to the main stakeholders for TPMS. Subsequently, interviews were conducted with the responding parties. A list of all contacted parties is given in Appendix A.

A workshop was organized in Brussels where relevant stakeholders like vehicle manufacturers, TPMS and tyre suppliers and road transport organizations were invited. The objective of the meeting was to agree on the information gained on TPMS throughout the study and discuss the outcome of cost-benefit calculations.

Issues addressed during the workshop were:
- The industry's vision on today's reality;
- Presentation of the project results and discussion of the underlying assumptions with the industry to verify that the conclusions drawn in the report are valid for the industry.

The initial assessment of the cost effectiveness from the end-user and societal perspective has been fine-tuned with the input from the stakeholder workshop.

1.4 Structure of the report

The structure of the report is based on the task description of the Service Request (No. 0712/2012/635955/ETU/CLIMA.C.2 implementing Framework Contract on ENTR/F1/2009/030 – Lot 5). The tasks and chapters are numbered accordingly:

Chapter 2	Task 1 – Rolling resistance contribution to LCV and HDV fuel consumption and CO_2 emissions
Chapter 3	Task 2 – State-of-the-art: TPMS technologies, suppliers, characteristics of main products
Chapter 4	Task 3 – Current market penetration of TPMS technology for LCVs and HDVs
Chapter 5	Task 4 – Safety
Chapter 6	Task 5 – Current and prospective cost effectiveness of TPMS technology for LCVs and HDVs.
Chapter 7	Task 6 – Rationale for public/legislative intervention

Task 1 has been performed by TUG with support from TNO.
Task 2 to 5 have been performed by TNO.
Task 6 has been performed by TNO with support from TUG.

2 Task 1 – Rolling resistance contribution to LCV and HDV fuel consumption

2.1 Background

Fuel consumption and CO_2 emissions[2] of road vehicle transport are to a large extent determined by the vehicle's driving resistances. Under-inflated tyres are known to increase rolling resistance (RR). Hence TPMS equipment is discussed – amongst other reasons – as a measure to reduce CO_2 emissions from road transport. In Task1 of the current study the potential effect of TPMS on the amount of CO_2 emitted by the LCV and HDV fleet has been investigated.

2.2 Method

The work to be delivered by the engine of a vehicle is defined by the driving resistances (air resistance, rolling resistance, work to overcome road gradients), by acceleration of masses and rotational inertias, by losses in the transmission system and by energy consumption of auxiliaries and power take off (PTO). The share of each energy consumer depends on the vehicle, the mission profile, the loading, and on ambient conditions. Due to the wide spread of values for these parameters in the LCV and HDV fleet, a disaggregated approach was chosen in this study, which considers bandwidths for the CO_2 influencing parameters based on a set of representative vehicles operated in different representative mission profiles.

Starting point of the investigations was disaggregated data on EU27 annual CO_2 emissions of the LCV and HDV fleet shown in Table 7. The segmentation method according to vehicle classes and mission profiles as well as the CO_2 numbers for N3 vehicles and for N2 vehicles with gross vehicle weight (GVW) >7.5tons have been elaborated in a DG Clima project related to CO_2 certification of HDV [LOT2, 2012]. Data on LCV, M2 and N2 vehicle classes with GVW <7.5tons have been derived from [LOT1, 2011] and data on fleet composition available from the database of the "Handbook Emission Factors of Road Transport" [HBEFA, 2010]. Main sources of the CO_2 emissions from the EU27 LCV and HDV fleet are N3 vehicles operated in long haul transport followed by LCV vehicles.

[2] CO_2 emissions are directly proportional to fuel consumption. Based on a typical chemical composition of diesel fuel the CO_2 mass emissions can be calculated by multiplication of the mass based fuel consumption with a factor of 3.05. The correlation factor between kg CO_2 and diesel fuel consumption in litres is 2.55. For simplicity reasons this chapter refers to CO_2 emission metrics rather than to fuel consumption.

Table 7: EU27 CO_2 emissions in kilotonne per year disaggregated by vehicle class and mission profile

Vehicle class			Mission profile						Sum
			Long haul	Regional delivery	Urban delivery	Municipal utility	Con-struction	vehicle class specific	
N1	Light Commercial Vehicles							96 700	**96 700**
N2 <=7.5t	Truck 2-axles	4x2 Rigid < 7.5t	4 941	3 294	2 196	914			**11 346**
N2 >7.5t		4x2 Rigid + (Tractor) 7.5-10t	2 648	1 765	1 177	490			**6 080**
N2 >7.5t		4x2 Rigid + (Tractor) > 10-12t	2 648	1 765	1 177	490			**6 080**
N3		4x2 Rigid + (Tractor) > 12-16t	2 648	1 765	1 177	490			**6 080**
N3		4x2 Rigid > 16t	12 518	2 782	1 855	1 159			**18 314**
N3		4x2 Tractor > 16t	80 016	24 894			10 669		**115 579**
N3		4x4 Rigid 7.5-16t				58	558		**616**
N3		4x4 Rigid >16t				91	875		**966**
N3		4x4 Tractor >16t					701		**701**
N3	Truck 3-axles	6x2/2-4 Rigid All Weights	9 984	2 286		2 801			**15 071**
N3		6x2/2-4 Tractor All Weights	19 430						**19 430**
N3		6x4 Rigid All Weights	3 355				5 964		**9 319**
N3		6x4 Tractor All Weights	2 428				719		**3 147**
N3		6x6 Rigid All Weights					1 516		**1 516**
N3		6x6 Tractor All Weights					157		**157**
N3	Truck 4-axles	8x2 Rigid All Weights		377		52			**429**
N3		8x4 Rigid All Weights					9 763		**9 763**
N3		8x6/8x8 Rigid All Weights					824		**824**
M2	Bus / Coach	Minibus						1 500	**1 500**
M3		City Class I						10 482	**10 482**
M3		Interurban Class II						6 437	**6 437**
M3		Coach Class III						5 807	**5 807**
			140 616	38 928	7 582	6 545	31 746	120 926	**346 344**

The effect of TPMS on CO_2 emissions on a fleet level was evaluated separately for each combination of vehicle class and mission profile as shown in Table 7. This was done based on the consolidation of findings of subtasks covering the following questions:

1) How does rolling resistance change with inflation pressure?
2) What is the tyre pressure distribution in the field?
3) How does TPMS influence tyre pressure distribution?
4) How does TPMS influence fleet average rolling resistance?
5) How does rolling resistance influence CO_2 emissions?

The methods and results for these five subtasks are described below. Results on the impact of TPMS on CO_2 emissions are then discussed in section 2.3.

2.2.1 *How does rolling resistance change with inflation pressure?*

The correlation of rolling resistance with tyre inflation pressure was investigated based on compiled data available from literature (e.g. [Michelin, 2005], [ExxonMobile, 2008]), feedback received from the questionnaires in this project and measured data on resistance forces available from the DG Clima HDV CO_2 project[3]. Figure 3 shows the derived dependency for change in rolling resistance (RR) per one bar change in inflation pressure as a function of “recommended pressure” (p_rec). Available information can be grouped into data on passenger cars (PCs) and data for N3 vehicles. For PCs on average a 25% increase of RR connected with a 1 bar pressure drop is reported. The average value for N3 vehicles was found to be 3.5% per 1 bar pressure drop (value referring to a baseline recommended pressure of 9 bar). The significantly lower sensitivity for the N3

[3] These recently performed measurements have not been reported yet.

vehicles compared to PCs can be explained by the much higher absolute level of recommended pressure and in differences in tyre sizes and construction.

In the current study the RR dependency with inflation pressure had to be applied to a large variety of vehicle classes from small LCVs up to large N3 vehicles. For this purpose a power function for RR increase with 1 bar pressure drop based on p_rec as input parameter was fitted to the data as shown Figure 3. The applied ranges for p_rec for the different LCV and HDV vehicle classes are also indicated in Figure 3. As a general simplification it was assumed that – for a given p_rec – the change in RR is linear with the change in inflation pressure.

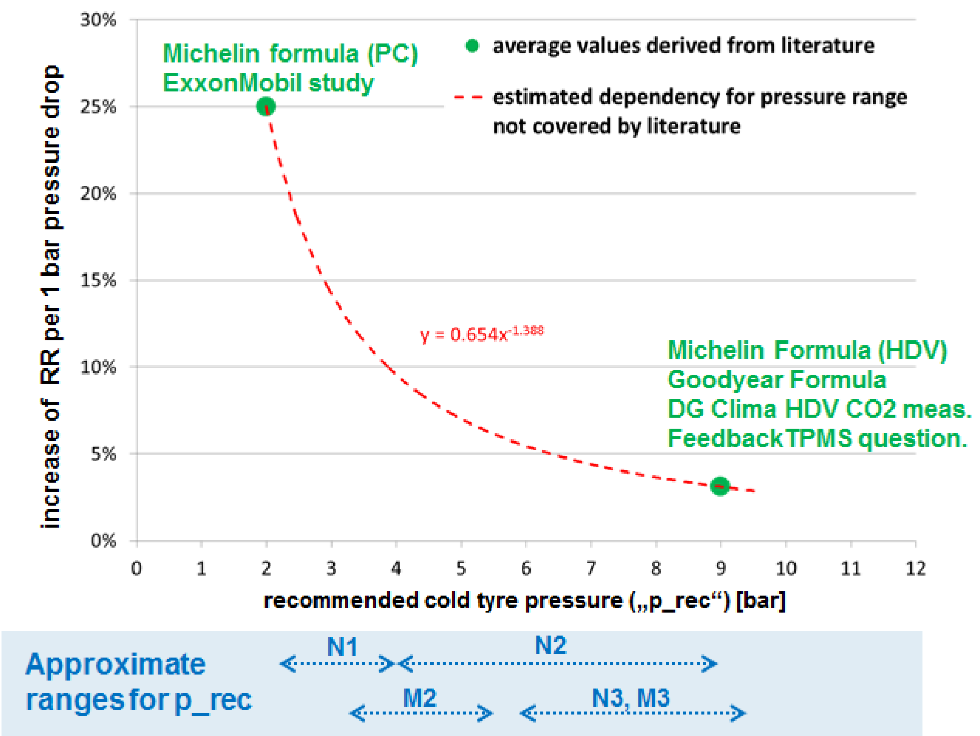

Figure 3: Increase of rolling resistance per 1 bar drop of tyre inflation pressure

2.2.2 *What is the tyre pressure distribution in the field?*

At the beginning of the study comprehensive data on tyre pressure distribution in the field was available only for passenger cars from [GRRF, 2008]. Due to the limited amount of time and budget it was decided to focus the investigations on HDVs and estimate the status quo for LCVs based on PC data. For HDVs a small field survey was conducted as part of this study. This data on HDV tyre pressure distribution was supplemented by data received from the questionnaires.

2.2.2.1 *Heavy duty vehicles*

Within the current study a small field survey on the HDV real world tyre pressure distribution was conducted in the greater area of the city of Graz (“TUG survey”). The focus of the investigations was on the vehicle categories N3, M3 and N2 with GVW >7.5t. In total pressure was measured on 498 tyres from 56 vehicles. The measurements have been performed at transport and bus companies and at cargo stations. Only vehicles and trailers which were “in-use” have been measured. For each tyre the recommended (cold) pressure was determined based on the tyre specifications, the maximum axle load and look-up tables from the tyre OEMs. If the tyre pressure was measured in “warm” conditions, the measured value has been converted to “cold” conditions. Wherever possible the drivers or mechanics have been interviewed about their common practice related to tyre pressure monitoring. Main findings derived from the interviews are:

- Only one vehicle equipped with TPMS was identified;
- There are also “external” TPMS systems, which monitor the tyre pressure based on a measurement of the tyre contact area. Such devices can be e.g. installed in the floor of garages or workshops. External TPMS are used e.g. by bus companies where the tyre pressure is monitored e.g. once a day. As this kind of system is not installed on the vehicle it is not included in the options studied in this report.
- It is a common practise to intentionally overinflate HDV tyres. For example several tyres with a recommended pressure of 8.5bars have been measured with an inflation pressure of 11 bars which was the maximum pressure available from the pressurised air system used for filling the tyre.

Figure 4 shows the results of the TUG survey for distribution of the pressure difference compared to the recommended values. In the picture data are shown separately for the main HDV vehicle categories and trailers. From the “TUG survey” data the following observations have been made:

1. The tyre pressure is approximately equally distributed around the recommended pressure “p_rec”. The average difference to p_rec was determined with +0.1 bar (on average a slight over-inflation);
2. Significantly under-inflated tyres are rather rare (0.6% of the tyres were below 50% of p_rec);
3. There are no significant differences in pressure distribution between the different HDV classes (incl. trailers);
4. The tyre pressure distribution in busses is closest to “p_rec”.

From the questionnaire feedback received from the tyre manufacturer organisation ETRMA-ETRTO also data on real world HDV tyre pressure distribution were available. These data were submitted as percentage of kilometres driven with under-inflated tyres in classes of relative under-inflation compared to the recommended pressure. Figure 5 gives a comparison of the ETRMA-ETRTO data with the results from the TUG survey. Compared to the TUG survey, the ETRMA-ETRTO data show a larger share of HDVs running with under-inflated tyres.

<u>In this study it was decided to use the tyre pressure distribution according to ETRMA-ETRTO in the assessment of CO_2 effects of TPMS for the vehicle categories N2, N3 and M3.</u>[4] This data is based on a much larger survey containing more than 600 vehicles. Data from the TUG survey have been used e.g. for assessment of the absolute level of recommend tyre pressure for the different vehicle categories.

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[4] Due to the higher shares of under-inflated tyres according to the ETRMA-ETRTO data this results in a higher calculated CO_2 benefit of TPMS compared to an assessment based on the TUG survey numbers.

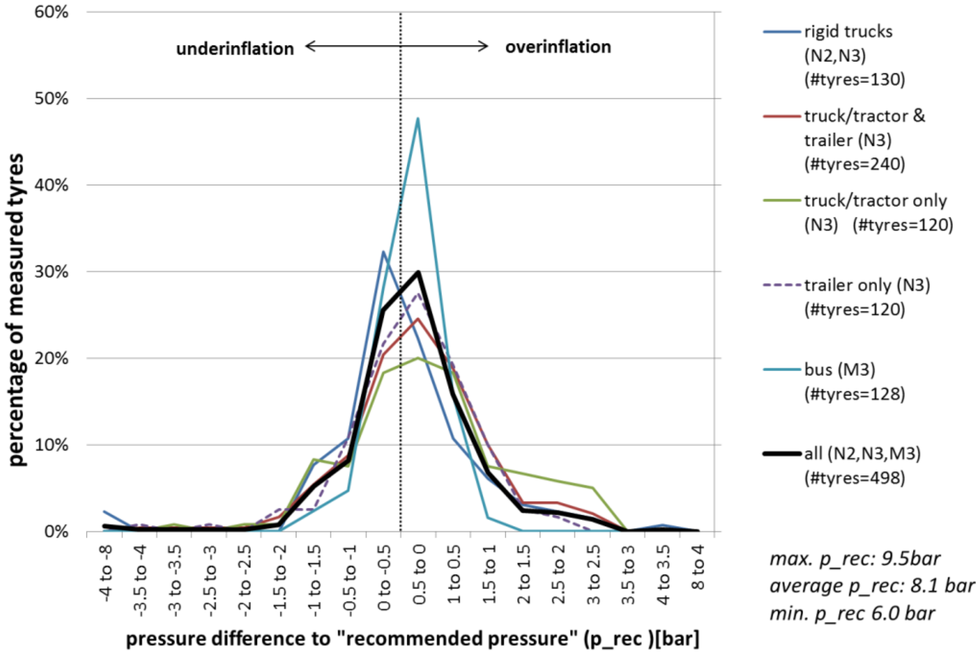

Figure 4: Tyre pressure distribution in the field – “TUG survey”

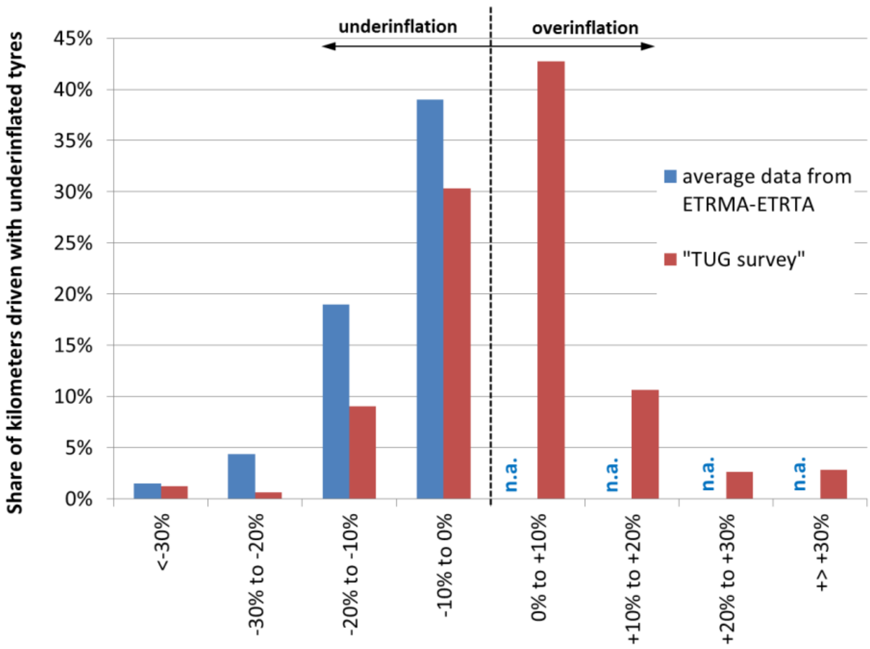

Figure 5: Comparison of HDV tyre pressure distribution data from ETRMA-ETRTO and the “TUG survey”

2.2.2.2 *Light commercial vehicles*

For Light Commercial Vehicles it was assumed that the distribution of relative tyre pressure difference to the recommended pressure is similar to the situation found for passenger cars in [GRRF, 2008]. Figure 6 shows a summary of the data from that study. In the current study, similar to the approach in [GRRF, 2008], only the datasets “NL”, “UK” and “France” (see Figure 6) have been used in the analysis.

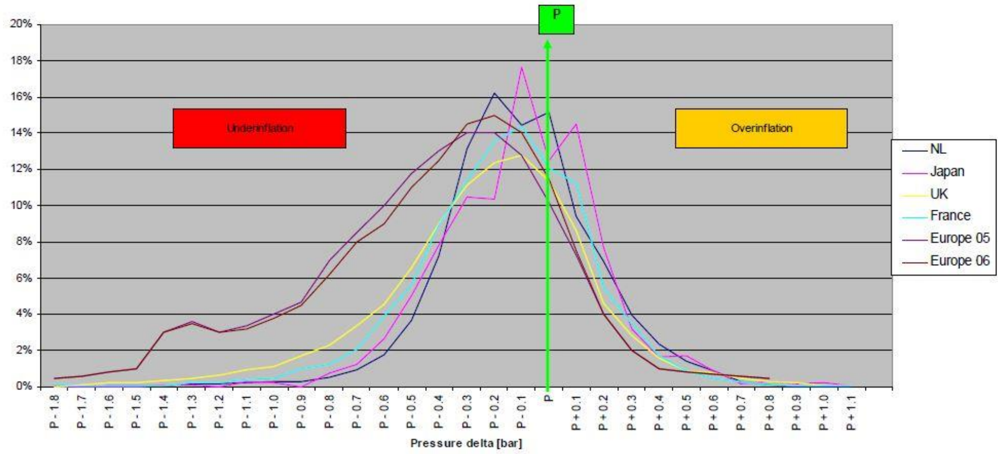

Figure 6: Summary of distributions for pressure difference to recommended pressure for passenger cars according to [GRRF, 2008]

2.2.3 *How does TPMS influence tyre pressure distribution?*

Information on the potential effect of TPMS application on the tyre pressure distribution in the fleet has been compiled from input of system suppliers, vehicle manufacturers and from [GRRF, 2008]. On this basis the following two scenarios for the impact of TPMS have been defined:

“High savings potential” scenario for TPMS CO_2 benefit

i.) Vehicle classes N2, N3, M3: TPMS systems fully prevent under-inflation by more than 10% below the recommended pressure;
Vehicle class N1: TPMS fully prevent under-inflation by more than 20% below the recommended pressure and reduce the number of under-inflated tyres between 10% and 20% by 50%;[5]

ii.) All the tyres identified in i) and ii) are driven with the correct recommended pressure;

iii.) Over-inflation is not affected (reduced) by TPMS system (a reduction of over-inflated tyres would give a negative effect on CO_2 emissions).

In the assessment of impact on CO_2 this scenario is further differentiated to:

a) TPMS installed on vehicles (trucks, tractors) and trailers
b) No TPMS installed on trailers

“Low savings potential” scenario for TPMS CO_2 benefit

Several influencing parameters appear plausible, which can reduce the “real” TPMS CO_2 effect compared to “best case” conditions. Such influencing factors could be e.g.:

- Reduction of over-inflated tyres due to TPMS monitoring
- System malfunctions and/or imperfections
- Drivers misuse e.g. due to non-acceptance of frequent warnings

[5] In the vehicles class N1 a significant share of “indirect” TPMS is expected (explanation “direct” / “indirect “ systems given in chapter 3). Furthermore N1 vehicles are operated with much lower absolute tire pressure levels so a lower relative TPMS detection rate is assumed compared to the heavier vehicle classes.

However, a precise definition of a “lower boundary scenario” for TPMS CO_2 benefits was not possible in this study. For that reason it was decided to apply a value of 50% of the effect of the best case scenario to be used as “lower boundary” in the discussions and in the sensitivity analysis of cost-benefit.

2.2.4 *How does TPMS influence fleet average rolling resistance?*

Combining the findings for the influence of inflation pressure on rolling resistance as presented in section 2.2.1, the data for tyre pressure distribution in the fleet discussed in section 2.2.2, and the assumptions made in section 2.2.3, the impact of TPMS on fleet average rolling resistance has been calculated. Table 8 shows the results for the main vehicle categories in the “best case” scenario. According to this approach for N1 and small N2 vehicles the fleet average rolling resistance can be reduced by at maximum 2.4% due to TPMS application. For the N3 and M3 vehicle categories these values were assessed to be 1.6%. For N3 vehicles only half of this reduction potential in rolling resistance can be realised if the trailer is not monitored by TPMS.

Table 8: Change of fleet average rolling resistance due to TPMS application (“high savings potential”)

vehicle category	applied tyre pressure distribution	average recommended pressure [bar]	change in fleet average RR
N1	PC	3.0	**-2.4%**
N2 <=7.5t	HDV	5.5	**-2.4%**
7.5t < N2 <= 10t	HDV	7.0	**-2.0%**
N2 >10t	HDV	8.0	**-1.6%**
N3 (TMPS on truck & trailer)	HDV	8.0	**-1.6%**
N3 (no TMPS on trailers)	HDV	8.0	**-0.8%**
M3	HDV	8.0	**-1.6%**

The vehicle category M2 was not included in the detailed impact assessment approach as the related vehicle specifications and operation conditions are not known to a sufficient level of detail. Hence no value for RR change for M2 vehicle is shown in Table 8. For the M2 category the CO_2 effects have been assessed based on averaging of results for N2 with GVW < 7.5tons and N1 vehicles.

2.2.5 *How does rolling resistance influence CO_2 emissions?*

The impact of rolling resistance on CO_2 emissions is strongly depending on the vehicle parameters (curb weight, payload, air resistance, drivetrain configuration and auxiliary power consumption) and the mission profile. Due to the wide spread of values for these parameters in the LCV and HDV fleet it was decided to assess the correlation between RR and CO_2 by means of a simulation-based approach. For this purpose the model PHEM (Passenger car and Heavy duty vehicle Emission Model, see e.g. [IVT, 2009]) was applied. PHEM has been developed at the TU Graz since the late 1990ies. The model calculates time-resolved fuel consumption and emissions of road vehicles in 1Hz for given driving cycles based on vehicle longitudinal dynamics and emission maps. In Figure 7 a scheme of the PHEM model is given. PHEM for example is used for the assessment of emission factors for the Handbook Emission Factors of Road Transport (HBEFA). Furthermore the PHEM software has been the basis for the software tool "VECTO" (Vehicle Energy Consumption calculation Tool), which is currently being developed by order of DG Clima for the purpose of simulation of HDV CO_2 emissions in the context of a EU certification process.

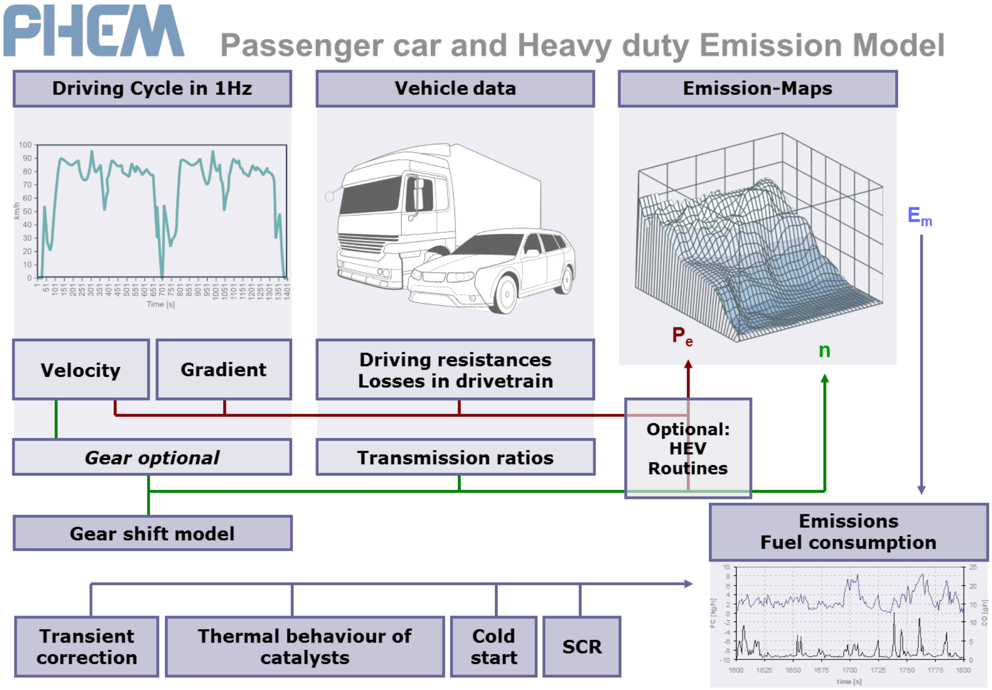

Figure 7: Scheme of the PHEM model

For the simulation of the CO_2 impact caused by a change of rolling resistance five representative vehicles have been defined, which shall cover the variety of conditions in the LCV and HDV fleet. Table 9 gives an overview of the main vehicle specifications. The corresponding parameters and CO_2 engine emission maps mainly have been taken from the HBEFA database on vehicle specifications and registration statistics supplemented by anonymised HDV component test data from the DG Clima HDV CO_2 project.

The applied driving cycles in the PHEM simulations were:

- for the vehicle categories N2, N3 and M3 the actual drafts for "mission profiles" from the DG Clima HDV CO_2 project;
- for N1 vehicles the Common Artemis Driving Cycle (CADC, 1:1:1 mix of urban, road and motorway).

M2 vehicles as well as N3 construction vehicles have not been simulated with PHEM due to the weak database on vehicle parameters and/or vehicle operation.

Table 9: Main vehicle specifications of the five representative vehicles used for simulation of the contribution of rolling resistance to total CO_2 emissions

			LCV	HDV 1 rigid truck	HDV 2 truck/tractor & trailer	HDV 3 city bus	HDV 4 coach
empty weight		[kg]	1 758	6 000	15 115	10 400	14 000
maximum allowed gross vehilce weight		[kg]	2 664	11 000	40 000	17 800	18 000
number axles vehicle		[-]	2	2	2	2	2
number axles trailer		[-]	---	---	3	---	---
payload	long haul	[kg]		3 750	19 300		
	other mission profiles	[kg]	327	2 500	12 900	3 700	2 600
rated power		[kW]	82	152	330	227	330
rolling resistance coefficients	fr0	[-]	0.0103	0.0071	0.0063	0.0065	0.0062
	fr1	[-]	0.000084	---	---	---	---
air drag	cd * A	[m²]	1.30	0.66	5.40	4.06	4.13

Table 10: Contribution of rolling resistance to vehicle CO_2 emissions

Mission profile	LCV (N1)	HDV 1 rigid truck (N2, N3)	HDV 2 truck/tractor & trailer (N3)	HDV 3 city bus (M3)	HDV 4 coach (M3)
Long haul		25%	30%		
Regional delivery		20%	21%		
Urban delivery		17%			
Municipal utility		12%			
City bus cycle mix				5%	
Coach					17%
CADC 1:1:1 mix	10%				

Note: HDV1 & 2 construction vehicles: estimated at 20%

Table 10 gives the results for the contribution of rolling resistance to total CO_2 emissions per vehicle category and mission profile. To assess this number in the PHEM simulations the rolling resistance coefficients have been varied and the resulting change in CO_2 emissions has been evaluated. The highest values assessed were 25 to 30% for N2/N3 vehicles in long-haul operation. Mission profiles containing higher shares of acceleration and deceleration events result in significantly lower importance of RR. For LCVs and N3 municipal vehicles (e.g. garbage trucks) the contribution of RR to CO_2 has been estimated at about 10%. The lowest influence of rolling resistance on CO_2 was 5% for city buses. These numbers can be interpreted as follows: If e.g. for a tractor-trailer combination (HDV2) in long haul operation the rolling resistance is reduced by 10%, this would give a CO_2 benefit of approximately 10%*30% = 3%.

2.3 Results for TPMS CO_2 saving potential

Table 11 gives the results for the CO_2 saving potential of TPMS disaggregated by vehicle class and mission profile. Shown numbers refer to the “high savings potential” scenario as defined in section 2.2.3. Cells containing two numbers refer to combinations of vehicle classes and mission profiles which are operated with a trailer. In these cells the upper values show the CO_2 saving potential if both truck and trailer are monitored by TPMS, while the lower values refer to the “no TPMS on trailer” case. The according numbers for CO_2 saving potential in the “low savings potential” scenario have been assumed to be 50% of the “high savings potential” (see section 2.2.3).

The highest CO_2 saving potential is assessed for N2 and N3 vehicles in long haul operation with 0.59% for small N2 vehicles and 0.48% for the N3 class in the “best case” scenario. The higher potential for small vehicle classes results from the assumption of a similar tyre pressure distribution for all N2/N3 vehicles and the lower level of recommended pressure in the small vehicle classes. The latter causes a higher sensitivity of rolling resistance on tyre pressure drop and gives a higher impact of TPMS on CO_2. If for N3 vehicles TPMS is only applied on the truck / tractor but not on the trailer, the TPMS impact on CO_2 is reduced to about 0.24%. For trucks mainly operated in other driving conditions than motorway driving (e.g. urban delivery or garbage trucks) a lower CO_2 saving potential compared to long haul conditions has to be expected. For LCVs the CO_2 saving potential of TPMS is assessed at about 0.24%. However, for LCVs it has to be mentioned that especially the underlying data on real world tyre distribution is very uncertain.

For city buses the lowest effect of TPMS on CO_2 in the HDV fleet was calculated (about 0.08% reduction). For coaches the CO_2 reduction was assessed at 0.27%. For the M2 class the TPMS CO_2 impact has been estimated based on the average of the N1 and the N2 with GVW <7.5tons classes and are hence very uncertain. However, M2 vehicles have an only very minor contribution to the total CO_2 emissions of the commercial vehicle fleet.

Table 11: Calculated reduction of CO_2 emissions due to TPMS application in the **"high savings potential"** scenario (cells with double numbers refer to vehicle segments operated with trailer, upper value = scenario TPMS on truck and trailer, lower value: no TPMS on trailer)

Vehicle class			mission profile					
			Long haul	**Regional delivery**	**Urban delivery**	**Municipal utility**	**Con-struction**	**vehicle class specific**
N1	Light Commercial Vehicles							-0.24%
N2 <=7.5t	Truck 2-axles	4x2 Rigid < 7.5t	-0.59%	-0.47%	-0.41%	-0.28%		
N2 >7.5t	Truck 2-axles	4x2 Rigid + (Tractor) 7.5-10t	-0.49%	-0.39%	-0.34%	-0.23%		
N2 >7.5t	Truck 2-axles	4x2 Rigid + (Tractor) > 10-12t	-0.40%	-0.31%	-0.27%	-0.19%		
N3	Truck 2-axles	4x2 Rigid + (Tractor) > 12-16t	-0.40%	-0.31%	-0.27%	-0.19%		
N3	Truck 2-axles	4x2 Rigid > 16t	-0.48% *-0.24%*	-0.31%	-0.27%	-0.19%		
N3	Truck 2-axles	4x2 Tractor > 16t	-0.48% *-0.24%*	-0.34% *-0.17%*			-0.32% *-0.16%*	
N3	Truck 2-axles	4x4 Rigid 7.5-16t				-0.19%	-0.32%	
N3	Truck 2-axles	4x4 Rigid >16t				-0.19%	-0.32%	
N3	Truck 2-axles	4x4 Tractor >16t					-0.32% *-0.16%*	
N3	Truck 3-axles	6x2/2-4 Rigid All Weights	-0.48% *-0.24%*	-0.31%		-0.19%		
N3	Truck 3-axles	6x2/2-4 Tractor All Weights	-0.48% *-0.24%*					
N3	Truck 3-axles	6x4 Rigid All Weights	-0.48% *-0.24%*				-0.32%	
N3	Truck 3-axles	6x4 Tractor All Weights	-0.48% *-0.24%*				-0.32% *-0.16%*	
N3	Truck 3-axles	6x6 Rigid All Weights					-0.32%	
N3	Truck 3-axles	6x6 Tractor All Weights					-0.32% *-0.16%*	
N3	Truck 4-axles	8x2 Rigid All Weights		-0.34%		-0.19%		
N3	Truck 4-axles	8x4 Rigid All Weights					-0.32%	
N3	Truck 4-axles	8x6/8x8 Rigid All Weights					-0.32%	
M2	Bus / Coach	Minibus						-0.37%
M3	Bus / Coach	City Class I						-0.08%
M3	Bus / Coach	Interurban Class II						-0.17%
M3	Bus / Coach	Coach Class III						-0.27%

Table 12 gives the summary of the results of the assessment of the TPMS CO_2 reduction potential per vehicle category in relative and in absolute values (as EU27 CO_2 reduction potential in kilotons per year) both for the "high savings potential" and the "low savings potential" scenario. The values shown have been calculated based on the allocation of the relative effects as shown in Table 11 to the absolute amount of EU27 CO_2 emissions per vehicle category given in Table 7. For the overall LCV and HDV fleet a relative CO_2 reduction potential of approximately 0.18% to 0.35% can be expected. N3 vehicles have the highest contribution to overall CO_2 emissions of the LCV and HDV transport sector. In this vehicle category about 240 to 480kt CO_2 can be reduced per year if TPMS is applied on the truck resp. the tractor only. This number increases to about 425 to 850kt per year if also the trailers are monitored on a fleet-wide level by TPMS. In the N1 class about 115 to 230kt have been assessed as annual TPMS CO_2 reduction potential. The overall

CO_2 reduction potential of TPMS on busses (M2, M3) was assessed to be rather limited.

Table 12: Summary of TPMS impact on CO_2 emissions per vehicle category

vehicle category		kt/year EU27 baseline	relative CO_2 effect within vehicle category		delta kt/year EU27 relative to baseline	
			"low savings potential" scenario	"high savings potential" scenario	"low savings potential" scenario	"high savings potential" scenario
N1		96 700	-0.12%	-0.24%	-114	-228
N2		23 506	-0.22%	-0.43%	-51	-101
N3	TPMS on truck & trailer	201 912	-0.21%	-0.42%	-424	-848
	no TPMS on trailer		-0.12%	-0.24%	-240	-480
M2		1 500	-0.17%	-0.34%	-3	-5
M3		22 726	-0.08%	-0.15%	-17	-35
total LCV and HDV	TPMS on truck & trailer	346 344	**-0.18%**	**-0.35%**	**-609**	**-1 217**
	no TPMS on trailer		**-0.12%**	**-0.25%**	**-425**	**-849**

2.4 Discussion

With a fleet-average CO_2 reduction potential of about 0.2% to 0.3% TPMS can make a non-negligible, albeit rather small contribution to reduce GHG emissions and fuel consumption in the LCV and HDV fleet.

The main uncertainties in the calculated effects result from the representativeness of data on tyre distribution in the field (especially for light commercial vehicles), the effectiveness of TPMS to reduce under-inflation and the estimation of how TPMS influences over-inflated tyres.

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3 Task 2 – State-of-the-art: TPMS technologies, suppliers, characteristics of main products

In this chapter, state-of-the-art technologies, suppliers and characteristics of TPMS (currently available and under development in the EU-27 and the USA) are identified and benchmarked.

This chapter is structured as follows: In section 3.1 background information is given on the development and use of TPMS in the past and why this is important for the state-of-the-art today. In section 3.2 the method for the technology research is discussed. In section 3.3 the current state-of-the-art as well as specific market suppliers and products are discussed. In the section 3.6, the future developments as well as market players and products are discussed. The chapter ends with conclusions and an outlook.

3.1 Background

TPMS was first adopted widely by the European market as an optional feature for high-end passenger vehicles in the 1980s and 1990s (e.g. Porsche's 959 in 1986, Renault's Scenic in 1996, Peugeot's 607 since 1999 and Renault's Laguna II since 2000).

With the enactment of the TREAD Act in the USA in 2000, the use of a suitable TPMS technology in all light motor vehicles (under 10,000 pounds) was mandated to help alert drivers of severe under-inflation events. In Europe TPMS has been made mandatory for M1 vehicles by Regulation (EC) 661/2009. Effectively, in the United States as of 2008 and the European Union as of November 1, 2012, all new passenger car models (M1) must be equipped with a TPMS. From November 1, 2014, all new passenger cars sold in the European Union must be equipped with TPMS. For N1 vehicles, TPMS is not mandatory, but if a TPMS is fitted, it must comply with the regulation .

3.1.1 Legislation

For the markets EU-27 and the USA, two types of regulation are currently in place for regulating the technical requirements for TPMS systems on light-duty vehicles:

- In the EU-27 market: Regulation No.64 of the Economic Commission for Europe of the United Nations (UN/ECE);
- In the US market: FMVSS 138.

Within regulation UNECE R64 as well as in FMVSS 138, several minimum performance criteria are listed. A short summary of these criteria is given below for the categories:

- Operation
- Malfunction
- Warning
- Pressure Range

Regulation No. 64 [UNECE, 2010][6]:

- Operation: The system shall operate from a speed of 40 km/h or below, up to the vehicle’s maximum design speed. The TPMS shall illuminate the warning signal not more than 10 minutes after the in service operating pressure in one of the vehicle’s tyres has been reduced by 20 per cent or it is at a minimum pressure of 150 kPa (=1.5 bar), whatever is higher.
- Pressure range: The TPMS shall illuminate the warning signal within not more than 60 minutes of cumulative driving time after the in- service operating pressure in any of the vehicle’s tyres, up to a total of four tyres, has been reduced by 20 per cent.
- Malfunction: The TPMS shall illuminate the warning signal not more than 10 minutes after the occurrence of a malfunction that affects the generation or transmission of control or response signals in the vehicle’s tyre pressure monitoring system. If the system is blocked by external influence (e.g. radio-frequency noise), the malfunction detection time may be extended.
- Warning: The warning indication shall be by means of an optical warning signal. The warning signal shall be activated when the ignition (start) switch is in the ‘on’ (run) position (bulb check). The warning signal must be visible even by daylight.

FMVSS 138 [FMVSS, 2005][7]:

- Operation: The TPMS must illuminate a low tyre pressure warning tell-tale not more than 20 minutes after the inflation pressure in one or more of the vehicle's tyres, up to a total of four tyres, is equal to or less than either the pressure 25 per cent below the vehicle manufacturer's recommended cold inflation pressure, or the pressure specified in this standard, whichever is higher; The TPMS must continue to illuminate the low tyre pressure warning telltale as long as the pressure in any of the vehicle's tyres is equal to or less than the pressure specified above and the ignition locking system is in the "On" ("Run") position, whether or not the engine is running, or until manually reset in accordance with the vehicle manufacturer's instructions.
- Pressure range: The TPMS low tyre pressure warning tell-tale has to fulfil above specifications at a minimum activation pressure. The minimum activation pressure is given for different tyre types and load ranges and depends on the maximum or rated inflation pressure (see table below).

Table 13: Low pressure warning telltale – minimum activation pressure [FMVSS, 2005]

Column 1 – tyre type	Column 2 – maximum or rated inflation pressure		Column 3 – minimum activation pressure	
	[kPa]	[psi]	[kPa]	[psi]
P-metric – Standard Load	240, 300, or 350	35, 44, or 51	140 140 140	20 20 20
P-metric – Extra Load	280 or 350	41 or 49	160 160	23 23
Load Range C	350	51	200	29

[6] In the case of vehicles of categories M1 up to a maximum mass of 3 500 kg and N1, in both cases with all axles equipped with single tyres.
[7] This standard applies to passenger cars, multipurpose passenger vehicles, trucks, and buses that have a gross vehicle weight rating of 4,536 kg (10,000 lbs.) or less, except those vehicles with dual wheels on an axle.

Column 1 – tyre type	Column 2 – maximum or rated inflation pressure		Column 3 – minimum activation pressure	
	[kPa]	[psi]	[kPa]	[psi]
Load Range D	450	65	240	35
Load Range E	550	80	240	35

- Malfunction: The vehicle shall be equipped with a TPMS that includes a telltale that provides a warning to the driver not more than 20 minutes after the occurrence of a malfunction that affects the generation or transmission of control or response signals in the vehicle's tyre pressure monitoring system. The vehicle's TPMS malfunction indicator shall meet either of the following requirements:
  - *Dedicated TPMS malfunction tell-tale.*
    TPMS malfunction tell-tale that is mounted inside the occupant compartment in front of and in clear view of the driver; it is identified by the word "TPMS" and it continues to illuminate the TPMS malfunction tell-tale for as long as the malfunction exists,
  - *Combination low tyre pressure/TPMS malfunction telltale*
    The TPMS flashes for a period of at least 60 seconds but no longer than 90 seconds upon detection of any specified condition after the ignition locking system is activated to the "On" ("Run") position. After this period of prescribed flashing, the tell-tale must remain continuously illuminated as long as the malfunction exists and the ignition locking system is in the "On" ("Run") position. This flashing and illumination sequence must be repeated each time the ignition locking system is placed in the "On" ("Run") position until the situation causing the malfunction has been corrected.
- Warning: Each TPMS must include a low tyre pressure warning tell-tale that is illuminated and is mounted inside the occupant compartment in front of and in clear view of the driver;

Both legislations discussed above show that TPMS on passenger cars (see definition in footnote 6 and 7) has to fulfil certain minimum performance criteria. These criteria are of specific interest when discussing the performance and particular features of currently available TPMS technologies for LCVs and HDVs (see section 3.3). As TPMS on light duty vehicles is already well regulated and widely adapted in the US and EU-27, below the same criteria, specifically the pressure range and accuracy, will be used as reference for LCVs and HDVs.

3.2 Method

The aim of this task is to make an inventory of:
- Current state-of-the-art and suppliers (section 3.3);
- Future developments with respect to TPMS and market players (section 3.4).

For this purpose, the following sources of information were used:
- Literature research (public domain information, e.g. internet);
- Questionnaire & interviews (focussed on different stakeholders involved in the application of TPMS: manufacturers of TPMS, tyres and vehicles).

Literature research
Literature from public domain sources was used to get insight into the TPMS system technology and classification. Due to the existing EU and US legislation for M1 vehicles, much literature on TPMS is focussed on this category. Since the technology for the LCV/HDV market is not intrinsically different, some of this literature is also applicable for this study.

Questionnaire & interviews
Questionnaires and interviews were used to get specific information about commercially used technologies and their market penetration.

3.3 Current state-of-the-art and suppliers

After the TREAD Act was passed, many companies responded to the new market opportunity by releasing TPMS products, often classified as [NHTSA, 2001]:
- Wheel-Speed Based – WSB (often referred to as 'indirect' TPMS) &
- Pressure-Sensor Based – PSB (often referred to as 'direct' TPMS)

For LCVs and HDVs, the same categories of TPMS exist as for the light-duty market. This section describes both systems and compares them with each other. Hereby, a more generalistic point-of-view is taken. For more specific examples of current products on the market, several systems are discussed in detail in Appendix 0. For each system, the following points are discussed and compared:
- State-of-the-art
  - Description of the working principle
  - Performance and particular features
- Suppliers
  - Main market players and relative market shares
  - Price range

3.3.1 Current state-of the-art

Description of the working principle
Direct TPMS employ pressure sensors on each tyre, either internal or external. The sensors physically measure the tyre pressure in each tyre, and, sometimes also the temperature inside the tyre, and report this information to the vehicle's instrument cluster or a corresponding monitor. These systems can identify under-inflation in any combination, be it one tyre or all four, simultaneously. Although the systems vary in transmitting options, most direct systems use radio frequency (RF) signals to send data to an electronic control unit (ECU). When a certain lower threshold is passed, an alert is given to the driver in the dashboard of the vehicle. Many TPMS products (both OEM and aftermarket solutions) can display real time tyre pressures at each location monitored while the vehicle is moving or parked.

Different pressure sensor systems exist with varying sensor positions:
- On the rim
- In the tyre
- On the valve

Most OEM-fitted direct TPMS have the sensors mounted on the inside of the rims (self-contained) or even inside the tyre. On the one hand, this provides good protection against external damage or theft. On the other hand, sensors are less easily accessible for service like battery change. In addition, the RF communication has to overcome the dampening effects of the tyre which increases the need for energy. In case of a low battery the whole sensor needs to be replaced, which requires dismounting of the tyres. Since this requires a relatively high effort, the lifetime of the battery becomes a crucial parameter. To save energy and prolong battery life, many direct TPMS sensors hence do not transmit information when not rotating (which also keeps the spare tyre from being monitored) or apply a complex and expensive two-way communication which enables an active wake-up of the sensor by the vehicle.

Most aftermarket systems have sensors mounted on the outside of the wheel (on the tyre pressure valve). Effectively, these sensors are less protected against mechanical damage, aggressive fluids and other substances as well as theft.

A schematic view of the **direct TPMS** technology is shown in Figure 8. In general a direct TPMS is a modular system and consists of the following hardware modules:

- Tyre sensor: One sensor is needed per wheel position. Each sensor sends a RF-transmitted signal to the ECU, via the RF-receiver;
- RF-receiver: The signal transmitted by the sensor(s) is received by the RF-receiver that is mounted as close as possible to the sensors;
- ECU: The RF-receiver is physically connected via an electrical communication line which transmits the data of each particular sensor. Via the ECU, sensor data is processed to enable detection of under-inflated tyres. For OEM installed TPMS, this functionality is generally integrated in the already existing vehicle ECU. In after-market applications the TPMS ECU and display are often installed as additional hardware;
- Display: For after-market TPMS a separate display is installed to inform the driver about the tyre pressure status. For OEM installed TPMS the display is integrated in the already existing display.

The direct TPMS sensor typically consist of the following hardware [Yole, 2006]:

- pressure sensor;
- temperature sensor (needed for pressure calibration);
- motion sensor: detects whether the vehicle is moving or not (influence on the data sampling frequency);
- analog-digital converter (converts the sensor signals into a digital signal for the microcontroller);
- microcontroller (computes the pressure and controls the oscillator that sends the RF signal to the ECU) +EEPROM (memory for the microcontroller program);
- system controller;
- oscillator;
- RF transmitter;
- low frequency receiver (used to determine the tyre localization).

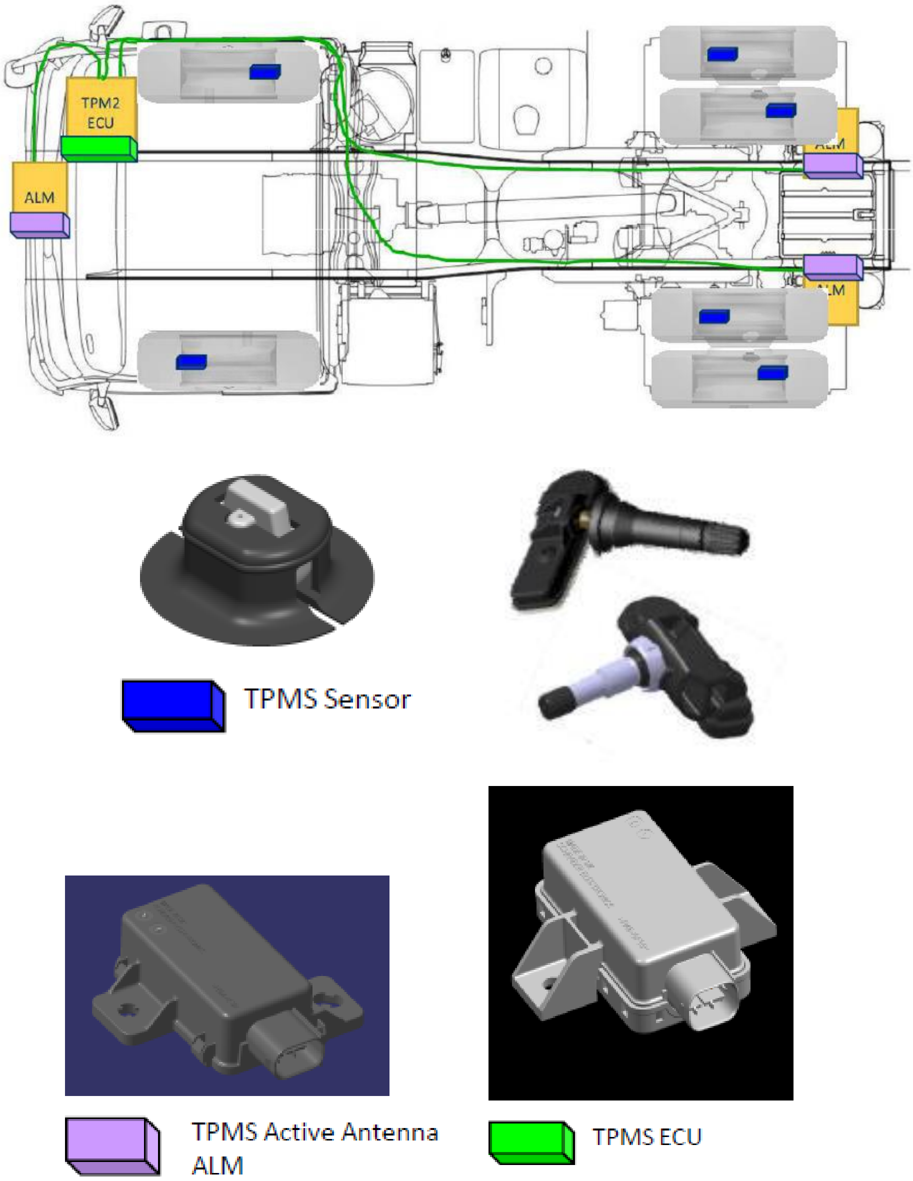

Figure 8: Direct TPMS (schematic view) [Schrader, 2013]

Technology used for passenger cars does not intrinsically differ from the technology used on LCVs or HDVs. Small differences lie in:

- increased amount of sensors and wiring harness due to increased number of wheels,
- installation of an additional ECU if existing one is not available for usage.

Indirect TPMS do not use physical pressure sensors. Instead, tyre pressures are inferred by using the vehicle's on-board systems, specifically the wheel speed sensors, to measure tyre-to-tyre differences in rotational velocities [NHTSA, 2001]. In principle, it uses the effect that an under-inflated tyre has a slightly smaller diameter (and hence a higher angular velocity) than a correctly inflated one. These differences are measurable through the wheel speed sensors of ABS (anti-lock braking system) / ESC (electronic stability control) systems. By linking these signals in an intelligent way with other signals such as the steering angle or the engine torque, the tyre pressure can be monitored indirectly. The tyre pressure is calculated in the engine control unit (ECU) based on an algorithm that calculates/compares relative tyre rolling between all wheels. Since these measurements are relative by nature, first generation systems have not been able to differentiate between two or more under-inflated tyres. Additionally, the position of the tyre under-inflation could not be displayed (no autolocation function).

Second generation indirect TPMS can also detect simultaneous under-inflation in up to all four tyres using spectrum analysis of individual wheels. This can be realized in software using advanced signal processing techniques. The spectrum analysis is based on the principle that certain resonance frequencies of the tyre/wheel assembly are highly sensitive to the inflation pressure. These oscillations can hence be monitored through advanced signal processing of the wheel speed signals. Current indirect TPMS consist of software modules being integrated into the ABS/ESC units.

After each adjustment of the tyre pressure or a change of wheels, a reset of the system is required. The reset is normally done either by a physical button or in a menu of the on-board computer..

Performance and particular features

Since **direct TPMS** applies pressure sensors to measure the tyre inflation, the pressure range easily covers the full range (0-12 bars) for LCV and HDV vehicles. It has a very high accuracy. In some cases (see STACK TPMS PRO in Annex 0), the accuracy of the pressure sensor is within the range of several millibars. The lifetime of the product largely depends on the lifetime of the battery inside the sensor. Throughout the available products in the market, the lifetime can vary largely. However, as a lower limit, TPMS manufacturers normally guarantee a battery lifetime of 3 years and some go up to 10 years. Reaction time of direct TPMS is fast and responsive within 1 minute of cumulative driving time.

Particular features of direct TPMS include:

- Autolocation: Autolocation is the ability to correctly determine the wheel position of an under-inflated tyre. Direct TPMS separately measures absolute pressure values of all tyres;
- Applicable for LCVs and HDVs: In theory, direct TPMS can be used on an unlimited amount of tyres and is therefore applicable for LCVs as well as HDVs;
- Load detection: In questionnaire responses it was found that some direct TPMS suppliers already have or are working on additional functionalities for tyre sensors, like detecting tyre load, tyre IDs and revolution count (tyre life);
- Telematics Fleet Management: several direct TPMS systems have the option of the TPMS to be used together with an online fleet management software. The measured pressure data of each wheel is hereby sent to an online cloud administered by the fleet manager. In case of tyre under-inflation, a message is sent to the driver of the vehicle, such that the tyre can be inflated again.

Indirect TPMS relies on ABS/ESC sensors to calculate the tyre inflation. The algorithms used for that are also sensitive to other external influences, like:

- road condition: temporary disabling in curvy, rough, wet, snowy, icy roads;
- driving speed: diffusion detection only possible in the range of 0 – 120 km/h;

- tyres: limited performance with snow chains, aftermarket tyres & twin-wheel tyres;
- payload.

Due to the above described influences, indirect TPMS in comparison to direct TPMS can be less accurate in certain situations. As an effect, signalling of warning thresholds cannot always be guaranteed without proper driver interaction. In the literature and product documents no exact values were found on the accuracy. However, as currently sold systems are available that comply with Regulation No.64, this indicates that a pressure drop of 20% with reference to the recommended tyre pressure can be detected by such systems. More specific information can be found for example on NIRA Dynamics indirect TPMS, TPI in Annex 0. In theory, the lifetime of indirect TPMS is unlimited, since there is no hardware (except the ECU) that can break.

Particular features of indirect TPMS include:
- Autolocation: If spectral analysis is used, autolocation is also possible for indirect systems, however still in relative measures.
- Applicable for LCVs: Currently, there are no indirect systems available that can monitor more than 4 wheel positions or twin wheels, i.e. 4 wheels on one axis. In addition, indirect TPMS is relying on ABS/ESC technology. However, according to OICA, this is no discriminating criterion as all vehicle in EU must be equipped with ABS [ABS, 2013]. Yet, a limitation in the number wheel positions makes indirect TPMS only limitedly suitable for the HDV market. For the LCV market, indirect systems can be considered as competing TPMS technology.
- Load detection: According to [ND, 2013], modern indirect systems on M1 passenger cars have sophisticated mechanisms for load compensation which are able to distinguish load differences of 250kg.
- No Telematics Fleet Management: No indirect TMPS systems have been found that offer this feature.

3.3.2 Suppliers

Main market players and their relative market shares
From questionnaires and interviews it was found that the market penetration of TPMS in the LCV/HDV market is currently very small (around 1%, see chapter 4). It is therefore very difficult to get concrete data on the main market players and their relative market share for the LCV/HDV market.

However, some important information can be used in order to make an estimate of the market size. As already stated above, indirect TPMS is only limitedly suited for the LCV/HDV market. In the following, it is thus assumed that only direct TPMS systems are relevant. An exception is made for N1 vehicles, since indirect systems could play a role there. In the EU, Schrader, Conti, and BERU/HUF are the main market players in sales of direct TPMS in passenger cars (see Figure 10) [Schrader, 2011]. Given that the technology for the LCV market is not intrinsically different to the passenger car market, it can be assumed that the same market players for M1 vehicles are also participating in the LCV market, perhaps even in the same market shares:
- Direct TPMS
  - Schrader Electronics: 56 %

- Conti: 27 %
- BERU: 14 %
- TRW: 2 %

Indirect TPMS has the potential to be applied on the European LCV market, however no exact market shares are known. While Continental supplies limited amounts of indirect TPMS, NIRA Dynamics has fully focussed on them. Other players are TRW and SRI/DunlopTech.

For the HDV market, no exact market shares are available to the contractor. A list of further market players has been made on basis of product specifications found in public sources. In Europe, WabCo is seen as key supplier by other suppliers for HDVs:

- Direct TPMS
  - Bridgestone
  - Pirelli
  - WabCo
  - Stack
  - VisiTyre
  - Pacific
  - Lear

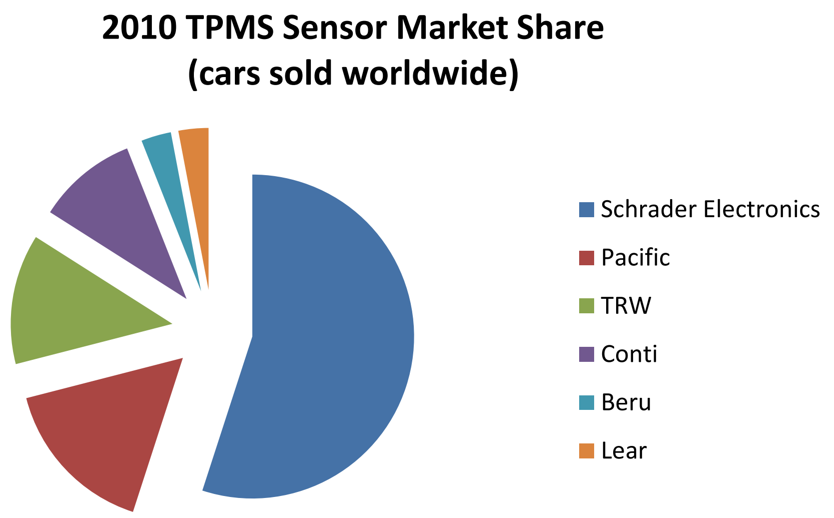

Figure 9: TPMS sensor market share in 2010 (cars sold worldwide) [Schrader, 2011]

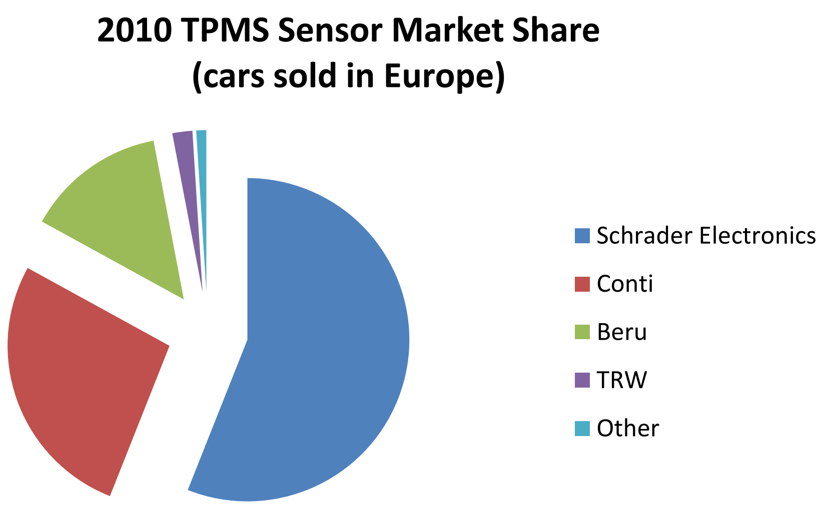

Figure 10: TPMS sensor market share in 2010 (cars sold in Europe) [Schrader, 2011]

3.4 Estimate of current and prospective costs

TPMS suppliers were asked to make an estimate of the costs of their TPMS system for different vehicle classes (N1, N2, etc.).

Questionnaire responses from manufacturers show that TPMS costs vary largely, from 5€ to 1000€, and depend on several factors, such as:

- Vehicle dimensions: number of wheels/sensors (i.e. truck only vs. truck + trailer)
- Sensor set-up: tyre-mounted vs. valve-mounted vs. rim-mounted sensors
- System fit: original equipment vs. aftermarket application
- Functions of the TPMS: extra features e.g. load detection or RFID functions
- Sales volume (scale of production)

In order to be able to carry out a cost-benefit analysis which adequately takes account of these factors (see chapter 6), an amendment to the questionnaire was sent out to acquire more detailed information on the costs (excl. VAT) of TPMS (see Annex A, Question A1.6). The EU vehicle classifications have been further split up into specific categories and axle-configurations, and hereby include factors that have an influence on the cost, like vehicle dimensions and system fit. Information on factors like TPMS function change for each system is difficult to obtain in standardized form. Therefore no differentiation has been made in this aspect.

Direct TPMS sensor costs may yet vary largely, depending on internal tyre-mounted (ca. 5 €/wheel) or external valve-mounted solutions (ca. 25 €/wheel). An indication for the bill of components for a low-end wheel module has been made in a study by [Yole, 2006]. Hereby, it was assumed that the TPMS chip integrates the sensors and system controller for data processing and transmission. It can be seen that the TPMS chip is by far the most expensive component, with a contribution of more than 50% to the bill of components.

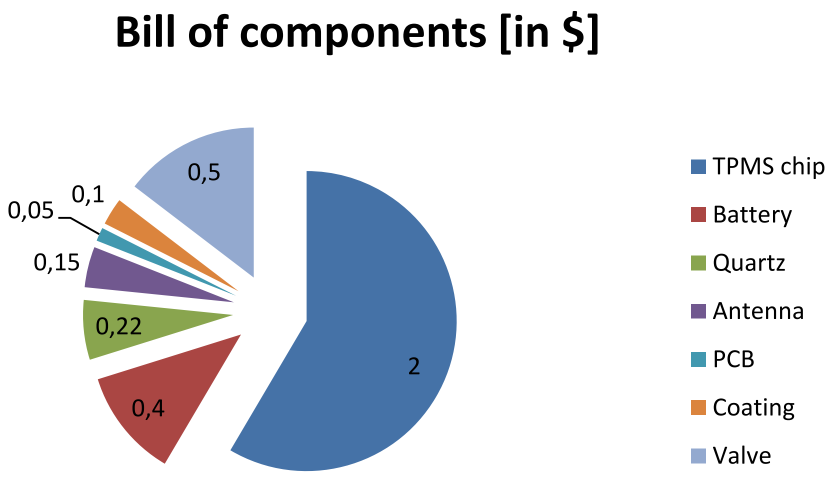

Figure 11: Bill of components for a TPMS sensor as given in [Yole, 2006]

The **"current costs"** have been estimated based on the average costs data as received through the questionnaire. Results are listed per vehicle segment in Table 14.

Table 14: **"Current costs"** for TPMS per vehicle segment (excl. VAT), truck-only (TO) and truck-trailer (TT) configuration based on average declared prices from TPMS suppliers.

		OEM-fitted		Retrofitted	
Vehicle segment		**TO [€]**	**TT [€]**	**TO [€]**	**TT [€]**
Service/delivery	**indirect**	8	n/a	n/a	n/a
	direct	44	n/a	88	n/a
Urban (delivery/collection)		164	n/a	348	n/a
Municipal utility		195	n/a	374	n/a
Regional (delivery/collection)		173	314	355	610
Long haul		185	338	365	651
Construction		234	395	422	731
Bus		174	n/a	327	n/a
Coach		209	n/a	378	n/a

A differentiation is made between OEM-fitted and retrofitted systems, as well as between truck-only (TO) and truck+trailer (TT) solutions. The following points are considered:

- Costs are expressed excluding VAT.
- For OEM-fitted systems and service delivery vehicles, differentiation is made between direct and indirect TPMS, since the price between these two can vary largely. The same differentiation is not included for other vehicle segments, since only service delivery vehicles are guaranteed to have only four wheel positions.
- Costs only consider investment costs. No additional consideration has been given to costs due to maintenance, replacement or additional factors. However, these factors are dealt with separately in the cost benefit analysis (chapter 6).

The weighted average was determined with use of Table 15. In Table 7 (chapter 2) an overview was given of the overall CO_2 contributions within Europe of different vehicle classes and mission profiles. Each mission profile is represented by a vehicle segment (e.g. regional delivery vehicle, long-haul vehicle, etc.). So, in order to determine the costs per vehicle segment, the weighted average was calculated. This is done by multiplying the cost of each vehicle type (e.g. N3 4x2 Tractor >16t) with their percentage share of CO_2 contributions within a certain vehicle segment and taking the sum over all vehicle classes. The share of CO_2 contributions within a certain vehicle segment are shown in Table 15. For example, in the long haul vehicle segment, it can be seen that the vehicle type *N3 4x2 Tractor > 16t* is responsible for 57% of all emissions. The costs of this vehicle type is therefore weighted stronger than for example a *N3 6x4 Tractor All Weights*.

Table 15: Weighting factors used to determine vehicle segment costs

			Long haul	Regional delivery	Urban delivery	Municipal utility	Construction	Bus	Coach	Service
N1	Light Commercial Vehicles									100%
N2 <=7.5t	Truck 2-axles	4x2 Rigid < 7.5t	4%	8%	29%	14%				
N2 >7.5t		4x2 Rigid + (Tractor) 7.5-10t	2%	5%	16%	7%				
N2 >7.5t		4x2 Rigid + (Tractor) > 10-12t	2%	5%	16%	7%				
N3		4x2 Rigid + (Tractor) > 12-16t	2%	5%	16%	7%				
N3		4x2 Rigid > 16t	9%	7%	24%	18%				
N3		4x2 Tractor > 16t	57%	64%			34%			
N3		4x4 Rigid 7.5-16t				1%	2%			
N3		4x4 Rigid >16t				1%	3%			
N3		4x4 Tractor >16t					2%			
N3	Truck 3-axles	6x2/2-4 Rigid All Weights	7%	6%		43%				
N3		6x2/2-4 Tractor All Weights	14%							
N3		6x4 Rigid All Weights	2%				19%			
N3		6x4 Tractor All Weights	2%				2%			
N3		6x6 Rigid All Weights					5%			
N3		6x6 Tractor All Weights					0%			
N3	Truck 4-axles	8x2 Rigid All Weights		1%		1%				
N3		8x4 Rigid All Weights					31%			
N3		8x6/8x8 Rigid All Weights					3%			
M2	Bus / Coach	Minibus						10%		
M3		City Class I						69%		
M3		Interurban Class II						21%	36%	
M3		Coach Class III							64%	

In Table 14, it can be seen that retro-fitted systems are more expensive than OEM-fitted systems. This can be explained by the fact that retrofitted systems require more installation effort. OEM solutions can be built into the vehicle before it is fully equipped, which reduces the installation effort. At the same time, it can be expected that OEM-fitted solutions are more tailored to a specific vehicle type.

For indirect TPMS, opportunity costs are not included here and might need to be taken into account. Opportunity costs can be generated for the driver due to limited performance of TPMS, for example if only OEM released (and a limited amount of aftermarket) tyres can be used with the system. The development costs are assumed to be included in the cost estimates as given by suppliers under the assumption of large scale production.

The lowest cost data from the questionnaires have been used to estimate the "prospective costs" of TPMS, which may be achieved in case of high volume production (e.g. in case of a regulated market). These are displayed in Table 16. The costs for OEM-fitted TPMS are based on 8€ per TPMS sensor/wheel plus additional 20€ supplementary costs (radio receiver unit, wiring harness, display, etc.) for each separate vehicle, effectively 20€ for TO and 40€ for TT configurations. Costs for retrofitted TPMS are based on 20€ per TPMS sensor/wheel.

Table 16: "Prospective costs" for TPMS per vehicle segment (excl. VAT), truck-only (TO) and truck-trailer (TT) configuration based on the lowest declared price assuming a high sales volume (e.g. in case of a regulated market)

		OEM-fitted		Retrofitted	
Vehicle segment		**TO [€]**	**TT [€]**	**TO [€]**	**TT [€]**
Service/delivery	**indirect**	5	n/a	n/a	n/a
	direct	20	n/a	40	n/a
Urban (delivery/collection)		54	n/a	108	n/a
Municipal utility		68	n/a	132	n/a
Regional (delivery/collection)		65	127	120	218
Long haul		70	136	129	240
Construction		78	146	144	264
Bus		50	n/a	80	n/a
Coach		52	n/a	80	n/a

Notes based on feedback received at the stakeholder workshop:
In the stakeholder workshop, it was brought to our attention by TPMS suppliers that discounts on extras (like TPMS) can be between 30 and 50%. At the same time OICA claimed that the estimates of the lowest and even the average costs are too low and do not reflect the actual costs of a TPMS system on a vehicle, which include e.g. costs of installation on the vehicle.

In deriving the final cost estimates the impact of various aspects affecting the final cost to the user have been taken into account in the following way:

- Compared to the price indicated by TPMS suppliers, the increase in vehicle price, as seen by an end-user, may be higher due to an OEM-mark-up on the purchase price from the component supplier including costs for system integration, installation on the vehicle (hardware, packaging, logistics, labour cost to install the system, validation tests, etc.), sales costs, amortization costs and an OEM profit margin.

- Costs, however, may also be affected downwards as a result of discounts negotiated by the vehicle manufacturer for purchase of large volumes of components, or by the end-user when purchasing the vehicle with a range of additional options.
- In the absence of detailed information on the two cost drivers, it has been assumed that the mentioned effects counteract, so that the price indications as provided by the TPMS suppliers can be considered a sufficiently good estimate of the additional vehicle costs due to TPMS application.

3.5 Pros and cons

The pros and cons of both systems can be summarized as:
- Direct TPMS is more expensive, able to meet homologation certification requirements and work under all conditions in the field.
- Indirect TPMS is less expensive, able to meet homologation certification requirements, yet works only with limited performance under all conditions in the field.

More specific advantages and disadvantages are discussed below.

Specific advantages/disadvantages of direct vs. indirect TPMS:
- Working principle:
  - A clear advantage of direct TPMS is the fact that it displays absolute pressure values, in comparison to relative values for indirect TPMS. Furthermore, since indirect TPMS uses the vehicles' wheel speed sensors as virtual pressure sensors, its operation requires specific tyres. There is a risk that the end user will mount non-suitable aftermarket tyres which make the indirect TPMS non-functional and even risky as the driver will think that he is still protected by the system, while he is not. NIRA Dynamics (see Annex 0) on the other hand states that "is rather the case that iTPMS work normally with almost any tire legally suitable for the vehicle. In contrast, direct TPMS with the sensors mounted on the rim do not always fit to aftermarket rims." [ND, 2013]. However, as a supplier of indirect and direct TPMS, this statement is judged misleading by Continental according to which indirect TPMS only functions with OEM released tyres.
  - Indirect TPMS requires the vehicle user to manually re-calibrate the system after each inflation. This process is non-fail-safe and creates a potential safety hazard, for example when using a defective inflation manometer, if the calibration procedure is misunderstood, or when taking into account other human errors.
- Performance:
  - Range: Direct TPMS can monitor pressure from 0 to 12bar. For indirect systems no specific values are known.
  - Resolution: Since indirect TPMS are more sensitive to external conditions, other parameters (like temperature) influence the accuracy. In comparison to indirect TPMS, direct systems are more accurate (several millibars vs. several bars). As a benefit, users of direct TPMS have the opportunity to detect earlier and more accurately if their tyres are under-inflated, providing the possibility to timely adapt the tyre inflation and thus save fuel consumption / CO_2 emissions.

  - Lifetime: For direct TPMS lifetime is determined by the lifetime of the battery of the TPMS sensor (between 3 to 10 years). Indirect TPMS in theory have unlimited lifetime.
  - Reaction time: For direct TPMS 1 minute, while indirect TPMS react within 60 minutes.
- Particular Features: Indirect TPMS is limited to single wheels. It therefore is only suited for the LCV market and limitedly suited for the HDV market.
- Costs: The costs associated to TPMS can differ largely and are discussed in more detail in the following section. Direct TPMS is more expensive than indirect TPMS when it comes to investment, replacement or additional costs:
  - Investment costs: Investment costs already differ largely, since direct TPMS requires additional hardware that needs to be installed on the vehicle. Indirect TPMS is a software solution which therefore requires less costs.
  - Replacement cost: Due to limited battery lifetime and risk of breakage (especially for external sensors), direct TPMS can generate additional replacement costs. This is not relevant for indirect TPMS.
  - Additional costs: Direct TPMS may generate extra costs for winter and summer sets of tyres or other rims. However, according to TPMS suppliers, the sensor can be used on different tyres without having to replace the sensor. Indirect systems do not require extra hardware thus asking only little installation, replacement or maintenance costs. This is also a benefit in user-friendliness.

3.6 Expected future developments and suppliers

In the previous section, the current state-of-the-art of TPMS and the suppliers for the LCV/HDV market have been documented. In this section an effort is made to include market and technology trends and how these may shape future developments and suppliers of TPMS. Use has been made of the answers to the questionnaires.

3.6.1 Trends, Threats and Opportunities

A number of trends, threats and opportunities have been indicated by stakeholders. Statements made by different stakeholders in their response to the questionnaire are listed in Table 17.

Table 17: Trends threats and opportunities indicated by stakeholders

Trends	Threats	Opportunities
Diesel price increase	-	Higher focus on tyre performance including a tyre’s rolling resistance – linked to the opportunity to save fuel
Cost pressure in fleet market	-	High number of tyre issues (compared to tractor business) leads to an awareness on how to reduce costs. TPMS offers opportunity to: • maximize tyre life (by helping to optimize tyre pressure at all

Trends	Threats	Opportunities
		times) and • optimize fuel costs / consumption.
Total cost of ownership	-	Total fleet management solutions
Tyre contracts increasing with large fleets	Fleet less observant of pressure condition	Fleet want pressure maintained within contract
Increasing focus at fleet on fuel consumption	-	Pressure a known way to affect fuel consumption
Indirect TPMS instead of direct TPMS	Smaller market for direct TPMS, especially for cost sensitive vehicle segments, high cost pressure on direct TPMS	TPMS getting more common, environmental and safety benefits, TPMS becoming cheaper and accepted by consumers
Universal programmable aftermarket direct TPMS sensors	OEMs lose original spare part business, open liability and warranty questions for the customers	Reduce the maintenance effort & cost for direct TPMS, reduce logistics effort for tyre workshops (spare parts)
Optimized tyre use, with A corresponding reduction of fuel consumption and contamination from CO2	Missed opportunity for decreasing CO_2 & other pollutant emissions as well as fuel consumption	-
Increment of the functionalities of the TPMS	-	Opportunity to know the tyre mileage to make a basic efficiency level calculation
Integration with on-board telematics systems	-	Improve fuel efficient driving (Eco-drive)
Wear reduction	-	Optimization of kilometric cost
Increased safety	-	Reduction of accidents due to tyres' misuse
TPMS fitment rates on LCV & HDV have been and are remaining very low	Fitment rates remain very low in the medium/long term. Missed opportunity for decreasing CO_2 & other pollutant emissions as well as fuel consumption.	-
More and more questions on why TPMS is compulsory in EU for M1 vehicles, but not on LCV/HDV while benefits would be much higher for those vehicles	Missed opportunity as yearly CO_2 emissions of a HDV is up to 70 times higher than of a M1 vehicle, and safety consequences of a HDV tyre failure are much higher than on a M1 vehicle.	-

Trends	Threats	Opportunities
Global warming, road traffic, fuel prices, road safety	-	Opportunity to partially mitigate the effects of those trends by implementing TPMS on LCV, HDV and Busses.
Introduction of TPMS	Absence of technology standards	-
Higher TPMS share expected due to Eco packages	-	Higher quantities, slowly decreasing price level

A number of trends that are listed several times are:

- *Cost pressure in fleet management* leads to an increased focus of fleet managers on tyre lifetime and fuel economy. Some suppliers see direct TPMS as an opportunity to meet the demand of fleet managers. Others think direct TPMS itself as too expensive to meet the market demand and thus see an opportunity for indirect TPMS. An important trend to mention here is the upcoming of onboard telematics systems, which empower full fleet monitoring.
- *Low market penetration of TPMS*. TPMS fitting rates on LCVs and HDVs are low. By some suppliers remaining low fitting rates is perceived as a threat and a missed opportunity to decrease fuel economy, CO_2 emissions and other pollutant emissions. Another supplier expects higher TPMS shares in the future and the opportunity to sell higher quantities with a resulting lower price level.

3.6.2 Future developments

Description of the working principle

In the past decades, the working principle of tyre pressure monitoring has not changed. Tyre pressure is either detected by direct or indirect measurement. This is not expected to change in the near future. Several developments can be seen with respect to system functionality. However, because this does not affect the working principle and to remain consistent in definitions, these developments are discussed under the following point.

Performance and particular features

As already stated in the previous section, load detection is already available for direct as well as indirect TPMS. No exact numbers were found on the accuracy of these features, apart from some supplier claiming that their TPMS is able to distinguish load differences of 250kg [ND, 2013]. TPMS suppliers have also indicated that this is something to further develop in the future.

In practise, over-loaded trucks are an issue [WIM, 2013]. From this perspective, mandatory fitting of TPMS could have an ancillary benefit. In principle mandatory fitment of TPMS could be motivated for the purpose of load detection. In that case it would be useful to know if there are other technical options for load detection. If so, and if these alternatives are better or cheaper, then a legislation for load detection could in the end not lead to fitting of TPMS but to fitting of other load detection systems, and would thus not have the ancillary benefit of CO_2 reduction.

In **direct TPMS**, there is an autonomous development towards increased functionality. With a sensor in every tyre, direct TPMS provides a stepping stone to further intelligent tyre applications. Information that could be interesting to store is for example:

- tyre type: summer/winter tyre,
- dates: manufacturing or last checked
- mileage
- casing life
- etc.

This could be realized with RFID technology and small storage devices.

Applying TPMS as enabler for intelligent tyre management requires that manufacturers see a business case for that. Without TPMS legislation that business case must come from reduced operating and maintenance costs. In chapter 6, aspects like operating and maintenance costs are dealt with in the cost benefit analysis

Especially in the LCV/HDV market, a shift is observed from tyre pressure monitoring of single vehicles to monitoring multiple vehicles and complete fleets. This is often integrated into a service contract with tyre manufactures (see Annex 0: Pirelli Cyberfleet/TMS and Bridgestone TPMS). The advantage of these fleet management systems is that the responsibility of proper tyre inflation is carried not only by the vehicle driver, but also by the fleet manager and fleet service contractor. Hereby, the possibility of tyre under-inflation could be reduced. It must be noted, that the problem of under-inflation is also tackled by several other (competing) technologies, e.g. remote tyre pressure and tyre condition monitoring. An example of such a system is sold by WheelRight® (www.wheelright.co.uk). In contrast to TPMS, this system is stationary and only activated when driving over it.

Battery-less TPMS is in some cases considered the next technological step for improving direct TPMS system technology to overcome the main drawback of maintenance effort and cost. Battery less systems gain their energy through electromagnetic coupling (see Annex 0). However, the market penetration of such systems is currently still low. The question remains whether this feature is cost effective. An alternative to energy generation with electromagnetic coupling is piezoelectric energy scavenging. Schrader has indicated to be working on a this.

The development of **indirect TPMS** technology that could monitor more than 4 wheel positions would eliminate a large drawback of indirect TPMS. However, no information was found on future developments for indirect TPMS in this direction.

3.6.3 Suppliers

Main market players and relative market share

At this moment, not enough market information is available to make a statement on future market players and relative market share. The main suppliers and relative market share are thus expected to remain as indicated 3.3.2.

Cost range

In an autonomous market scenario, TPMS suppliers expect the market penetration of TPMS on LCVs/HDVs to slowly increase in the following 2 to 6 years (see chapter 4). As a result of an increased scale of production, the cost of manufacturing and the price of TPMS is thus expected to reduce. However, it must be noted, that the increase of market penetration is expected to be low. Due to the small share of costs that sensors take up compared to installation costs, it is difficult to forecast an exact percentage of price reduction.

3.7 Conclusions and recommendations

The conclusions of this chapter are summarized in Table 18 (Current state-of-the-art and suppliers) and Table 19 (Expected future developments and suppliers). The information gained above shows that TPMS technology for the LCV and HDV market is mature.

Table 18: Current state-of-the-art suppliers

	Direct TPMS	**Indirect TPMS**
Description of the working principle	Direct TPMS employs pressure (& temperature) sensors - mostly battery-powered - on each tyre (internal or external) that physically measure the inflation pressure.	Indirect TPMS measures the tyre pressures by monitoring individual wheel rotational speeds and other signals available outside of the tyre itself (e.g. from existing sensors for ABS, ESC).
	The tyre pressure is reported to the vehicle's instrument cluster or a corresponding monitor by use of RF signal transmission.	The tyre pressure is calculated in the ECU based on an algorithm that calculates/compares relative tyre rolling.
	Per wheel a pressure sensor system needs to be installed, either on the rim, in the tyre or on the valve.	Indirect TPMS is purely software based. No additional sensors are used.
Performance	Range: 0 -12 bar	Range: n/a
	Resolution: 0.01 bar, +/- 0.1%	Resolution: n/a [bar], - 20%
	Lifetime: 3-10 yrs	Lifetime: unlimited
	Reaction time: 1 min	Reaction time: up to 60 min
Particular features	Autolocation	Autolocation, only if spectral analysis is used
	Applicable to an unlimited amount of wheels per vehicle	Limited to vehicles with non-twin wheels
	Load detection	Load detection
	Telematics Fleet Management	Not offered
Main market players	Schrader, Continental, BERU/HUF, TRW	NIRA Dynamics SRI/DunlopTech
Relative market share	(see Figure 10)	No data available
Cost range (p. vehicle)	35-1000 €	5-10 €
Advantage	Absolute pressure values based on pressure sensors	Low costs (production and maintenance)
	Low risk for (un)intentional misuse (no driver interaction required)	Lifetime equal to that of vehicle
	Performance not affected by road conditions, driving speed and tyres	

	Direct TPMS	Indirect TPMS
Disadvantage	High costs (production and maintenance)	Relative pressure values based on ABS sensors
	Limited lifetime of sensors and batteries	High risk for (un)intentional mis-use (driver interaction required)
		Limited accuracy due to influence of road conditions, driving speed and tyres (e.g. twin wheels)

Table 19: Expected future developments

	Direct TPMS	Indirect TPMS
Particular features	Load detection	Load detection
	Intelligent tyre (i.e. by use of RFID technology) to track info on: - summer/winter tyre, - manufacturing date, - mileage, - casing life - etc.	Extension of operating speeds
	Battery-less TPMS (i.e. by use of transponder technology)	-
	Telematics Fleet Management Tools (i.e. combining TPMS data with other data like GPS, CAN, etc.) in a single wireless telematics transmission	-

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4 Task 3 – Market penetration of TPMS for LCVs and HDVs

In this chapter, the market penetration of TPMS is studied for LCVs and HDVs. It is differentiated between retro-fitted and OEM fitted TPMS.

The chapter is structured as follows: The background and method for Task 3 is largely the same as for Task 2 and is thus not repeated in this chapter. Instead a set of research questions are formulated in section 4.1. The results are discussed in two separate sections: 4.2 gives insight into the market penetration of TPMS – current as well as projected; 4.3 provides an overview of the current split in OEM and retrofitted TPMS. When referring to the market, throughout this chapter, this refers to the LCV/HDV market unless specified differently. The chapter is closed with conclusions and an outlook.

4.1 Research questions

In the questionnaire, vehicle, tyre and TPMS manufacturers were asked to give an estimate of the current and the projected market penetration of TPMS on new vehicles. Two questions were formulated:

- Current market share of TPMS:
  What is the current market share of LCVs and HDVs that are being equipped with TPMS in the EU?
- Projected market share:
  In an autonomous market trend, in the absence of additional policy measures, how do you expect the share of TPMS on LCVs and HDVs to be on the short term (in 2 years) and on the longer term (in 6 years)?

Furthermore, suppliers were asked to give an estimation of market shares for OEM-fitted and retrofitted TPMS:

- Share of TPMS - OEM fitted and retrofit systems:
  What is the share of TPMS sold by OEM vehicle manufacturers, retailers (for retrofit applications) and/or other parties?

In the questionnaire, suppliers had the opportunity to give detailed answers on the market penetration for different vehicle categories, LCV (M2<2.61t and N1) and HDV (M2>2.61t, M3, N2,N3), see Annex 0. The results from the questionnaires were discussed with the stakeholders by telephone.

4.2 Market penetration of TPMS on new vehicles – current and projected

Supplier responses concerning the market penetration are shown in Figure 12 in a box-plot. This means that the average of all respondents is plotted as a column bar, the standard deviation is shown respectively by the upper and lower leg. One column with a specific colour displays the result for one vehicle category. The plot displays the market penetration on the y-axis [in %] at three different time instances [in years] on the x-axis, 2012 (current), 2014 (in 2 years) and 2018 (in 6 years).

Of 34 questionnaire that were sent out in total, 8 replies have been received (participation rate: 24%). However, only 4 replies have been received containing useful input for this section, 3 from direct TPMS manufacturers and 1 from a manufacturer of indirect TPMS.

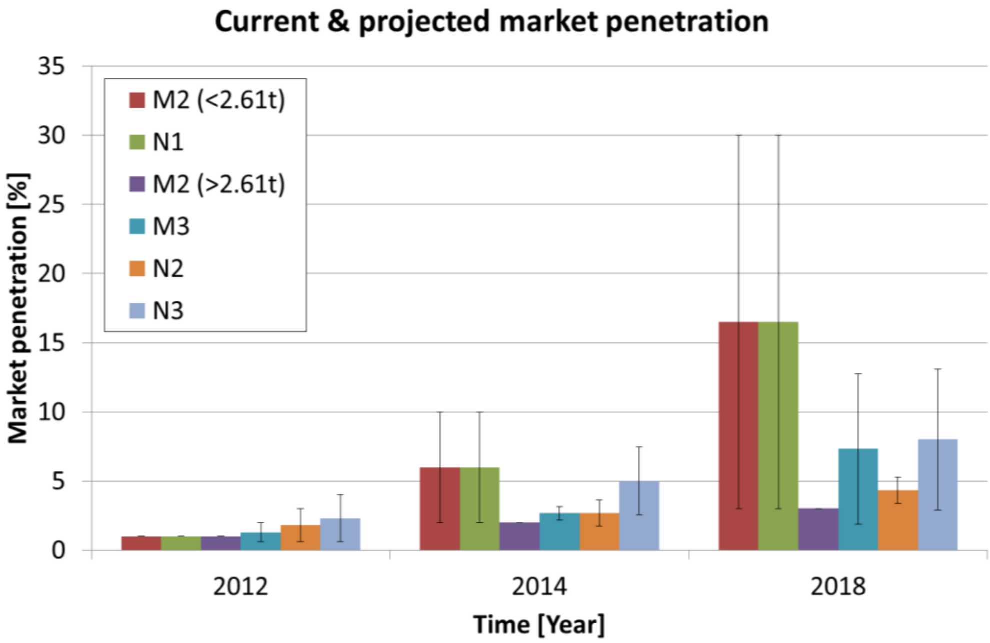

Figure 12: Current and projected market penetration of TPMS on new vehicles: Different colours indicate different vehicle categories

Looking at the results, it can be seen that the current market penetration (2012) is estimated to be low for all vehicle categories – on average between 1 and 2.3%, with responses ranging from 1 to 4%. In addition, it can be seen that the standard deviation for the 2012 estimates for M2 (<2,61t), N1, and M2 (>2,61t) vehicles are zero. This results from the fact, that only one of the four replies gave estimates for these vehicle categories. The same applies to the projected market penetration for M2 (>2,61t) vehicles in 2014 and 2018. Despite the small number of respondents, a clear trend in the responses can still be seen when looking at the projected market share for 2014 and 2018:

- In 2014, the respondents expect a market penetration of on average 2 to 6%, with responses ranging from 2 to 10%.
- In 2018, the respondents expect a market penetration of on average 3 to 16.5%, with responses ranging from 3 to 30%.

It can be noted, that especially TPMS on M2 (<2,61t) and N1 vehicles are expected to gain a large market penetration. This notion can be explained by the fact that of the two respondents to this question one party was a supplier of indirect TPMS, the other was a supplier of direct TPMS. The supplier for indirect TPMS expects market penetration of TPMS to gradually rise to about 30% of all vehicles in 2018. This, the supplier explains, has to do with an expected spill-over effect of indirect TPMS application in passenger cars to light commercial vehicles with the same configuration (i.e. ABS/ESC available, four wheel positions and no dual wheels on a single axis). Since the investment costs of this technology, which has no additional hardware, is so small in comparison of the vehicle cost, it is expected that OEMs will include this technology as a special feature in LCVs also.

In the stakeholder workshop it was stated by TPMS suppliers that actually both, direct and indirect TPMS, will profit from this spill-over effect for LCVs. As examples, van-derived M1 cars are listed such as the Renault Kangoo, Fiat Doblo, Peugeot Partner and Boxer, and the Citroen Berlingo and Jumper. These vehicles have all their passenger vehicle versions equipped with direct TPMS (as specified in Regulation 64). Since the van-derived cars are not much different in design, their LCV version could easily be equipped with TPMS should there be a demand. However, the autonomously achieved share is expected to be limited.

When only taking into account the responses from direct TPMS suppliers, the expected market penetration in 2014 and 2018 is expected to be low:

- In 2014, on average 2 to 5%, with responses ranging from 2 to 8%.
- In 2018, on average 3 to 8%, with responses ranging from 3 to 15%.

According to TPMS suppliers, the reason for the low penetration is that end-users especially in the LCV/HDV market are very cost-sensitive and at the moment do not have confidence in the potential savings in terms of fuel, tyre life, etc. Next to markets in N1 and M2 (<2.61t), the markets for TMPS in N3 and M3 vehicles are expected to grow the fastest, since there the fuel savings potential is thought to be the highest.

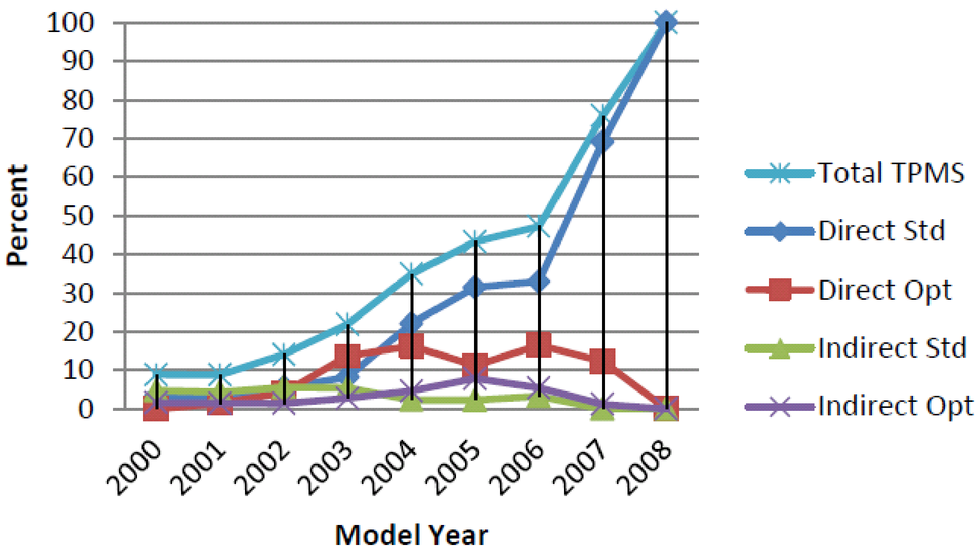

Figure 13: Effect of market regulation of TPMS on shares in passenger cars in the US [NHTSA, 2012]

The effect of a possible TPMS regulation on the market penetration can easily be compared to the regulation that was implemented in 2007 on the US market for passenger cars. Figure 13 shows an estimate of the percentage of new vehicle models sold in the US with TPMS for model years 2000-2008 (TPMS became mandatory for all new vehicles manufactured on or after September 1, 2007). These estimates are based on Ward's Automotive Yearbook data for 98 popular vehicle models. The steep rise in overall TPMS share seen in 2007 is a result of the phase-in schedule specified by FMVSS No. 138, which required that at least 20% of all model year 2006 vehicles and 70% of all model year 2007 vehicles were to be equipped with TPMS. The graph also shows that indirect systems were not very common before the standard, and that none of the included vehicle models in model year 2006-2008 were equipped with an indirect system. As mentioned above, new designs of indirect systems compliant with FMVSS No. 138 began to appear in model year 2009 [NHTSA, 2012].

4.3 Market split OEM- & retrofitted TPMS on new vehicles – current situation

On the question of how many TPMS products in the market are currently OEM-fitted and how many retro-fitted, a large variation in responses is perceived. According to two responses the market is split up in 60-90% OEM-fitted products and 40-10% retro-fitted products.

Important to note here, is that there is a non-negligible share of retro-fitted TPMS. Regulation of the market would therefore imply moving revenues from independent suppliers to OEMs.

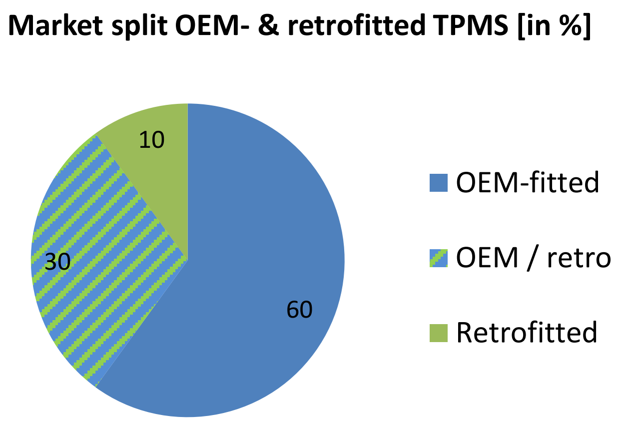

Figure 14: Market split for OEM- and retrofitted TPMS [in %]

4.4 Discussion

It must be noted that the results derived in this chapter are based solely on the questionnaire respondents. The number of respondents is small and varies between 1 to 4. Based on this information, it can be stated that the market penetration of TPMS is very low for the LCV and HDV market. As already shown in the previous chapter, several TPMS suppliers expect the market penetration to remain low unless the market is further regulated. Further developments with respect to market penetration depend on possible future policy measures to be taken.

4.5 Conclusions and recommendations

In an autonomous market development, in the absence of additional policy measures, the market penetration of TPMS is estimated to remain on average low in the near future (2014 and 2018).

Further developments are expected to differ per vehicle class:

- TPMS on M2 (<2,61t) and N1 vehicles, for example, are expected to gain significant market shares due to similarities with the mandatory fitment of TPMS on M1 vehicles.
- Next to M2 and N1 markets, the market for TMPS in N3 and M3 vehicles are expected to grow the fastest, since there the fuel savings potential is thought to be the highest.

Since OEM-fitted TPMS are on average cheaper than retro-fitted TPMS, it is important to note that mandatory fitment of TPMS might have consequences for retailers. With a market share for retrofit systems of between 10 to 40% of all TPMS sold, this effect can be significant.

4.6 References

[NHTSA, 2012] An Evaluation of Effectiveness of TPMS in proper Tire Pressure Maintenance, NHTSA, 2012

5 Task 4 – Safety

5.1 Background

The handling behaviour of road vehicles is and should be robust to tyre inflation pressure changes. However, in the case of severe tyre under-inflation the effect is not negligible and can contribute indirectly to road accidents. For Light Commercial Vehicles (LCVs) and Heavy Duty Vehicles (HDVs) the load variation is greater than for passenger cars and it is expected to be more difficult to maintain the tyre pressure at the correct value. The aim of this part of the study is to assess in which situations and to what extent the implementation of TPMS will reduce road accidents caused by LCVs and HDVs. Furthermore, it is envisaged to gain a clear understanding of the minimum technical requirements for TPMS in order to improve the current status in road safety.

5.2 Method

This study is based on calculations using tyre experimental data and advanced tyre models developed at TNO, numerical computations using state of the art – vehicle dynamics and accident reconstruction – software and an extended literature survey including published technical reports, scientific papers, publically available statistics and academic books. The source of information is indicated in the text where appropriate. The analysis is structured in four sections.

In the first section the impact of inflation pressure on tyre properties is examined using tyre measurement data and the semi-empirical Magic Formula (MF) tyre model developed at TU-Delft & TNO. The MF tyre model is the most referenced one in Science Scopus and utilized by a number of OEMs in their development procedures. In the second section the impact of underinflated tyres on vehicle performance has been studied by performing simulations using CarSim® software and analysing the results. Only one vehicle model has been considered as an example. It is the “Large European Van” found in the CarSim® database.

In the third section the potential overall safety benefit of introducing TPMS has been assessed using existing accident statistics. For calculation purposes two scenarios have been considered: an optimistic and a pessimistic one. Finally, a method for performing the cost benefit analysis is suggested and the missing inputs for realizing it are identified.

5.3 Results

5.3.1 Analysis of under-inflated tyre behaviour

Tyre properties are a function of inflation pressure. This dependence is shown quantitatively for a tyre of type 225/50 R17 in Table 20 to Table 22 [TNO Automotive, 2007]. The type of tyre chosen and the pressures for which it has been tested is representative of a medium-size van. According to our knowledge there are no extensive relevant studies publically available for HDV tyres. However, from an engineering point of view according to TNO experts the same trend also holds for LCV and HDV tyres. Quantitative deviations between different tyre sizes and types are expected.

Table 20: Tyre vertical stiffness for different inflation pressures (vertical load 7 kN) – type of tyre: 225/50 R17 [TNO Automotive, 2007]

Pressure [bar]	**Vertical Stiffness** [N/m]	**Pressure reduction %**	**Stiffness reduction %**
3.0	298300	0	0
2.5	264100	-16.6%	-11.4%
1.9	210700	-36.6%	-29.3%

Table 21: Tyre longitudinal stiffness for different inflation pressures (vertical load 7 kN) – type of tyre: 225/50 R17 [TNO Automotive, 2007]

Pressure [bar]	**Longitudinal Stiffness** [N/m]	**Pressure reduction %**	**Stiffness reduction %**
3.0	244300	0	0
2.5	236200	-16.6%	-3.3%
1.9	224800	-36.6%	-7.9%

Table 22: Tyre lateral stiffness for different inflation pressures (vertical load 7 kN) – type of tyre: 225/50 R17 [TNO Automotive, 2007]

Pressure [bar]	**Lateral Stiffness** [N/m]	**Pressure reduction %**	**Stiffness reduction %**
3.0	166000	0	0
2.5	147400	-16.6%	-11.2%
1.9	129200	-36.6%	-22.1%

Reduced inflation pressure leads to lower tyre stiffness values and non-optimal tyre-road contact which result in higher deformations and consequently increased tyre wear and reduced service life. Furthermore, according to [rubbernews, 2013] greater deflection causes larger cord and wire movement in the tyre footprint region, causing more stress and strain within the rubber matrix and more heat generation. Thus, underinflated tyres build up higher temperatures than normally inflated tyres. For example for a tyre inflated at 3.1 bar when travelling with a speed of 104 km/h the maximum tyre temperature is 60.55 ^{o}C. However, the same tyre inflated at 2.4 bar or 1.72 bar reaches maximum temperatures of 65 ^{o}C and 73.3 ^{o}C respectively. In Figure 15 the change in maximum lateral force for a specific tyre considering different operating temperatures is shown. The difference between a tyre operating at 70 ^{o}C and a tyre operating at 30 ^{o}C is almost 11 % [Masahiko, 2003]. The trend is the same but differences exist between tyre types.

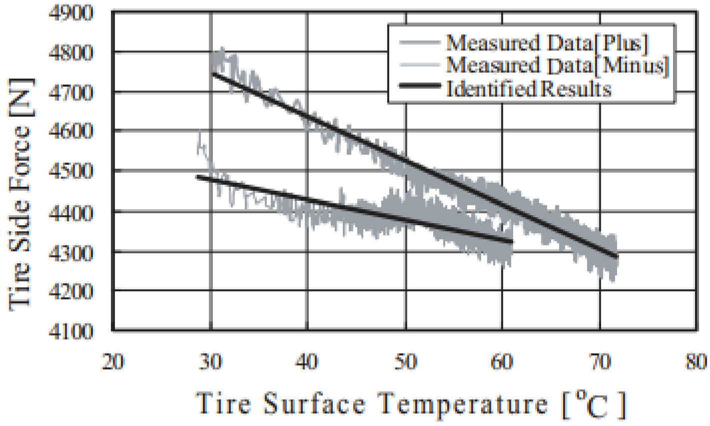

Figure 15: Change of maximum tyre side force for different temperatures [Masahiko, 2003]

Table 23 lists the reduction in expected service life for an under-inflated or over-inflated truck tyre [Continental, 2013]. Correlation between tyre wear and under-inflation was also found in another study performed for NHTSA [Thiriez, 2001]. For vehicles that have tyres with shallower tread depths (<1.6 mm) the percentage of tyres also being under-inflated by 0.5 bar or more was higher than for vehicles that have tyres with deeper tread depths (>3.2 mm). For example, for the rear right tyre the increase was from 15.3% to 25.6%. This means that one out of four vehicles with significant low tyre tread depth is also underinflated. It was also shown that rear tyres with any kind of tread depth were more likely to be under-inflated than front tyres.

Table 23: Expected truck tyre service life versus pressure [Continental, 2013]

Tyre pressure in % of the recommended value	Reduction in service life
+20%	-10%
-16%	-17%
-30%	-55%

A further point to consider is the maximum tyre-road grip which is also dependent on the inflation pressure [TNO Automotive, 2005]. In some tyres the deviation from the recommended pressure has a positive effect and can result in higher friction values. In other types of tyres the influence is negative, e.g. for a tyre with dimensions 205/55 R16 a downward deviation of 0.5 bar from the reference pressure lead to a 7% reduction of the maximum friction coefficient.

From the results we may conclude that tyre properties don’t change substantially (about 10%) for tyre pressure deviations up to 15%. For greater deviations the impact on tyre condition and behaviour is noticeable.

5.3.2 *Analysis of vehicle performance with underinflated tyres*

To compute the effects of tyre under-inflation on LCV and HDV handling performance the “Large European Van” model from the CarSim® Mechanical Simulation software database has been used (Figure 16).

Figure 16: Reference vehicle model

Braking performance
The performance of a vehicle under hard braking (near wheel lock up) is directly related to the maximum friction coefficient. For tyres with reduced grip at reduced inflation pressure the braking distance will be affected negatively. Table 24 summarizes the loss in braking performance for a vehicle with an initial speed of 50 km/h under hard braking for two different road conditions. It is assumed that all tyres are under-inflated to such an extent (-20%) that it results in a 7% loss on maximum grip. For less intense braking conditions intermediate results are to be expected.

Table 24: Braking distance for two different road conditions and initial speed 50 km/h

Speed: 50 km/h	**Braking distance under hard braking [m]**			
	Tyres at reference pressure	*Under-inflated tyres*	*Difference*	*Change [%]*
Wet road: $\mu = 0.5$	19.29	20.74	1.45	7.5%
Icy road: $\mu = 0.3$	32.15	34.57	2.42	7.5%

Handling performance
The handling performance of the van has been studied using Carsim® software for three different vehicle configurations
a) Van with properly inflated tyres
b) Van with front tyres underinflated by 20%
c) Van with rear tyres underinflated by 20%.
In all configurations a 1000 kg load placed 2.5 m from the front axle has been assumed. Two driving scenarios have been considered to evaluate the response of the van.

In the first driving scenario the van moves with an increasing velocity along a circular path of constant radius (160 m). At a certain speed-lateral acceleration the vehicle becomes unstable. The maximum lateral acceleration at which the van becomes unstable is shown in Table 25. Only in case of under-inflated rear tyres a reduced performance is observed.

In the second driving scenario the vehicle moves with a constant velocity along a circular path with downhill grade of 3%. Suddenly the driver applies braking which causes a 0.45g deceleration. The maximum speed before the van becomes unstable is different for the three configurations. The results are shown in Table 26.

Performance is reduced in both cases, with the largest effect in the case of under-inflated front tyres.

Table 25: Maximum lateral acceleration before vehicle becomes unstable while cornering

Maximum lateral acceleration while cornering		
	[g]	*Change [%]*
Tyres properly inflated	0.69	0
Front tyres under-inflated (80% of nominal pressure)	0.72	4.1
Rear tyres under-inflated (80% of nominal pressure)	0.64	-7.2

Table 26: Maximum speed to negotiate a turn while braking in an inclined road

Maximum speed while cornering and braking on an inclined road		
	[km/h]	*Change [%]*
Tyres properly inflated	84	0
Front tyres under-inflated (80% of nominal pressure)	81	-3.5%
Rear tyres under-inflated (80% of nominal pressure)	*82*	-2.3%

The results presented are in line with the study [NHTSA, 2004] conducted by the National Highway Traffic Safety Administration. In that study an experimental investigation of the impact of tyre under-inflation on the handling performance of a vehicle was conducted. Deviations from the presented results are expected for different tyre types, vehicle configurations, load distributions and other parameters that affect vehicle dynamics.

5.3.3 Potential safety benefits

In order to identify the potential safety benefits by the introduction of TPMS in LCV and HDV categories the following steps have been undertaken:

1. Collection of statistical data regarding the share of poor tyre maintenance as a contributing factor in accidents. Since no detailed data are collected for LCVs and HDVs the data concern all vehicle categories.
2. Collection of statistical data regarding the driving behaviour (over speeding) and the tyre condition.
3. Collection of statistical data that show the increased accident risk in case of poor tyre maintenance.
4. Collection of statistical data regarding the share of LCVs and HDVs accidents that are the result of loss of attention, braking and loss of control. Accidents that are due to loss of attention can’t be correlated to the tyre condition. Furthermore, the effect of tyre condition on the braking performance is not consistent for all tyre types.
5. Collection of statistical data regarding the share of LCVs and HDVs accidents that are due to loss of control and lead to occupants fatalities. Identification of factors (speed, road surface condition) that increase the accident risk (yaw instability, rollover, off road).

6. Collection of statistical data regarding the share of LCVs and HDVs with underinflated tyres.
7. Collection of statistical data regarding the effectiveness of TPMS in maintaining the correct tyre pressure.
8. Estimation of share of accidents versus speed range based on empirical studies.
9. Development of a pessimistic and optimistic scenario regarding the share of single vehicle accidents that will be prevented due to proper tyre maintenance.
10. Calculation of potential benefits including reduced external costs.

According to a survey [TÜV, 2003] carried out by TÜV tyre defects were a contributing factor for 9.2% of the passenger car accidents. Out of the total tyre related accidents 36.8% was attributed to wrong/insufficient maintenance (low inflation pressure, low tyre tread depth, over aged tyres). Thus, insufficient tyre maintenance is a contributing factor in 3.4% of the total fatal accidents. In a study for NHTSA [NHTSA, 2012a] the analysis showed that in 9% of crashes one or more vehicles experienced tyre problems in the pre-crash phase. Approximately, 10% of those were underinflated by more than 25 percent of the recommended pressure. In 26.2% of the cases the tyres had very low tyre tread depth (<1.6 mm) and about 8% had tyre tread depths between 1.6-3.2 mm. In reference [Lahti, 2007], which covers the period between 1991 and 2005 for Finland, tyre related accidents accounted - on average - for 16% of the total fatal accidents. The most common tyre defects identified were:

- Unsuitable tyres (33,5%)
- Worn tyres (44 %)
- Under-inflated tyres (15%)

Thus, according to this reference insufficient tyre maintenance is a contributing factor in 11.7% of the total fatal accidents. Furthermore, in a van related study (small scale) performed in UK [TRL, 2003] tyre defects were identified as a contributing factor in 2.7% of the fatal accidents caused by vans. As analysed in section 5.3.1 worn tyres and under-inflation are highly correlated. Based on the data presented an estimation is made that in 3.4%-11.7% of the total fatal accidents insufficient tyre pressure maintenance is a contributing factor.

Findings show that aggressive driving behaviour and tyre condition are correlated. According to [Lahti, 2007] in fatal accidents, drivers who broke the rules (e.g. speed limits) had on average more worn-out tyres than drivers who complied with the rules. Their tyres were also more worn out than on average in cars and vans driven on Finnish roads. More specific, of vehicles with illegal - less than 1.6 mm - tyre tread depth about 70% had a rule-breaking driver, while the corresponding figure for at least 3.5 mm tyre tread depth was 44%.

According to [NHTSA, 2012a] out of the tyre-related crashes, half (50%) involved a single vehicle while out of crashes that did not involve tyre-related factors, only 31% involved a single vehicle. Thus single vehicle accidents and tyre related issues are highly correlated. When tyres are underinflated by 25% or more, tyre problems are three times as likely to be cited as critical events before a crash. Furthermore, when tyres have less than 1.6 mm tread depth they are three times as likely to be cited as critical events before a crash.

There are a large number of HDV and LCV accidents that happen at road intersections (27%), in queues (20.6%) or after a lane departure (19.5%) [IRU, 2007]. The first two types of accidents occur when the vehicle is following a rather straight trajectory and involve mainly braking actions. It is known from statistical data that during emergency braking situations only a small number of vehicles utilize the maximum tyre-road friction coefficient (<5%) [Hannawald 2012]. In the third type of accident a single vehicle departs the road, due to either driver inattention, drowsiness, or other incapacitation, and then impacts something. Due to the fact that during braking different tyre types behave differently under different road conditions it is difficult to assess - within this framework- the impact of tyre condition on these types of accidents for LCVs and HDVs.

Loss of control accidents occur frequently in freeway entrance/ exit ramps and curves. In a truck related study [TNO, 1997] it was found that about 20% of heavy truck accidents are due to loss of control. 61% of heavy truck rollover crashes are attributed to speed through curves, 26% are caused by the vehicle running onto the soft shoulder and 10% are related to evasive manoeuvres. In [Volvo, 2013] it was stated that for accidents with heavy trucks causing serious to fatal injuries of truck occupants 15% out of them is due to instability (rollover and yaw instability accidents) and 35% due to driving off road (with and without rollover). In a further study [Kharazi, 2008], which was based on the Large Truck Crash Causation Study, it was concluded that negotiating a curve was the main critical manoeuvre leading to loss of control. Downhill grade and braking on wet road conditions were found to be highly correlated factors to accident risk. More specific, a dry road surface was the dominant condition in truck accidents; however, the percentage of wet surface condition showed an increase from 16.2% for all trucks in traffic accidents to 22.2% for trucks with loss of control. This represents a 37% increase which was expected due to the fact that low friction reduces the maximum speed for which instability occurs. A low friction surface contributes to more than 50% of yaw instability of trucks. Roads with downhill grade (> 2%) are associated with about one-third of the trucks with loss of control, while this figure for all trucks involved in traffic accidents is only 19.4%. Again downhill grade reduces the maximum speed for which instability occurs. In a European study [IRU, 2007] performed in 2007 it was found that single truck accidents accounted for 7.4% out of the total truck accidents. 11.3% of the accidents took place after an overtaking manoeuvre. Based on the same statistics about 21.6% of the accidents were the result of too high speed and 9.9% due to loss of friction (handling at the limits of tyre –road forces). Based on these findings it is estimated that the percentage of road accidents involving LCVs and HDVs which are caused due to high speed and lead to loss of control is about 20%. It is difficult to estimate in how many of these tyres were a contributing factor, since no detailed statistics are being kept. According to [Leduc, 2009] more than 75% of the trucks on the roads in the European Union have tires which are, on the average, 12% underinflated. This will be considered as the pessimistic scenario. As an optimistic scenario we will consider that in all speed related accidents tyres were underinflated.

Having implemented a TPMS doesn't necessarily mean that tyre under-inflation is completely prevented. Considering results of section 2.2.2 and [NHTSA, 2012b] the introduction of TPMS has led to a 55.6% reduction of vehicles with one or more severely underinflated tyres. This is interesting proof that in case of mandatory fitment of TPMS it is not guaranteed that 100% of tyres will be correctly inflated.

This will be considered as the case for the pessimistic scenario (consistent with the “low savings potential” scenario developed in chapter 1). In the optimistic scenario we will assume that TPMS completely prevents under-inflation (consistent with the “high savings potential” scenario developed in chapter 1).

To estimate the reduction in accidents due to the introduction of TPMS we base our analysis on the findings of [Monash, 1999] and [NHMRC, 1997]. According to these references in the speed range between 100-110 km/h 40% of the accidents are due to loss of control, while in the range 70-90 km/h that is only the case for 16% of the accidents. Furthermore, the relationship between over-speeding (with respect to speed limit) and accident involvement is shown in Figure 17.

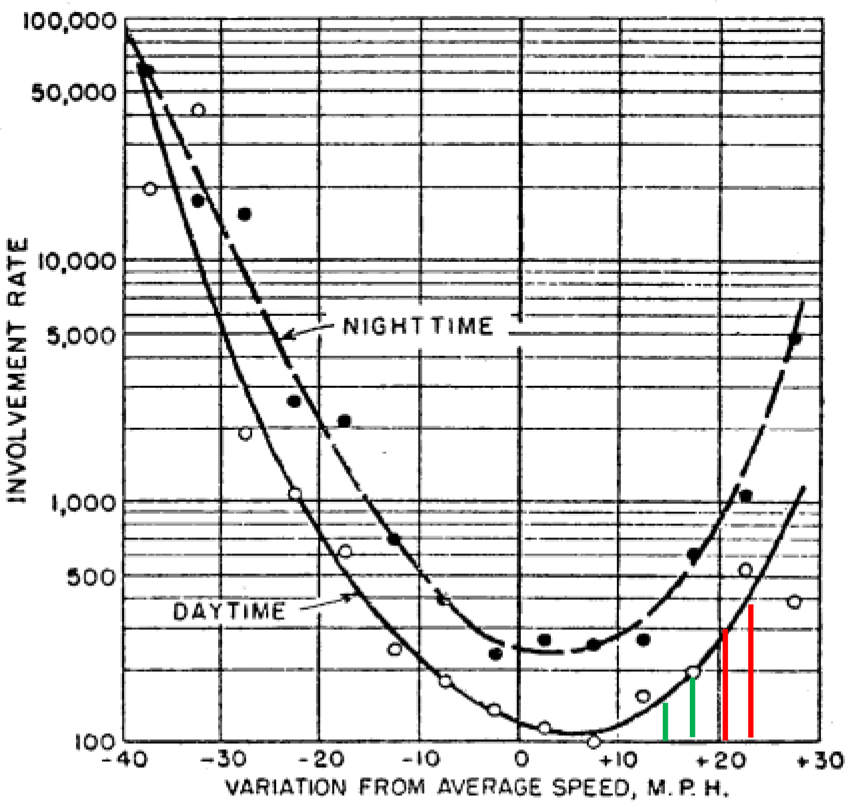

Figure 17: Over-speeding and accident rate involvement [NHMRC, 1997]

Based on the results of section 5.3.2 we expect that vehicles with properly inflated tyres improve their stability, leading to loss of control occurring at higher speeds (approximately 5 km/h) compared to vehicles with severely under inflated tyres. However, at very high speeds even a proper tyre inflation pressure will not prevent the accident. Therefore, we develop two scenarios. We consider the influence of tyre behaviour on reducing road accidents at high speeds to be limited in the optimistic scenario a) up to +40 km/h overspeed with respect to the optimal speed and in the pessimistic scenario b) up to +30 km/h over speed with respect to the optimal speed. Based on this assumption we assume that in the optimistic case the tyre condition is a contributing factor in 30% of the accidents while in the pessimistic scenario only in 5%. Under these assumptions we expect in the optimistic scenario approximately a 20% reduction of speed related accidents and in the pessimistic a 7% reduction.

Table 27: Expected accident reduction with the introduction of TPMS on LCVs and HDVs

	Reduction due to correct tyre inflation	TPMS effective-ness	Reduction of tyre & speed related LCV and HDV accidents	Share of tyre & speed related LCV and HDV accidents	Reduction of total LCV and HDV accidents
Pessimistic scenario	7%	55%	4%	20%	0.8%
Optimistic scenario	20%	100%	20%	20%	4%

This conclusion is in line with the conclusions drawn in [TRL, 2003]. However, no details are given in that reference with respect to the methodology used to derive this conclusion.

5.3.4 *Cost-benefit analysis*

Due to the complexity of the problem and the lack of reliable data, we estimate, as an example, the benefit of introducing TPMS only for the HDVs category and by taking into account only the reduction in single vehicle accidents. The total benefit is expected to be higher if we would include also other types of accidents. However, this will require a more thorough analysis which was not possible on the basis of available data and within the limitations of this study. It is proposed to conduct the cost-benefit analysis and to use the average cost per injury type according to reference [UniCologne, 2007]. A schematic of the proposed procedure is shown in Figure 18. However, most of the required inputs are missing because relevant statistics are not being kept. Therefore, the benefit will be estimated as an example by considering only parts that can be estimated (denoted with red colour).

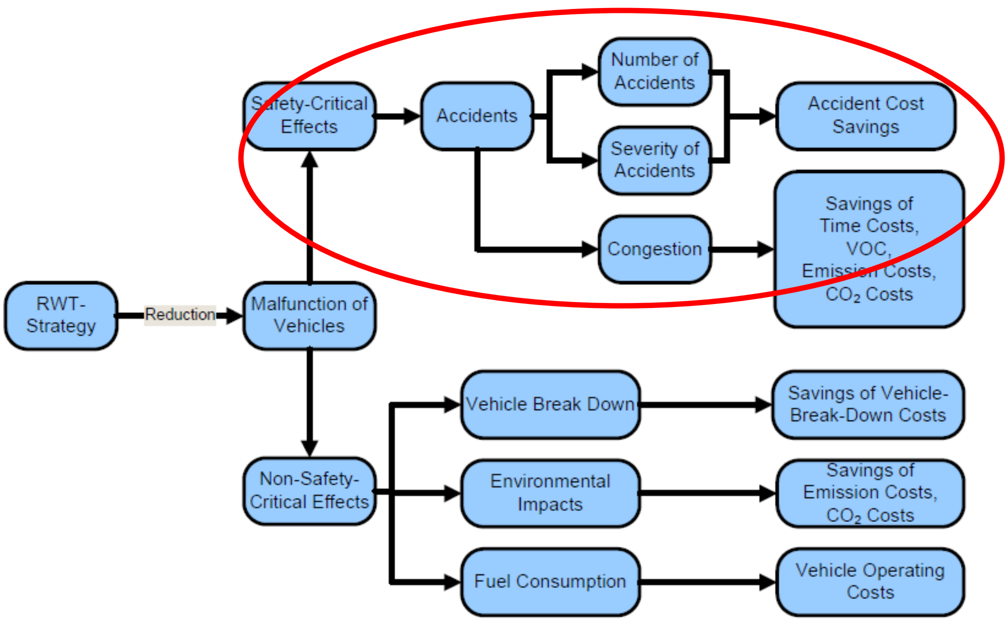

Figure 18: Cost-benefit analysis [UniCologne, 2007]

The cost of road accidents is reported in Table 28 [UniCologne, 2007]. According to [Volvo, 2013] only 15% to 20% of the road users that are seriously injured or killed in accidents involving heavy trucks are truck occupants. Furthermore:

- About 50% are single vehicle accidents with only one truck involved.
- About 45% of the accidents include a rollover, either in the initial phase, or later as a consequence of specific driving manoeuvres.
- The majority of the accidents causing injury to truck occupants occur in rural areas, on rural roads and on highways, i.e. roads with speed limits of 70 km/h or higher.

Table 28: Unit cost per road accident [UniCologne, 2007].

Road accident	Cost €
Death	1,000,000
Severe injury	135,000
Slight Injury	15,000
Congestion	10,000

According to EU statistics [EC, 2013] in a period of one year 309 drivers and passengers of HDVs and 275 drivers and passengers of LCVs were killed. Furthermore, according to [Volvo, 2013] 50% of the truck drivers killed or severely injured are involved in single vehicle accidents. This means that approximately 292 HDV and LCV occupants were killed in a period of one year due to single vehicle accidents.

Assuming, as a worst case estimate, that all fatal single vehicle accidents are tyre and speed related, and taking account of external costs as listed in Table 28, the estimated external cost in this case is 292 M€ per year. An accident reduction of 4 to 20% will then lead to a reduction of external costs of 11 to 58 M€. This estimate for the societal cost reduction due to improved safety as a result of TPMS should be considered indicative, and can be used to check whether safety benefits of TPMS can significantly affect the overall societal cost effectiveness. The estimated costs are optimistic in the sense that they are based on the assumption that all fatal single vehicle accidents are speed and tyre related. At the same time only one type of accident has been quantified, while it is likely that TPMS may also reduce other types of accidents and thereby lead to lower numbers of casualties and injuries (car occupants as well as unprotected road users) and lower congestion costs.

5.4 Conclusions

In this task an analysis has been conducted with respect to accidents that involve LCVs and HDVs and that are the result of not proper tyre inflation maintenance. Tyre under-inflation has been found to be significantly important in road safety for deviations of 15% and more with respect to the nominal inflation pressure. However, it must be stressed that different tyre types show different sensitivity to under inflation. In any case, the impact of under inflation on the tyre service life and tread wear has been found significant.

Tyre under-inflation does not affect the braking performance of all types of tyres and for all road surface conditions alike. Tyre condition and tread depth is more significant in wet rather on dry surfaces. Calculations show that proper tyre inflation can increase the stability of a LCV by approximately 5 km/h. However, this depends also on the inclination of the road, the type of the vehicle and the number of underinflated tyres. More detailed conclusions require a case to case analysis.

Based on various studies, speed related accidents account for almost 20% of HDV accidents. Given the impact of tyre pressure on the speed at which loss of control occurs, a reduction in the number of speed and tyre related accidents due to proper tyre pressure conditioning should be expected and has been calculated. More precise calculations can be made in case a more detailed analysis per vehicle configuration is performed. Finally, an indicative cost benefit analysis has been conducted based on the expected reduction of speed related accidents of HDVs and LCVs in the EU.

Severe tyre under-inflation contributes in accident causation of LCVs and HDVs. A pressure deviation of more than 15% results in noticeable change of tyre properties (more than 10%) which affects the wear rate of the tyre and the braking and handling performance of the vehicle. The increased heat generation due to tyre under inflation further reduces the maximum lateral tyre force. The trend among different tyre types is more or less the same, but significant quantitative deviations exist. Furthermore, the impact of tyre pressure on the stability of the vehicle depends on its configuration (number of axles, number of tyres, trailer, existence of ESP). Thus, in order to perform a complete analysis of the road safety benefit a more detailed analysis is necessary.

Properly maintaining the tyre inflation pressure can reduce the number of speed and tyre related accidents by 4% to 20%. A societal cost reduction of 11 to 58 M€ per year is estimated in the EU as a consequence of avoided fatalities resulting from single vehicle accidents by HDVs. This may be considered a lower bound for the possible monetised safety benefits of applying TPMS to LCVs and HDVs.

5.5 References

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6 Task 5 – Current & prospective cost effectiveness of TPMS technology for LCVs and HDVs

The principle research questions to answer in this chapter concerns the cost-effectiveness of TPMS for LCVs and HDVs. The cost-benefit analysis is carried out from a societal as well as an end-user perspective.

The chapter is structured as follows:
- In section 6.1 reference is made to some recent cost-benefit analyses on heavy duty vehicles that have been performed by order of the European Commission.
- Section 6.2 and 6.3 describe the method that is used and assumptions that are made in more detail. The approach largely builds on the findings of previous chapters.
- The results of the cost-benefit analysis are discussed in section 6.4 for a defined reference case with varying oil prices. In addition sensitivity analyses are carried out to assess the impact of uncertainties in data and assumptions in the approach on the estimated cost-effectiveness of TPMS.
- The chapter is closed with discussions, recommendations and conclusions.

6.1 Recent studies on GHG emissions reduction in HDVs

In recent years three important studies have evaluated the greenhouse gas (GHG) reduction potential and marginal abatement costs for different technologies that may be applied to Heavy Duty Vehicles. These studies are:

[Ricardo, 2011]	Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicle – Lot 1: Strategy
[TIAX, 2011]	European Union Greenhouse Gas (GHG) Reduction Potential for Heavy-Duty Vehicles
[CE, 2012]	Marginal abatement cost curves for Heavy Duty Vehicles

TPMS has not been part of these evaluations. The cost-effectiveness of TMPS for HDVs will be assessed in this chapter using a similar methodology as applied in the above-mentioned studies to other CO_2 reduction options. Also relevant data on reference vehicles from the above studies are used in the assessment presented here.

6.2 Method

The cost-benefit analysis is carried out from a societal perspective as well as an end user perspective. In the cost-benefit analysis from the **societal perspective** the following costs and cost savings are taken into account:
- Costs:
  - additional investment costs for TPMS (price excl. applicable taxes),
- Costs savings:
  - fuel cost savings (based on fuel price excl. applicable taxes) and
  - costs and savings associated with a reduced amount of maintenance:
    - extended lifetime of tyres
    - optimized inflation frequency
  - cost savings associated with less service disruptions:

    - reduced roadside tyre breakdown
  - cost savings associated with a reduction of external costs:
    - reduced amount of accidents (fatalities, injuries, congestion)
    - reduced amount of emissions

A societal discount rate of 4% is used. The result for the societal perspective is expressed as marginal GHG abatement costs in Euros per tonne of avoided CO_2-equivalents [€/tCO_2].

In the cost-benefit analysis from the **end-user perspective**, the following costs and cost savings are taken into account:

- Costs:
  - additional investment costs for TPMS (price incl. applicable taxes),
- Cost savings:
  - fuel cost savings (based on fuel price incl. applicable taxes) and
  - cost and savings associated with a reduced amount of maintenance:
    - extended lifetime of tyres
    - optimized inflation frequency
  - cost savings associated with less service disruptions:
    - reduced roadside tyre breakdown

An end user discount rate of 8% is used. The result for the end-user perspective will be presented as change in the total cost of ownership (ΔTCO) of the vehicle, as well as in the payback period for the investment in TPMS.

The list of cost-savings considered above might not be complete. Other external cost savings could also be important to take into account, e.g.:

- cost savings due to noise decrease (as effect of proper tyre inflation),
- reduced raw material usage (as effect of extended tyre carcass lifetime) and chance for tyre retreading

For reasons of scope as well as lack of available data, these aspects have not been included in the assessment. Also these cost impacts are expected to be smaller than the impacts of the aspects that are included.

The effects associated with the introduction of TPMS are quantified by assessing the Net Present Value (NPV) of the costs and the cost savings. Sensitivity analyses will be carried out to explore the impact of variations in the fuel price (as function of oil price), and of different scenarios for the cost of the technology (initial investment). The assessment is made for the following vehicle categories:

- LCV categories: 1 mission profile per vehicle class.
- HDV categories: 7 mission profiles will be considered.

For all categories account is taken of typical values with respect to fuel consumption (in relation to vehicle type and typical mission profile), vehicle lifetime and annual mileage. This information is available through [TIAX, 2011].

As stated in the title of this document, the aim of the study is to evaluate the potential of TPMS as a means to reduce LCV and HDV fuel consumption and CO_2 emissions. For this reason, the cost-benefit analysis is calculated for two different cases:

- A first analysis is performed on the basis of investment costs and fuel cost savings only.

- A second analysis is performed based on the investment cost and the full costs savings potential of TPMS (i.e. including costs changes due to extended lifetime of tyres, optimized inflation frequency, etc.)

In both cases, a sensitivity analysis is carried out based on a best case and a worst case estimate of investment costs and fuel savings potential.

The assumptions and substantiations for the cost-benefit analyses are provided in the next section 6.3.

6.3 Quantification of investment costs and various cost saving potentials

6.3.1 Characteristics of vehicle segments

The average vehicle lifetime, annual mileage as well as fuel consumption for different vehicle segments is provided in Table 29. The same estimates are used as in [TIAX, 2011]. The lifetime of a technology is an important factor in the calculation the annuity of costs. The lifetime of TPMS – the full period in which it is used and thus its benefits are valid - effectively depends on three factors:
- The vehicle lifetime,
- The tyre lifetime and
- The TPMS sensor lifetime.

In the following tables, the lifetime of these three components are compared to get an insight into the limiting factor for TPMS. Estimates for the vehicle lifetime are taken from [TIAX, 2011], see Table 29.

Table 29: Estimates for vehicle lifetime, annual mileage and fuel consumption [TIAX, 2011]

Vehicle segment	Vehicle lifetime [years]	Annual mileage [km/year]	Fuel consumption [l/100 km]
Service/delivery	10	35000	16
Urban (delivery/collection)	19	40000	21
Municipal utility	17	25000	55.2
Regional (delivery/collection)	12	60000	25.3
Long haul	8	130000	30.6
Construction	19	50000	26.8
Bus	14	50000	36
Coach	12	52000	27.7

Estimates for the lifetime of TPMS sensors and tyres have been determined through expert opinions of suppliers. The lifetime of a tyre depends on the type as well as the mission profile of the vehicle. In [Weissman, 2003], a comparison is provided for the limited warranty of certain tyres and ranges from 50,000 to 80,000 miles, respectively 80,000 to 130,000 kilometres. Expert opinions underlined this information and gave some further insights as provided in Table 30.

Table 30: Tyre lifetime for different vehicle segments and tyre positions, based on an expert opinions

Vehicle segment	Tyre lifetime [km]	Average [km]
Service/delivery	17.5” Steer: 80,000 17.5” Drive: 129,000	104,500
Urban (delivery/collection)	Urban 295/80R22.5 Steer: 142,000 Urban 295/80R22.5 Drive: 140,000 Urban 315/80R22.5 Steer: 101,000 Urban 315/80R22.5 Drive: 109,000	121,500
Municipal utility	Municipal 295/80R22.5 All pos: 21,000 Municipal 315/80R22.5 All Pos: 23,000 Retread 315/80R22.5 All Pos: 22,000	22,000
Regional (delivery/collection)	Regional 315/80R22.5 Steer: 194,000 Regional 315/80R22.5 Drive: 207,000 Retread 315/80R22.5 Drive: 191,000	200,500
Long haul	Longhaul 315/70R22.5 Steer: 247,000 Longhaul 315/70R22.5 Drive: 237,000 Retread 315/70R22.5 Drive: 203,000	242,000
Construction	Construction 315/80R22.5 Steer: 112,000 Construction 315/80R22.5 Drive: 89,000	100,500
Bus	Urban 275/70R22.5 All Pos: 92,000	92,000
Coach	Regional 295/80R22.5 All Pos: 100,000 Regional 315/80R22.5 All Pos: 87,000	93,500

Based on expert opinion, a tyre should be retreadable at least 1 time. On average, tyres for long haul vehicles are retreaded two-times, tyres for distribution and construction vehicles can even be retreaded three-times (dependent on the size). For city busses it is common to have 3 retreads. It is recommended to replace any tyres in service older than 10 years from the date of manufacture [BS, 2008].

Taking into account the average tyre lifetime in kilometres from Table 30 (where no data is available for retreads), assuming that a retread adds another tyre lifetime, and dividing the tyre lifetime including retreading by the annual mileage per vehicle segment, yields the tyre lifetimes in years for different amounts of retreads as indicated in Table 31. For comparison, the TPMS lifetime is listed in the column to the right. The lifetime of direct TPMS is largely determined by its battery lifetime (3 to 10 years). For the purpose of this assessment the average lifetime is assumed to be 7 years. For battery-less solutions as well as for indirect TPMS, this lifetime is potentially unlimited and is thus not the deciding lifespan for the cost-benefit analysis.

In bold is shown the tyre lifetime of each number vehicle segment, if the average number of retreads are taken as discussed above (construction, municipal, busses and coaches: 3x, long haul: 2x, service, urban and regional: 1x). Tyre lifetime is in some cases below and other cases above 7 years. This shows that in some cases TPMS lifetime is decisive, while in other cases it is the tyre lifetime. Supplier interviews have stated that TPMS sensors can survive several retreads and tyre change. However, it was also noted by OICA, that extra costs can be generated because TPMS sensors are often destroyed when tyres are changed or additional sensors are equipped on winter tyres.

Table 31: Estimates of tyre and TPMS lifetime based on an expert opinion and [Weissman, 2003]

Vehicle segment	Tyre lifetime (1x retread) [years]	Tyre lifetime (2x retread) [years]	Tyre lifetime (3x retread) [years]	TPMS sensor lifetime [years]
Service/delivery	**6**	9	12	7
Urban (delivery/collection)	**6**	9	12	7
Municipal utility	2	3	**4**	7
Regional (delivery/collection)	**7**	10	13	7
Long haul	3	**5**	7	7
Construction	4	6	**8**	7
Bus	4	6	**7**	7
Coach	4	5	**7**	7

It was decided to take the TPMS sensor lifetime of 7 years as reference case for all vehicles segments, but it needs to be added, that in some cases the lifetime can be shorter, due to:

- Reduced amount of retreads;
- Sensor breakage during retread or tyre change.

6.3.2 *Investment costs*

Investment costs for TPMS have been determined in chapter 3 based on data collected through a stakeholder questionnaire. The estimates for the current and prospective costs are shown in Table 32 and TO = TPMS applied to truck / tractor only

TT = TPMS applied to truck / tractor + trailer

Table 33 (excl. VAT), respectively. Abbreviations TO and TT are used for the terms *truck only* and *truck + trailer*.

Table 32: "Current costs" for TPMS per vehicle segment (excl. VAT)

Vehicle segment		OEM-fitted TO [€]	OEM-fitted TT [€]	Retrofitted TO [€]	Retrofitted TT [€]
Service/delivery	**indirect**	8	n/a	n/a	n/a
	direct	44	n/a	88	n/a
Urban (delivery/collection)		164	n/a	348	n/a
Municipal utility		195	n/a	374	n/a
Regional (delivery/collection)		173	314	355	610
Long haul		185	338	365	651
Construction		234	395	422	731
Bus		174	n/a	327	n/a
Coach		209	n/a	378	n/a

TO = TPMS applied to truck / tractor only

TT = TPMS applied to truck / tractor + trailer

Table 33: "Prospective costs" for TPMS per vehicle segment (excl. VAT)

Vehicle segment		OEM-fitted TO [€]	OEM-fitted TT [€]	Retrofitted TO [€]	Retrofitted TT [€]
Service/delivery	**indirect**	5	n/a	n/a	n/a
	direct	20	n/a	40	n/a
Urban (delivery/collection)		54	n/a	108	n/a
Municipal utility		68	n/a	132	n/a
Regional (delivery/collection)		65	127	120	218
Long haul		70	136	129	240
Construction		78	146	144	264
Bus		50	n/a	80	n/a
Coach		52	n/a	80	n/a

TO = TPMS applied to truck / tractor only

TT = TPMS applied to truck / tractor + trailer

6.3.3 Fuel cost savings

Fuel cost savings are calculated from a societal and end-user perspective. A sensitivity analyses is carried out for varying fuel prices (as a function of oil price). The relation between oil price and fuel price is based [AEA, 2012], see Figure 19.

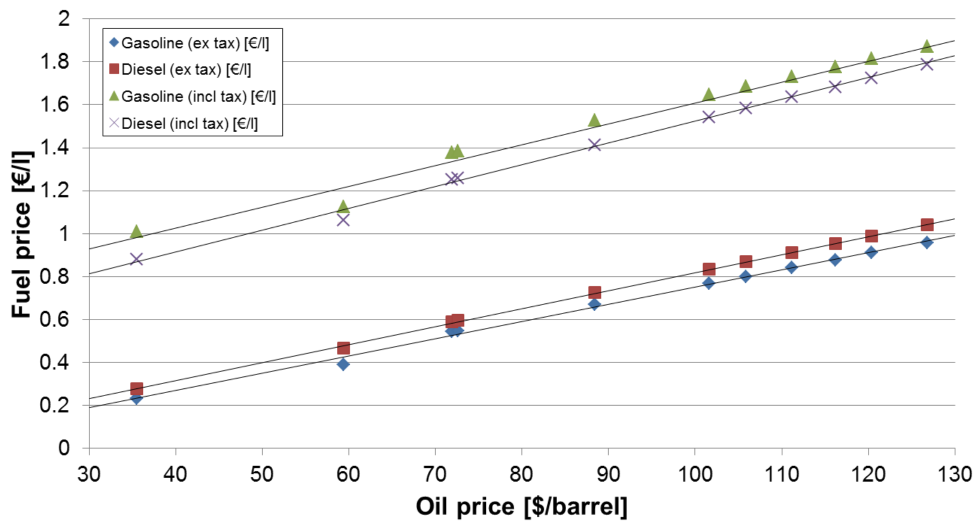

Figure 19: Relationship oil-price to fuel price [AEA, 2012]

The relationship for diesel fuel price to oil price is determined via a linear fit (with the following constants: a = 0.0084, b = -0.0198, c=0.5789):

- Fuel price (excl. taxes): a * oil price + b
- Fuel price (incl. taxes): (1+VAT) * fuel price (excl. taxes) + c

Since many distributors and fleet owners in Europe can deduct VAT on fuel from their taxes, in the cost-benefit analysis VAT for end-users is disregarded. Accordingly, at an oil price of 100 $/barrel, a fuel price is calculated of 0.82 € (excl. taxes) and 1.26 € (incl. taxes).

For the optimistic, high savings potential scenario Table 34 shows the average fuel cost savings potential per vehicle segment, together with the absolute annual savings in Euros from the societal and end-user perspective at an oil price of 100 $/barrel. The estimates for fuel savings potential correspond to the values estimated in Task 1 (Table 12).

Table 34: Annual fuel cost savings (**“high savings potential”** scenario) for truck only (TO) and truck + trailer (TT) configuration for an oil price of 100 $/barrel

	Fuel savings					
	Potential		Societal		End-user	
Vehicle segment	**TO [%]**	**TT [%]**	**TO [€]**	**TT [€]**	**TO [€]**	**TT [€]**
Service/delivery	-0.24%	n/a	11	n/a	17	n/a
Urban (delivery/collection)	-0.32%	n/a	22	n/a	34	n/a
Municipal utility	-0.20%	n/a	23	n/a	35	n/a
Regional (delivery/collection)	-0.24%	-0.35%	30	43	46	67
Long haul	-0.26%	-0.48%	85	156	131	240
Construction	-0.26%	-0.32%	28	35	44	54
Bus	-0.13%	n/a	19	n/a	28	n/a
Coach	-0.24%	n/a	28	n/a	43	n/a

The fuel cost savings for the low savings potential scenario are shown Table 35.

Table 35: Fuel savings (**“low savings potential”** scenario) for truck only (TO) and truck + trailer (TT) configuration for an oil price of 100 $/barrel

	Fuel savings					
	Potential		Societal		End-user	
Vehicle segment	**TO [%]**	**TT [%]**	**TO [€]**	**TT [€]**	**TO [€]**	**TT [€]**
Service/delivery	-0.12%	n/a	5	n/a	8	n/a
Urban (delivery/collection)	-0.16%	n/a	11	n/a	17	n/a
Municipal utility	-0.10%	n/a	11	n/a	18	n/a
Regional (delivery/collection)	-0.12%	-0.17%	15	22	23	33
Long haul	-0.13%	-0.24%	43	78	66	120
Construction	-0.13%	-0.16%	14	18	22	27
Bus	-0.06%	n/a	9	n/a	14	n/a
Coach	-0.12%	n/a	14	n/a	21	n/a

6.3.4 Costs savings associated with a reduced amount of maintenance: extended lifetime of tyres

In chapter 3 it was also shown that a reduced inflation pressure leads to lower tyre stiffness. This again leads to higher deformations and consequently increased tyre wear and reduced service life. The reduction in expected service life for an under-inflated or over-inflated truck tyre has been shown in Table 23. In order to be able to apply these data to the pressure distribution data assessed in WP1 by TUG and ETRMA/ETRTA (see Figure 5), the data in Table 23 has been fitted and extrapolated, resulting in Table 36. The average of values have been taken for under-inflation levels between 0 to 10%, 10% to 20% and 20 to 30%. For values above 30%, the reduction in service life is taken to be 55% or larger.

Table 36: Reduction of service life in terms of level of under-inflation (see chapter 3)

Level of under-inflation [%]	**Reduction in service life [%]**
0-10%	3%
10-20%	17%
20-30%	41%
≥30%	≥55%

Combining Figure 5 and Table 36 it can be concluded that without TPMS:

- 2% of the fleet have a reduced tyre service lifetime of 55% or more,
- 4% of the fleet have a reduced tyre service lifetime of 41%,
- 19% of the fleet have a reduced tyre service lifetime of 17% and
- 39% of the fleet have a reduced tyre service lifetime of 3%.

Using the assumptions with respect to the impact of TPMS on tyre pressure which form the basis of the “high savings potential scenario” for the TPMS CO_2 benefit (see chapter 2), the following calculation can be made (see Table 37) to determine the potential cost savings due to extended tyre service lifetime.

Service life costs depend on the type of tyre and vehicle segment. For long haul tyres, this is equal to about 1.30€ to 1.80€ per tyre per 1000km [Michelin, 2013]. With an average cost of 1.50€/1000km, effectively for HDVs 0.13€ can be saved per tyre per 1000km (see calculation in Table 37). For LCVs, since the TPMS impact is expected to be only 50% between 10-20% under-inflation, the cost savings is determined at 0.1€ per tyre per 1000km.

Table 37: Calculation of average cost savings, per tyre per 1000 kms, related to an extended service lifetime

service costs [€/1000km]	1.500	incl. effect of current shares of levels of under-inflation

under-inflation [%]	0-10%	10-20%	20-30%	>30%
tyre inflation distribution [%]	39%	19%	4%	2%
associated reduction in lifetime [%]	3%	17%	41%	55%
TPMS impact [%]	0%	100%	100%	100%
share of tyres effected by TPMS [%]	0%	19%	4%	2%
cost savings [€/1000km]	0.040	0.269	0.943	1.665

average cost savings [€/1000km]	0.13	
service costs [€/1000km]	1.362	incl. effect of optimal tyre inflation

Table 39 shows the estimated cost savings, taking into account the annual mileage of the different vehicle segments, as well as the wheel configurations as shown in Table 38.

The number of wheels is taken for a specific configuration. It is known that many more configurations exist, however the exact shares of different wheel configurations per vehicle segment have not been determined in this study. As seen in Table 39, the cost savings related to an increased amount of tyre lifetime can be significant. Depending on the number of wheels, this estimate can be larger or smaller. More research would be needed to obtain a more precise and representative cost saving.

Table 38: Number of wheels

	Number of wheels per vehicle	
Vehicle segment	**TO [#]**	**TT [#]**
Service/delivery	4	n/a
Urban (delivery/collection)	6	n/a
Municipal utility	6	n/a
Regional (delivery/collection)	6	12
Long haul	6	12
Construction	6	12
Bus	6	n/a
Coach	6	n/a

Table 39: Annual cost savings due to extended tyre lifetime for truck only (TO) and truck + trailer (TT) configuration

	Service lifetime-related cost savings	
Vehicle segment	**TO [€]**	**TT [€]**
Service/delivery	7 – 14	n/a
Urban (delivery/collection)	15 – 29	n/a
Municipal utility	9 – 18	n/a
Regional (delivery/collection)	22 – 44	44 – 88
Long haul	48 – 95	95 – 191
Construction	18 – 37	37 – 73
Bus	18 – 37	n/a
Coach	19 – 38	n/a

The savings potential shown in Table 39 is based on the assumptions of the high savings potential scenario as defined in chapter 2. In a low savings potential scenario, the cost savings are 50% lower. It is seen that the tyre lifetime savings potential is significant and can annually range up to 191 € for a long haul vehicle with TT-configuration.

Furthermore, it can be considered that the improved tyre lifetime also has 2nd and 3rd order effects on the environment and the cost effectiveness for example due to:

- impact on additional raw material use,
- increased number of retreads with TPMS, since the tyre casing is less damaged during use.

These effects have not been taken into account.

6.3.5 *Cost savings associated with a reduced amount of maintenance: optimized inflation frequency*

In order to compare costs of maintaining the right pressure with or without TPMS an estimate is made of the difference in check / pressure adjustment frequency and associated labour costs between the current situation and a situation in which vehicles are equipped with TPMS:

- In the current situation without TPMS, tyre pressure is also regularly adjusted. It may be assumed that in general the tyres of a vehicle are periodically (weekly, monthly, …) checked with a pressure gauge. If necessary, the tyres are inflated with an air-pressure supply.
- With **TPMS**, it can be assumed that tyres are automatically and continuously checked by the TPMS. Tyres will be inflated anytime there is a tyre pressure warning.

In both cases tyres will be inflated regularly but the frequency may be different.

Manual checking and inflation costs time and money. Depending on whether TPMS is fitted or not, the frequency is increased or decreased. It was shown in chapter 2, that vehicles with TPMS will on average drive with less tyre under-inflation than without TPMS. This would suggest that users of TPMS adapt their tyre pressure on average more often than users of vehicles without TPMS. The same conclusions were drawn from an online panel study performed by TNS sifo on behalf of NIRA Dynamics for passenger car drivers [TNS sifo, 2012]. Study results have shown that on average vehicle drivers with TPMS adjust their tyre pressure more frequently than vehicle drivers without TPMS. On average, a shift is seen from twice annually to quarterly. However, it must be noted that:

- This study is focussed on M1 passenger cars. The shift in check frequency is probably different for LCV and HDV vehicles, since M1 users may not be representative for the LCV or HDV market.
- In the survey the group sizes with TPMS / without TPMS / unknown are not even. The group with TPMS is only 7% of the total number of users. With n=1003, this still corresponds to about 70 users.
- Limited resolution: User replies are grouped in categories like quarter-yearly, twice a year, monthly, etc. Hereby, the resolution of responses are limited.(quarter yearly could mean every 2 months, but also every 4 months).

The costs of periodic tyre pressure checks / adjustments are estimated as follows:

- Time to check and adjust tyre pressure: 5 [mins] for truck only
- Average labour rate: 35 €/h

⇨ Cost per check: 3 €

⇨ Annual cost (weekly checks): 156 €
⇨ Annual cost (monthly checks): 36 €
⇨ Annual cost (quarter-yearly checks): 12 €
⇨ Annual cost (half-yearly checks): 6 €
⇨ Annual cost (yearly checks): 3 €

Based on the above a shift in check frequency from half-yearly to quarter-yearly as a result of TPMS creates additional annual **cost** of 6€:

However, potentially, the ownership of TPMS can also generate cost savings. It could be the case for some users that as a result applying TPMS the check frequency is decreased. In the situation without TPMS a user could e.g. perform checks monthly, just to be sure. In the situation with TPMS he can rely on the TPMS and will only adjust tyre pressure when necessary. If this would on average be 4 times a year rather than monthly, the attributed cost savings are 24€. It should be noted though that in this case the associated fuel savings will be limited or even negative as a lower check frequency is likely to lead to a higher average level of under-inflation.

In general the additional cost or cost savings related to shifts in check frequencies will be different for each user and depends on the original check frequency and the new check frequency. A number of possibilities can be thought of (see Table 40).

Table 40: Annual costs/cost savings attributed to a change in check frequency for a truck only configuration displayed in Euros [€]

New check frequency / Original check frequency	Monthly	Quarter-yearly	Half-yearly	Yearly
Monthly	0	24	30	33
Quarter-yearly	-24	0	6	9
Half-yearly	-30	-6	0	3
Yearly	-33	-9	-3	0

It is important to note that in case of increased amount of pressure inflations, the cost savings potential of optimized check frequencies is in indeed rather an additional cost. Depending on the new check frequency, costs (savings) can vary between -3 to -33€. Based on the assumptions above, an estimate is made for truck only configurations of roughly 12€ additional costs per year. Taking into account double check time for truck trailer configurations, the resulting costs are calculated as given in Table 41.

Table 41: Costs attributed to a change in check frequency for truck only (TO) and truck + trailer (TT) configuration

	Check frequency-related cost savings	
Vehicle segment	**TO [€]**	**TT [€]**
Service/delivery	-12	n/a
Urban (delivery/collection)	-12	n/a
Municipal utility	-12	n/a
Regional (delivery/collection)	-12	-24
Long haul	-12	-24
Construction	-12	-24
Bus	-12	n/a
Coach	-12	n/a

6.3.6 Costs savings associated with less service disruptions: reduced roadside tyre breakdown

When a tyre is under-inflated, the chance of a tyre blow-out and roadside breakdown increases. As a result, the vehicle cannot be used for a certain period of time and needs to be repaired. The amount of down-time and corresponding costs vary largely from case to case. In a previous project performed by TNO for the Dutch Ministry of Infrastructure and Environment [TvdT, 2012], two distributors have been asked how many tyre blow-outs they experience yearly on their fleet and what are the costs associated per breakdown. Answers provided the following insights:

- Tyre blow-outs per year vary from 1 up to 50 for fleets of 50 vehicles. This corresponds to on average 0.02 to about 1 break-down per vehicle per year.

However the large variation in numbers make it difficult to project one true factor and remains subject of large uncertainty.
- Costs associated per down-time (1 tyre blow-out) varied between 500 to 1700€.

Assuming the same reduction potential in tyre blow-outs as for accidents, i.e. 4-20%, the change in costs of service disruptions can be calculated as follows:
- Average cost associated with down-time event: 1000€
- Yearly cost associated with down-time per vehicle without TPMS:
  - Best case: 20€
  - Worst case: 1000€
- Estimated yearly cost saving per vehicle resulting from reduced down-time with TPMS:
  - Best case: 0.77-2.20€
  - Worst case: 40-200€

Due to several uncertainties in this calculation, it remains difficult to provide a good estimate for the potential cost savings associated to reduced roadside tyre breakdown. Cost savings could be in the order of several Euros to several tens of Euros per vehicle annually. It is assumed that a 10% chance in break-down (once every ten year per vehicle) is more realistic. In this case, the cost saving per vehicle is between 4 and 20€. An average of 12€ is taken as input for the cost-benefit analysis (see Table 42).

The assumed chance of 10% represents a specific case. According to statistics used by Continental, 30% is a more realistic case. The cost savings factor would thus be three-times higher. Furthermore, it is also be noted that the costs for HDVs is probably more expensive than for LCVs. In the current model, this is not taken into consideration.

Table 42: Down-time cost savings for truck only (TO) and truck + trailer (TT) configuration

	Down-time-related cost savings	
Vehicle segment	**TO [€]**	**TT [€]**
Service/delivery	12	n/a
Urban (delivery/collection)	12	n/a
Municipal utility	12	n/a
Regional (delivery/collection)	12	12
Long haul	12	12
Construction	12	12
Bus	12	n/a
Coach	12	n/a

Further costs savings associated with reduced tyre breakdown could be generated for example due to increased highway safety (the effect of tyre blowout on the surrounding traffic) These have not been further analysed.

6.3.7 Costs savings associated with a reduction of external costs: reduced amount of accidents (fatalities, injuries, congestion)

In chapter 3, it was shown that the use of TPMS can improve vehicle safety. It is expected that the number of yearly fatal road accidents can be reduced which effectively leads to a reduction of associated costs of 11-58 M€ in the EU. Taking into account the annual mileage of LCVs and HDVs in 2010, 542,652 million kms [TREMOVE, 2010], this equals an annual cost saving 0.00002 to 0.0006€ per kilometre per vehicle. When combining these cost savings with the annual mileage of the single vehicle categories from [TIAX, 2011], the following savings are calculated (see Table 43):

Table 43: Accidents-related cost savings for truck only (TO) and truck + trailer (TT) configuration

	Accidents-related cost savings	
Vehicle segment	**TO [€]**	**TT [€]**
Service/delivery	1-4	n/a
Urban (delivery/collection)	1-4	n/a
Municipal utility	1-3	n/a
Regional (delivery/collection)	1-6	1-6
Long haul	3-14	3-14
Construction	1-5	1-5
Bus	1-5	n/a
Coach	1-6	n/a

6.3.8 *Costs savings associated with a reduction of external costs: reduced amount of emissions*

Next to carbon dioxide, the calculated fuel savings potential of TPMS also results in a reduction of other emissions, like nitrogen oxides (NO_x) and particulate matter ($PM_{2.5}$, PM_{10}). Emissions have a negative impact on several societal aspects [CE, 2008] in the form of:

- Health impacts
- Building and material damages
- Crop losses in agriculture and impacts on the biosphere
- Loss of biodiversity and ecosystems (soil and water/groundwater)

Associated with these impacts are societal costs, for example health costs generated due to aspiration problems by fine particles. Reducing emissions therefore results in a reduction of external costs. An analysis of these costs for NO_x and $PM_{2.5}$ has been performed by CE Delft [CE, 2008]. External cost factors derived from this study are:

- NO_x: 4,400 €/t
- $PM_{2.5}$: 26,000 €/t

Representative values for emissions of specific vehicle segments are known from [VERSIT, 2013] and are displayed in Table 44.

Table 44: Representative vehicle segment emissions (NOx, $PM_{2,5}$)

Vehicle segment	**NOx [g/km]**	**$PM_{2.5}$ [g/km]**
Service/delivery	4.8	0.02
Urban (delivery/collection)	4.8	0.02
Municipal utility	10	0.02
Regional (delivery/collection)	4.9	0.01
Long haul	2.7	0.01
Construction	5.5	0.01
Bus	4.5	0.01
Coach	1.6	0.01

Assuming that to first order the savings potential for NO_x and $PM_{2.5}$ is proportional to the savings potential for fuel consumption, the following external cost savings are calculated (see Table 45):

Table 45: Annual cost savings related to a reduction of emissions for truck only (TO) and truck + trailer (TT) configuration

	Cost savings related to a reduction of emissions	
Vehicle segment	**TO [€]**	**TT [€]**
Service/delivery	1-2	n/a
Urban (delivery/collection)	1-3	n/a
Municipal utility	1-2	n/a
Regional (delivery/collection)	2-3	2-5
Long haul	2-4	4-8
Construction	2-3	2-4
Bus	1-1	n/a
Coach	0-1	n/a

6.4 Cost benefit analysis

In this section, the results of the marginal abatement costs, ΔTCO and break-even period are calculated and analysed in detail. In order to decouple possible pre-mature conclusions on the environmental effectiveness and the cost-effectiveness, two cases are treated:

- One case considers the fuel consumptions savings only as potential benefit and is calculated purely with the investment costs and the fuel cost savings. Hereby, a statement can be made on the cost-effectiveness of TPMS as a means to reduce LCV and HDV fuel consumption and CO_2 emissions.
- Another case takes into account the total of cost savings for TPMS including all aspects assessed in the previous sections as far as they apply to the user perspective resp. the societal perspective (see section 6.2). Herewith, it is possible to draw conclusions on the overall cost-effectiveness of TPMS.

The sensitivity of the cost-effectiveness to variations in costs and savings potential is assessed in the following way (see sections 3.4 and 6.3.2):

- Investment costs have been determined on the basis of supplier responses. Two cases are regarded:
  - A “current cost” scenario based on the average costs from the questionnaire responses
  - A “prospective cost” based on the lowest cost data from the questionnaire responses, which assume high production volumes
- Fuel costs savings are based on the calculated fuel savings potential. Two cases are regarded (see section 2.3):
  - A “high savings potential” scenario assuming full user response to TPMS warnings
  - A “low savings potential” scenario, assuming 50% of the effect of the “high savings potential” scenario.

When combining these assumptions, four different overall scenarios are formed (see Table 46).

- **"Current cost / high savings potential":** This scenario is represents the current situation in terms of TPMS production volumes and voluntary adoption. It seems reasonable to assume that voluntary fitment results in the highest savings potential, since it is likely that end users that invested in TPMS voluntarily will act on pressure warnings.
- **"Prospective costs / high savings potential"**: This scenario can be thought to e.g. represent a situation in which TPMS application is mandated (leading to high production volumes and therefore low investment costs) and user response to TPMS signals is high.
- **"Current costs / low savings potential"**: This scenario is used as a worst case scenario. It may represent a future situation in which investment cost remain high while TPMS only results in low savings potential. But it also can be considered representative for a current situation in which TPMS application leads to a reduction of tyre over-inflation, which partly counteracts the estimated savings due to full prevention of under-inflation.
- **"Prospective costs / low savings potential"**: This scenario could e.g. occur in a situation in which TPMS application is mandated (leading to high production volumes and therefore low investment costs) but where user response to TPMS signals is low and/or systems are tampered with. It also caters for the possibility that TPMS application leads to a reduction of tyre over-inflation, which partly counteracts the estimated savings due to full prevention of under-inflation.

Together with a high resp. low fuel savings potential also a high resp. low reduction of external costs due to reduced tyre-related accidents has been assumed.

Table 46: Matrix of scenarios for the sensitivity analysis

		Savings + safety potential	
		High	**Low**
Investment costs	**Current**	- Average investment costs - High savings & safety potential	- Average investment costs - Low savings & safety potential
	Prospective	- Low investment costs - High savings & safety potential	- Low investment costs - Low savings & safety potential

6.4.1 *Investment costs vs. fuel cost savings only*

6.4.1.1 *"Current costs / high savings potential" scenario*

Figure 20 shows the marginal abatement costs (societal perspective) for an investment in OEM-fitted TPMS. Abatement costs are shown in Euros per tonne of CO_2 for different oil prices in $ per barrel. Each vehicle segment is represented with a different colour line code.

When only taking into account investment costs vs. fuel cost savings in the "current costs / high savings potential" scenario, cost effectiveness from a societal perspective strongly depends on the vehicle segment and the oil price. It can be seen that at an oil price of 100 $/barrel many vehicle segments have positive abatement costs (i.e. implementation of TPMS leads to net costs for society).

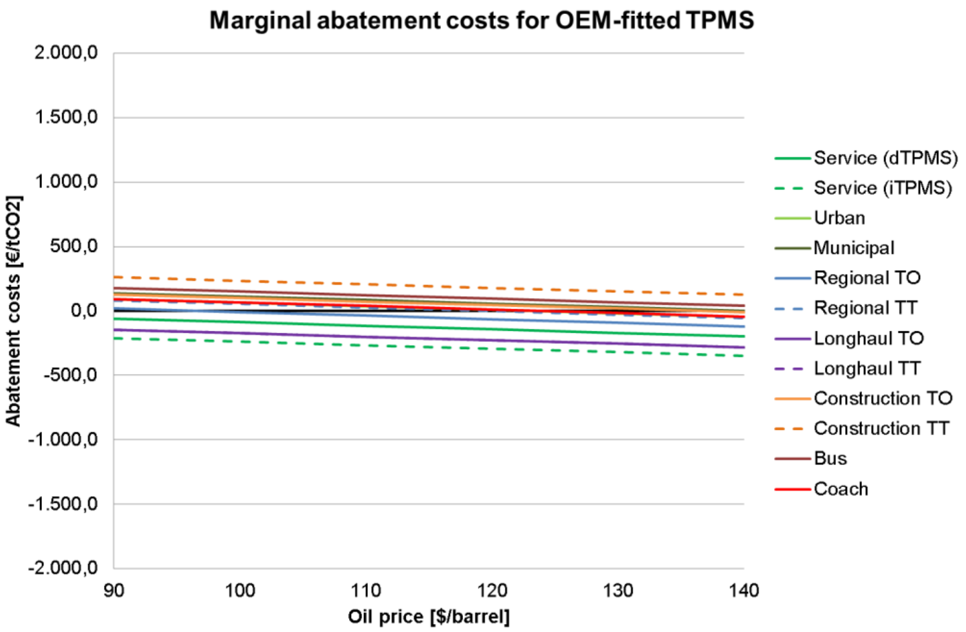

Figure 20: Fuel cost savings only (**"current costs / high savings potential"** scenario) – Marginal abatement costs for an investment in OEM-fitted TPMS

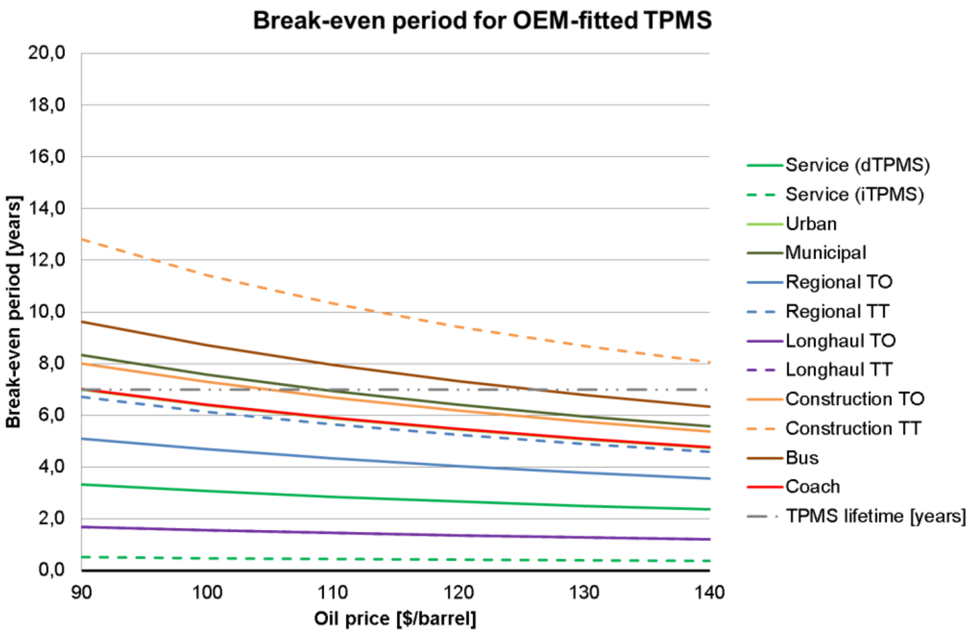

Figure 21: Fuel cost savings only (**"current costs / high savings potential"** scenario) - Break-even period for an investment in OEM-fitted TPMS

Exceptions are long-haul TO and TT configurations, as well as service delivery vehicles with direct or indirect TPMS. Regional TT configurations have an abatement cost of about 0€. The reasons for these exceptions are:

- Service delivery vehicles (with indirect TPMS) have relatively low investment costs while

- Long-haul vehicles have a relatively high savings potential (due to their large fuel consumption and high mileage).

Figure 21 shows the break-even period for an investment in OEM-fitted TPMS, also as function of the oil price The break-even period is given in years. The y-axis has been limited to 20 years, since a break-even period larger than 20 years is not considered cost-effective. The average lifetime of TPMS (7 years) is plotted with a dashed grey line. When looking at the break-even period of the investment and making assumptions as noted in the **"current costs / high savings potential"** scenario, it is seen that cost-effectiveness from an end-user perspective also strongly depends on the vehicle segment and the oil price.

Depending on the application, investment costs take a long time to be earned back, between 0,5 and 13 years. In some cases the payback time is above the TPMS lifetime, e.g. for construction TT in all cases and for busses at an oil price above 125 $/barrel. Overall it can be seen that in most vehicle segments OEM-fitted TPMS systems are still earned back within 7 years. The most cost-effective cases are observed for service delivery vehicles and long-haul vehicles. Indirect TPMS has the shortest break-even period, since it has the lowest investment costs.

For retro-fit TPMS (see Figure 22), abatement costs shift further upwards (more positive) and thus becomes less attractive from a societal perspective. The only exception is for long haul vehicles where TPMS are still cost effective in all oil price scenarios. The higher costs of retro-fitted systems also imply longer break-even periods (see Figure 23). For most vehicle segments this period is far longer than the TPMS lifetime. Longhaul and service delivery (at an oil price above 105 $/barrel) and regional delivery TT remain the only vehicle segments for which retrofit TPMS appears cost-effective from a user perspective.

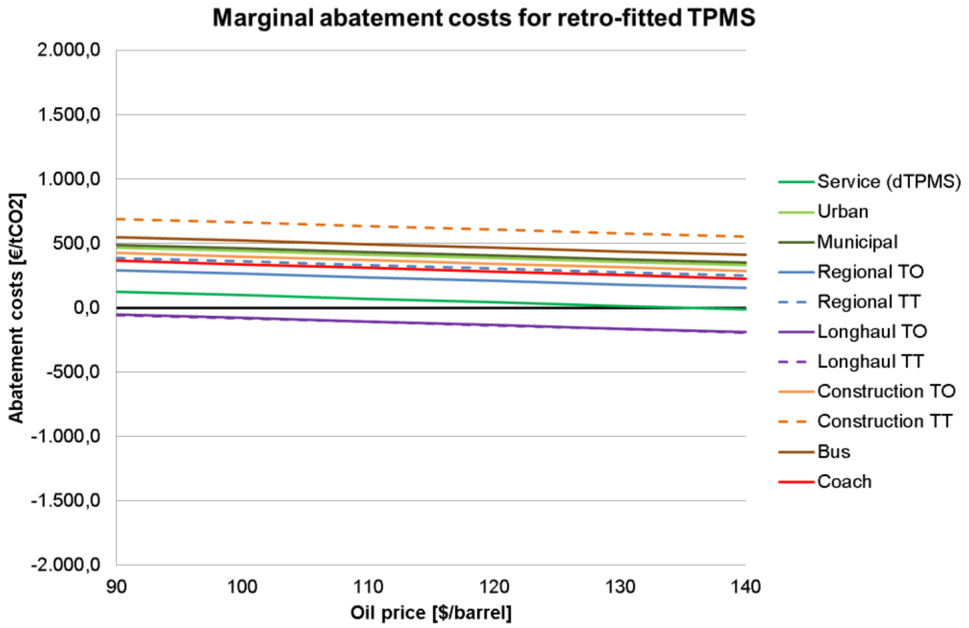

Figure 22: Fuel cost savings only (**"current costs / high savings potential"** scenario) – Marginal abatement costs for an investment in retro-fitted TPMS

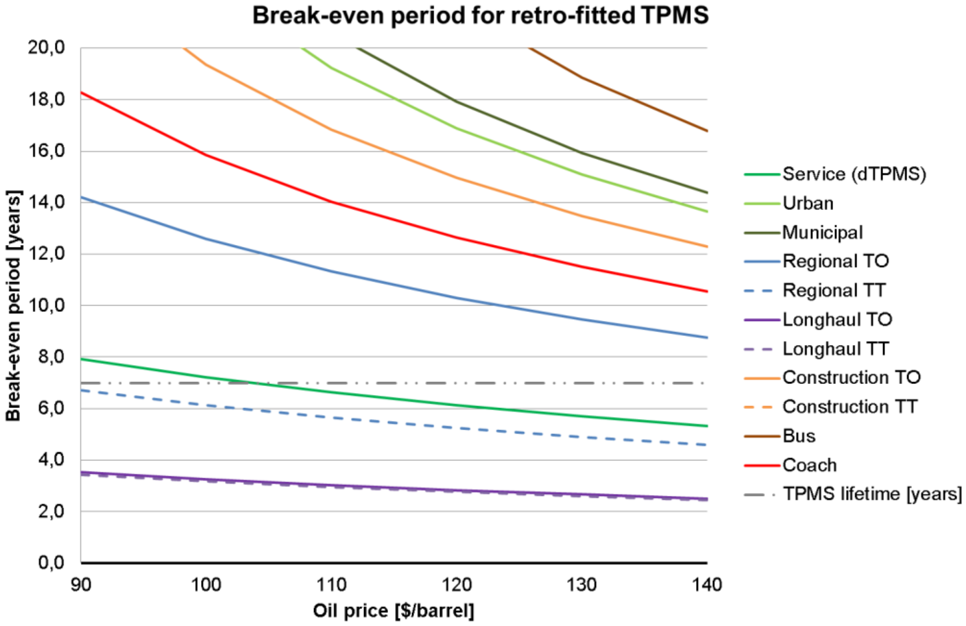

Figure 23: Fuel cost savings only (**"current costs / high savings potential" scenario**) - Break-even period for an investment in retro-fitted TPMS

6.4.1.2 "Prospective costs / high savings potential" scenario

Figure 24 shows the marginal abatement costs (societal perspective) for an investment in OEM-fitted TPMS, when considering the "prospective costs / high savings potential".

On a whole, it is seen that all vehicle segments have relatively similar abatement costs. In all cases the costs are negative meaning the implementation of TPMS leads to net cost savings for society. The highest abatement cost is achieved for a construction vehicle TT with TPMS, since it has the highest investment costs and relatively low fuel cost savings potential.

In Figure 25, it can be seen that in this scenario all vehicle segments earn their investment in OEM-fitted TPMS back within the overall lifetime of the technology. This is between 0.5 to 3 years, depending on the oil price and the segment.

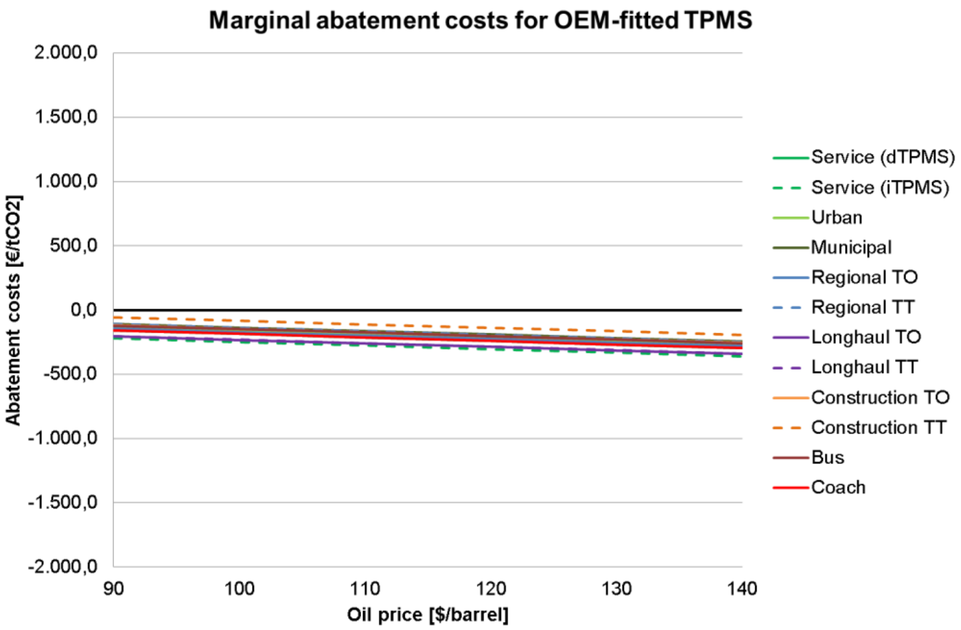

Figure 24: Fuel cost savings only (**"Prospective costs / high savings potential"** scenario) - Marginal abatement costs for an investment in OEM-fitted TPMS

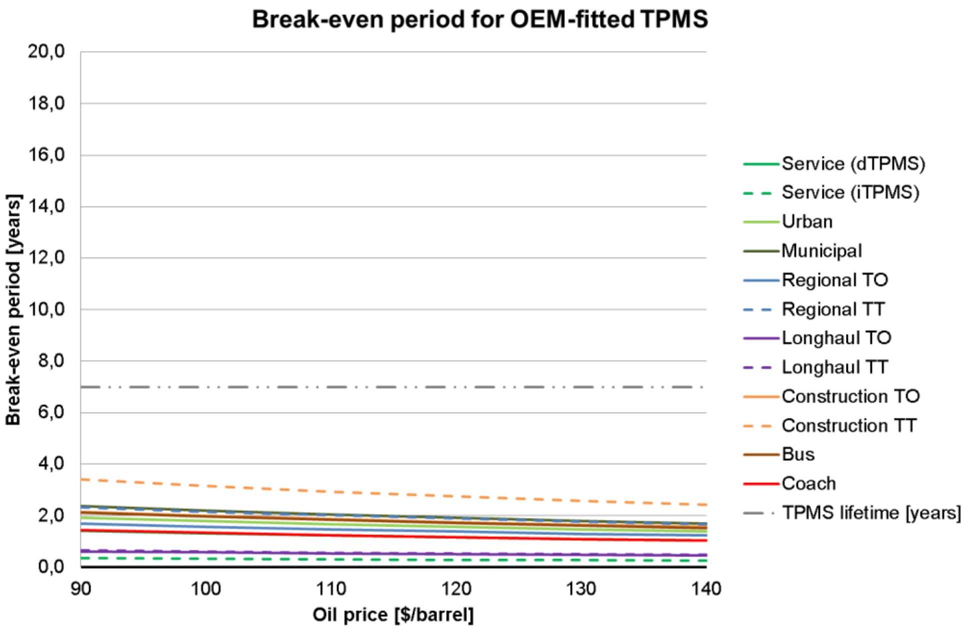

Figure 25: Fuel cost savings only (**"Prospective costs / high savings potential"** scenario) - Break-even period for an investment in OEM-fitted TPMS

Figure 26 shows the marginal abatement costs for an investment in retro-fitted TPMS. Compared to the previous case, it can be seen that the curves shift upwards in the plot, which indicates that retro-fitted TPMS has higher abatement costs and would therefore cost society more than if TPMS is OEM-fitted (see above). This can be related to the higher costs of retro-fitted TPMS: However, overall it is seen that the abatement costs are still negative in most cases so that this scenario still saves costs for society if fitted.

An exception should be noted for the construction vehicle with TT configuration. As already described above, this is the least profitable case. The higher costs for retrofit TPMS can actually lead to positive abatement costs for the construction vehicle, which makes the investment less rewarding from a societal point of view.

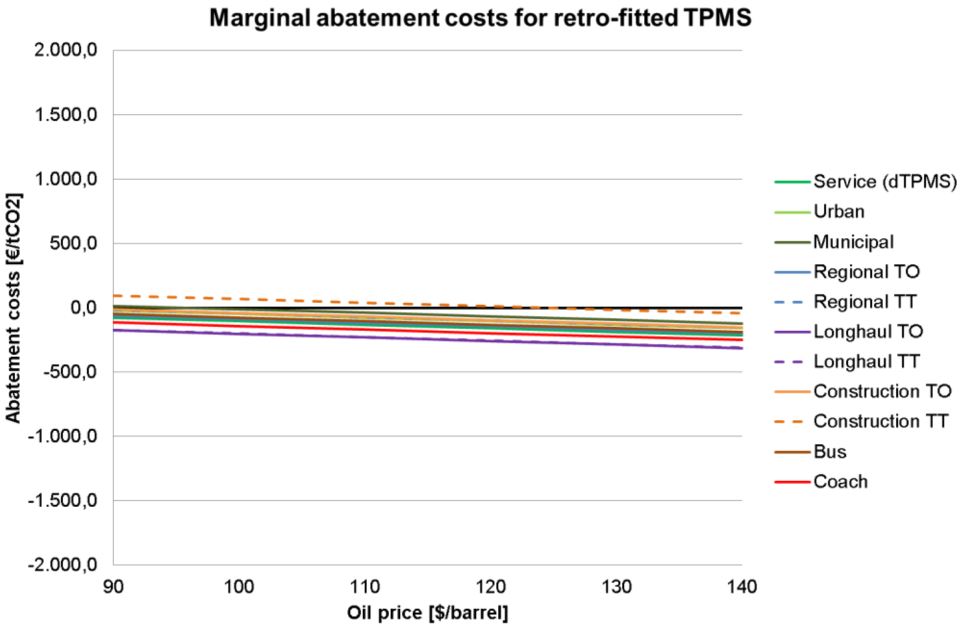

Figure 26: Fuel cost savings only ("**Prospective costs / high savings potential**" scenario) - Marginal abatement costs for an investment in retro-fitted TPMS

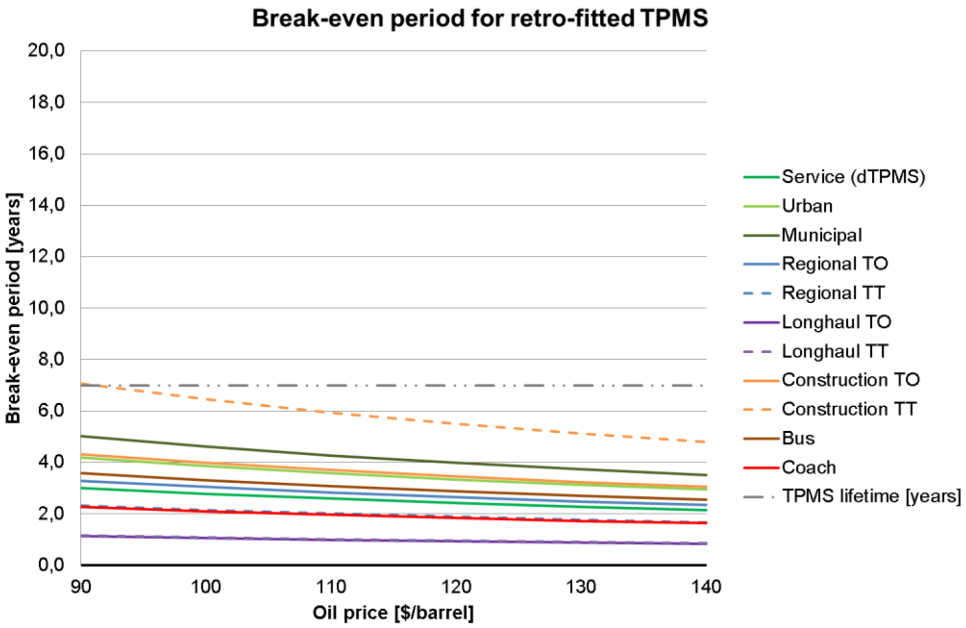

Figure 27: Fuel cost savings only ("**Prospective costs / high savings potential**" scenario) - Break-even period for an investment in retro-fitted TPMS

For the end-user perspective the same conclusion is drawn from the plot of break-even periods (Figure 27). From an end-user perspective, however, the investment in TPMS can even be interesting for construction vehicles, since the investment is earned back within the lifetime of the product.

6.4.1.3 *"Current costs / low savings potential" scenario*

The "current costs / low savings potential" scenario is the least optimistic scenario. The abatement costs for OEM-fitted TPMS is shown below in Figure 28. The abatement costs are only negative for long-haul and for service delivery vehicles, both direct and indirect TPMS. The difference in cost-effectiveness between direct and indirect TPMS is explained by the large difference in investment costs (44€ vs. 8€). Since the savings potential of both technologies are the same, the difference in investment cost has a large effect. It must be noted that the performance of direct TPMS is higher than indirect TPMS, however in these calculations only the warning threshold of the technology is decisive for the savings potential. In both cases, an under-inflation of 20% has been used.

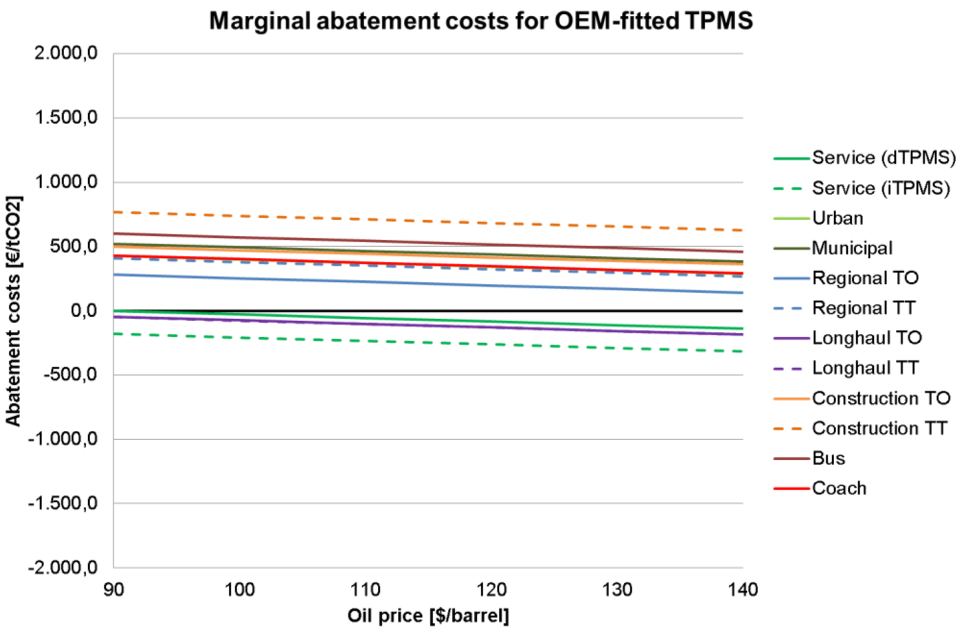

Figure 28: Fuel cost savings only (**"Current costs / low savings potential"** scenario) – Marginal abatement costs for an investment in OEM-fitted TPMS

In this scenario the break-even period (see Figure 29) for OEM fitted TPMS is also much higher than the TPMS lifetime in most segments. Most cost-effective applications remain long-haul TO and TT, as well as service delivery vehicles with direct or indirect TPMS.

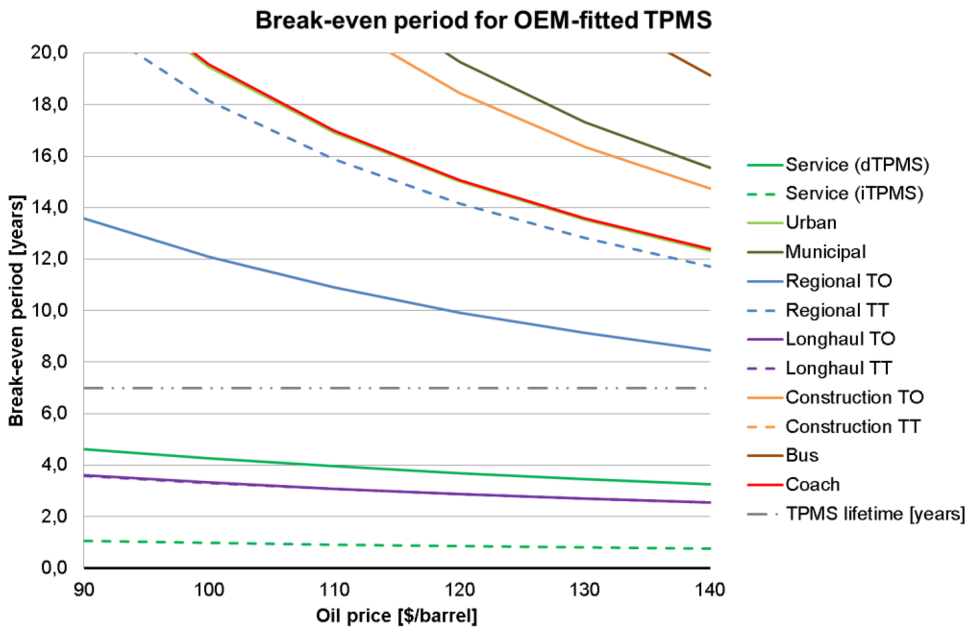

Figure 29: Fuel cost savings only (**"Current costs / low savings potential"** scenario) - Break-even period for an investment in OEM-fitted TPMS

In the retro-fitted TPMS case (Figure 30 and Figure 31), the cost-effectiveness of TPMS reduces even further. From a societal perspective, not even TPMS on long-haul vehicles can be considered cost-effective. All abatement costs are positive.

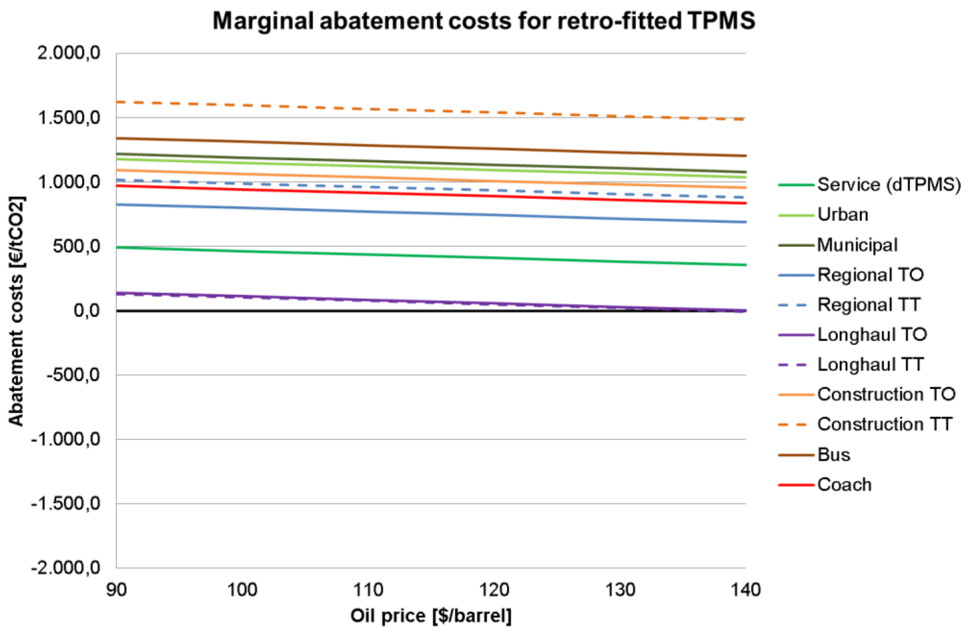

Figure 30: Fuel cost savings only (**"Current costs / low savings potential"** scenario) – Marginal abatement costs for an investment in retro-fitted TPMS

From the user perspective, the break-even period is only lower than the product lifetime for long-haul vehicles at an oil price of 110 $/barrel or larger.

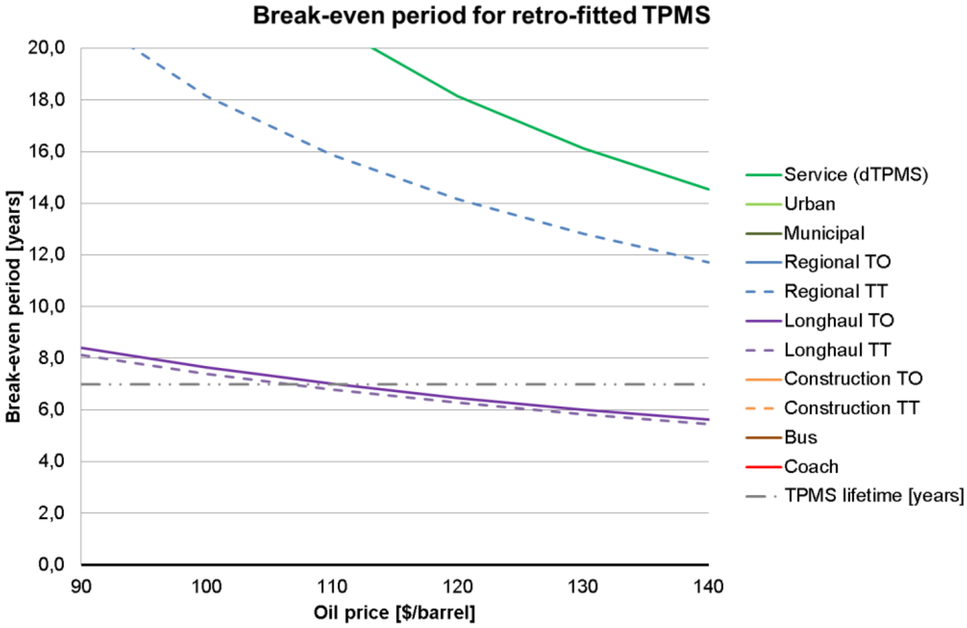

Figure 31: Fuel cost savings only (**"Current costs / low savings potential"** scenario) - Break-even period for an investment in retro-fitted TPMS

6.4.1.4 *"Prospective costs / low savings potential" scenario*

In the "prospective costs / low savings potential" scenario, OEM-fitted TPMS (see Figure 32 and Figure 33) is cost-effective from a societal and end-user perspective for most vehicle applications.

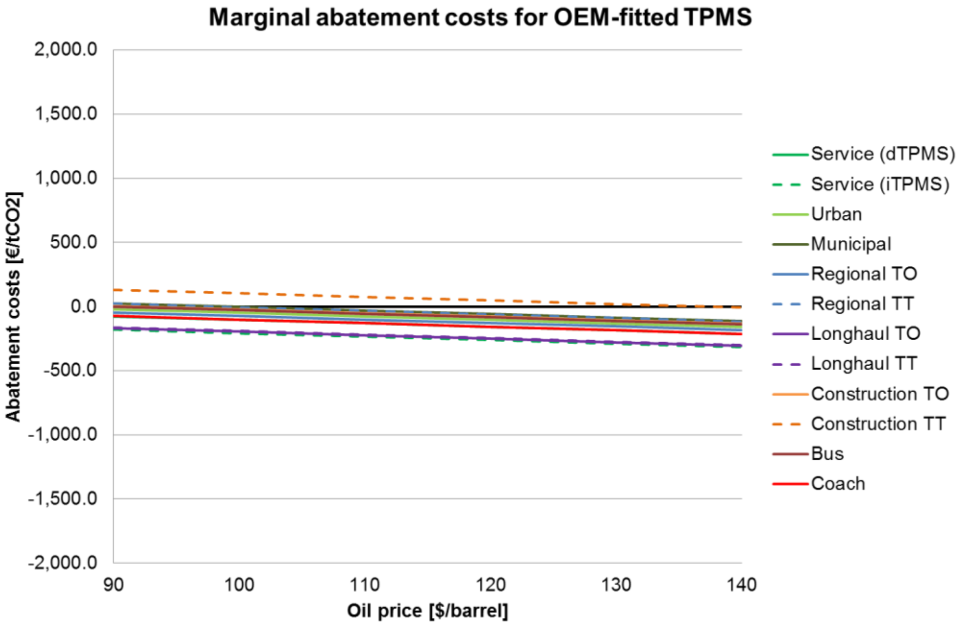

Figure 32: Fuel cost savings only (**"Prospective costs / low savings potential"** scenario) – Marginal abatement costs for an investment in OEM-fitted TPMS

Only construction vehicles with TT configuration have positive abatement cost and a longer break-even period than the expected TPMS lifetime.

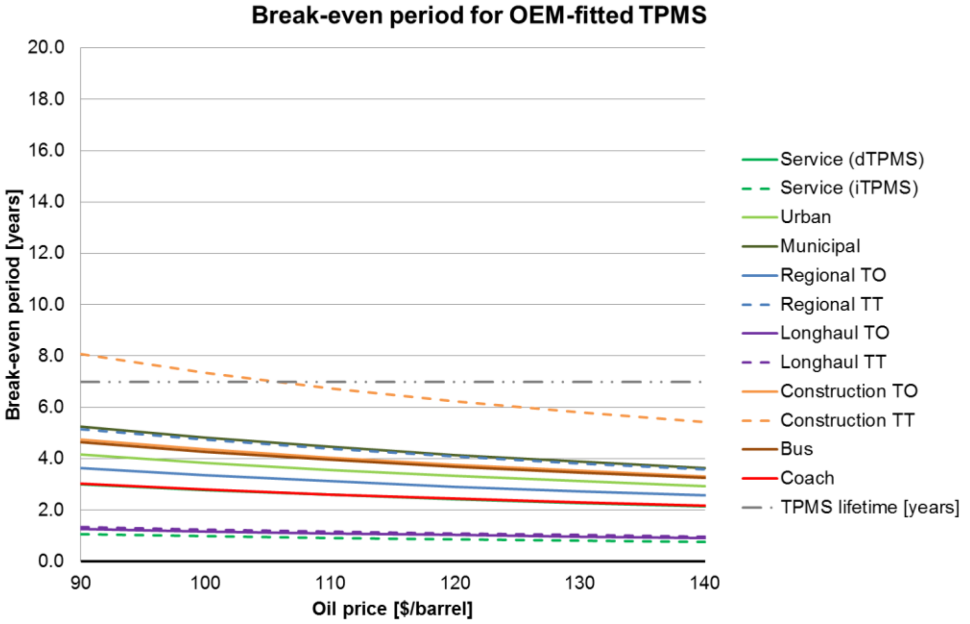

Figure 33: Fuel cost savings only (**"Prospective costs / low savings potential"** scenario) – Marginal abatement costs for an investment in OEM-fitted TPMS

In the retro-fitted case (see Figure 34 and Figure 35) , cost-effectiveness is reduced to a number of applications. Seen from a societal perspective, vehicle segments like long haul TO and TT as well as busses have negative abatement costs.

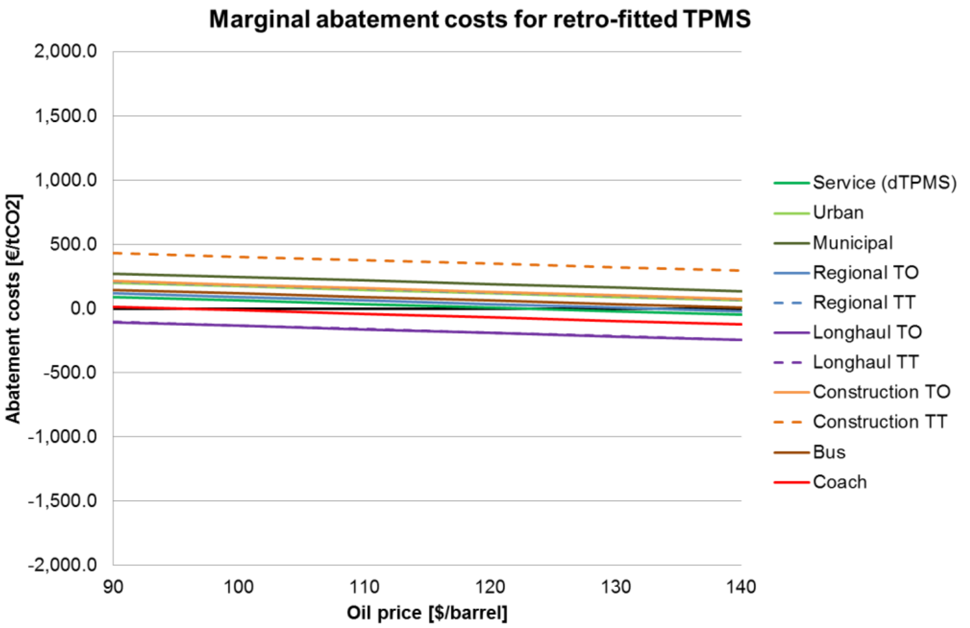

Figure 34: Fuel cost savings only (**"Prospective costs / low savings potential"** scenario) – Marginal abatement costs for an investment in retro-fitted TPMS

From an end-user perspective, additionally service delivery vehicles have a favourable break-even period lower than 7 years. For other applications, this strongly depends on the oil price.

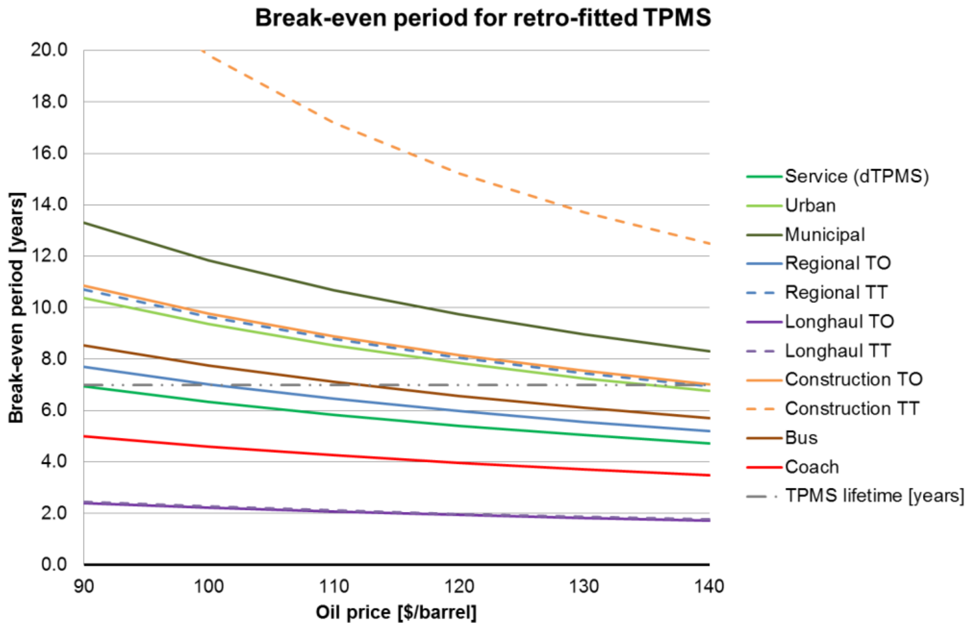

Figure 35: Fuel cost savings only (**“Prospective costs / low savings potential”** scenario) – Marginal abatement costs for an investment in retro-fitted TPMS

6.4.2 *Investment costs vs. total cost savings*

Below same plots are shown as above, however this time for the case in which not only fuel cost savings are considered, but also other saving potentials as identified in section 6.2 and quantified in section 6.3.

6.4.2.1 *“Current costs / high savings potential” scenario*

In the “current costs / high savings potential” scenario, OEM-fitted TPMS is cost-effective for all vehicle segments at all oil prices (see Figure 36 and Figure 37).

When considering retro-fitted TPMS (see Figure 38 and Figure 39), only application in the following segments is considered cost-effective, from both a societal as well as an end-user perspective:

- Service delivery (direct and indirect TPMS)
- Long-haul TO and TT
- Regional TO and TT
- Coach
- Bus

For the following segments TPMS is not cost-effective in any oil-price scenario:

- Construction TT
- Municipal

For yet another group of vehicle segments the cost-effectiveness of TPMS is depending on the oil-price:

- Construction TO
- Urban

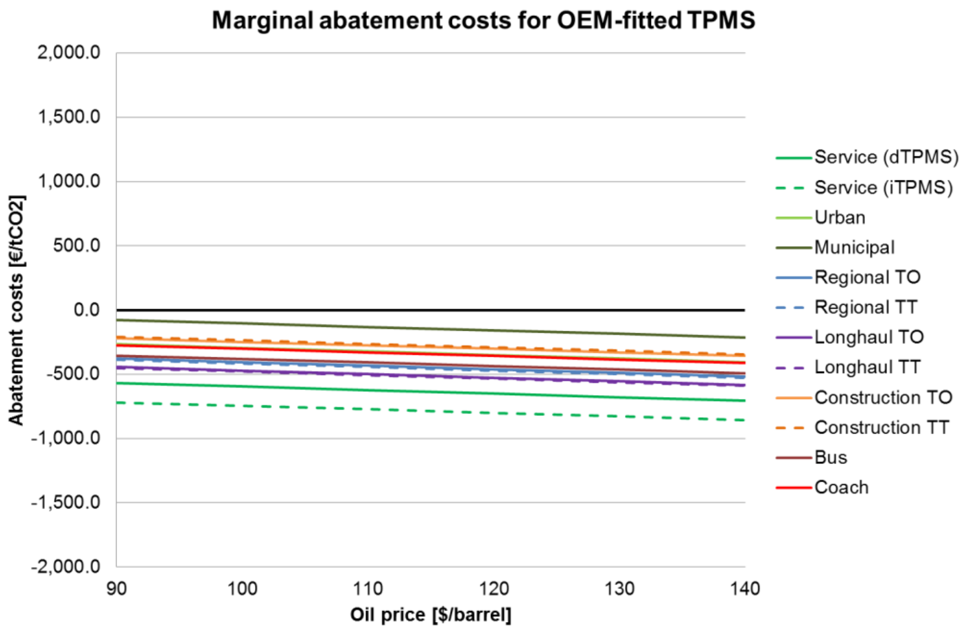

Figure 36: Total cost savings (**"Current costs / high savings potential"** scenario) – Marginal abatement costs for an investment in OEM-fitted TPMS

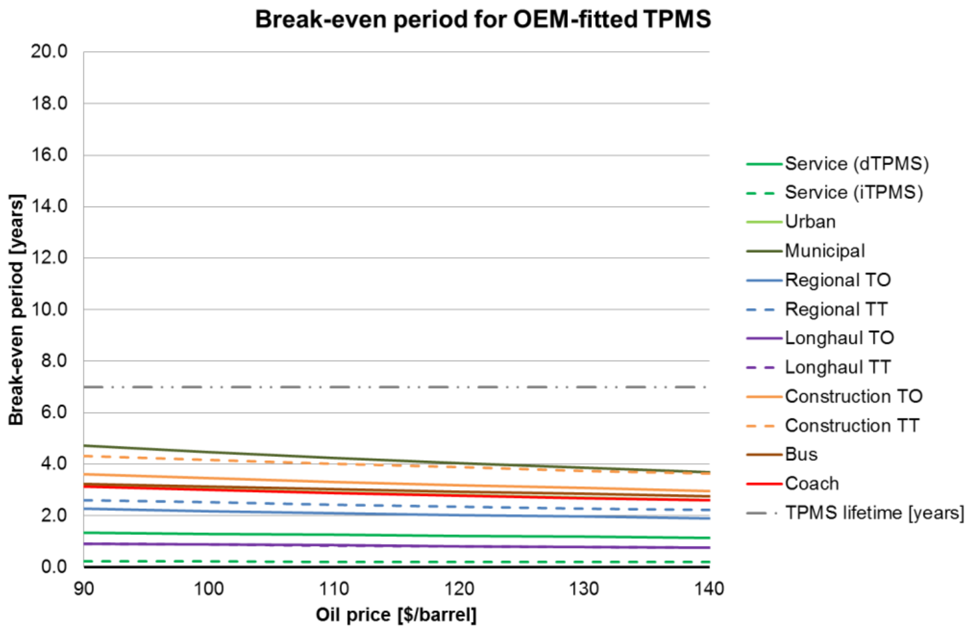

Figure 37: Total cost savings (**"Current costs / high savings potential"** scenario) - Break-even period for an investment in OEM-fitted TPMS

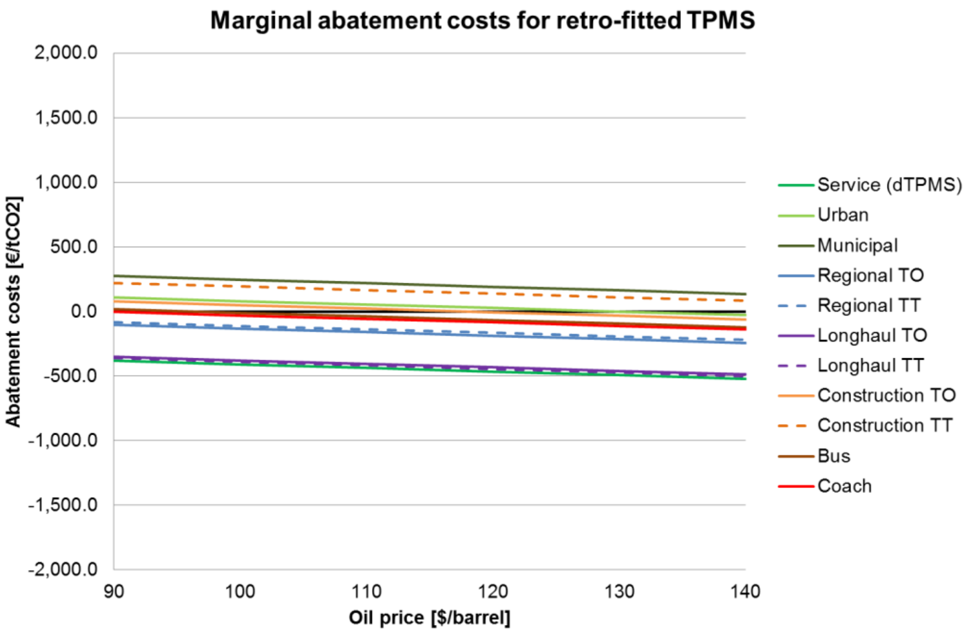

Figure 38: Total cost savings (**"Current costs / high savings potential"** scenario) – Marginal abatement costs for an investment in retro-fitted TPMS

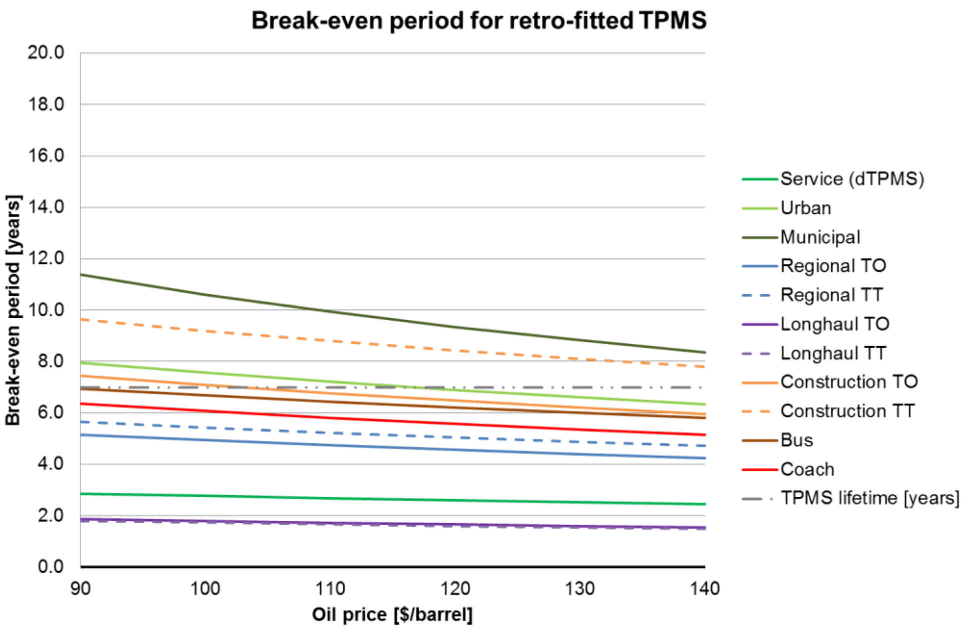

Figure 39: Total cost savings (**"Current costs / high savings potential"** scenario) - Break-even period for an investment in retro-fitted TPMS

6.4.2.2 "Prospective costs / high savings potential" scenario

From both a societal as well as an end-user perspective, the cost-effectiveness of TPMS increases if also other savings than just the fuel cost savings are taken into account. For Scenario A (Figure 40 to Figure 43) OEM-fitted and retrofitted TPMS systems are cost-effective for all vehicle segments at all oil prices.

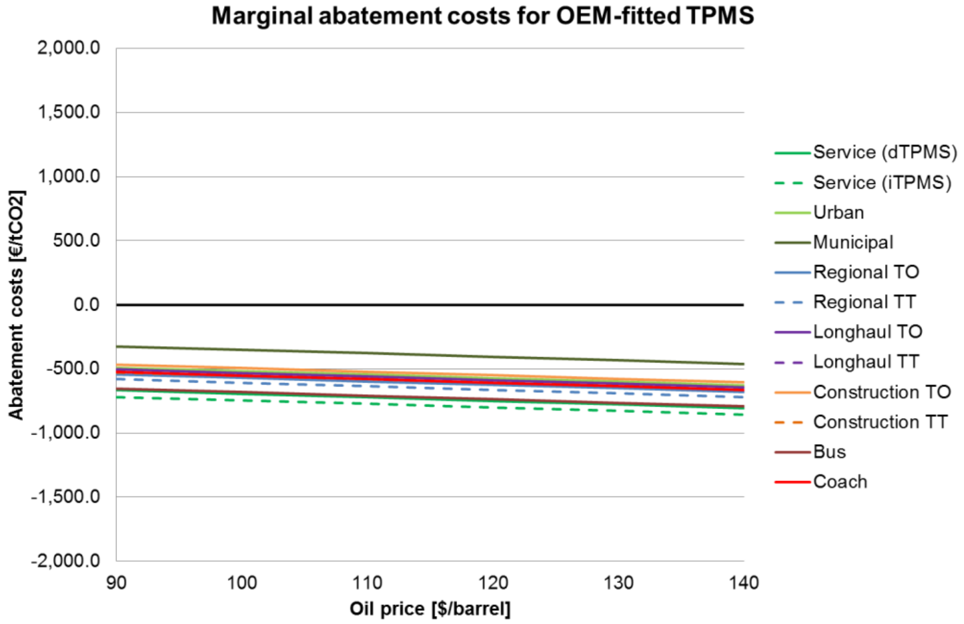

Figure 40: Total cost savings (**"Prospective costs / high savings potential"** scenario) – Marginal abatement costs for an investment in OEM-fitted TPMS

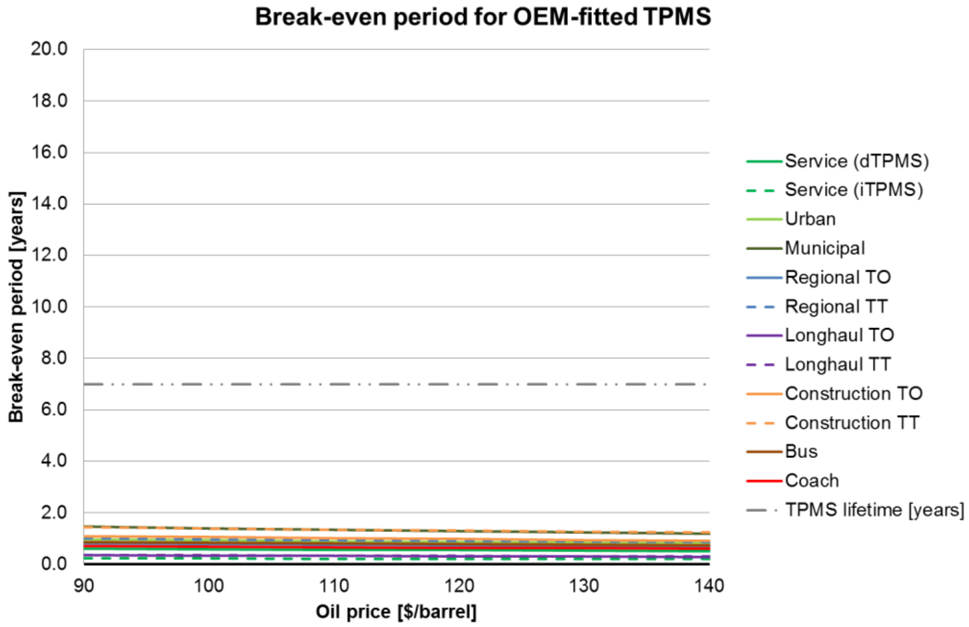

Figure 41: Total cost savings (**"Prospective costs / high savings potential"** scenario) - Break-even period for an investment in OEM-fitted TPMS

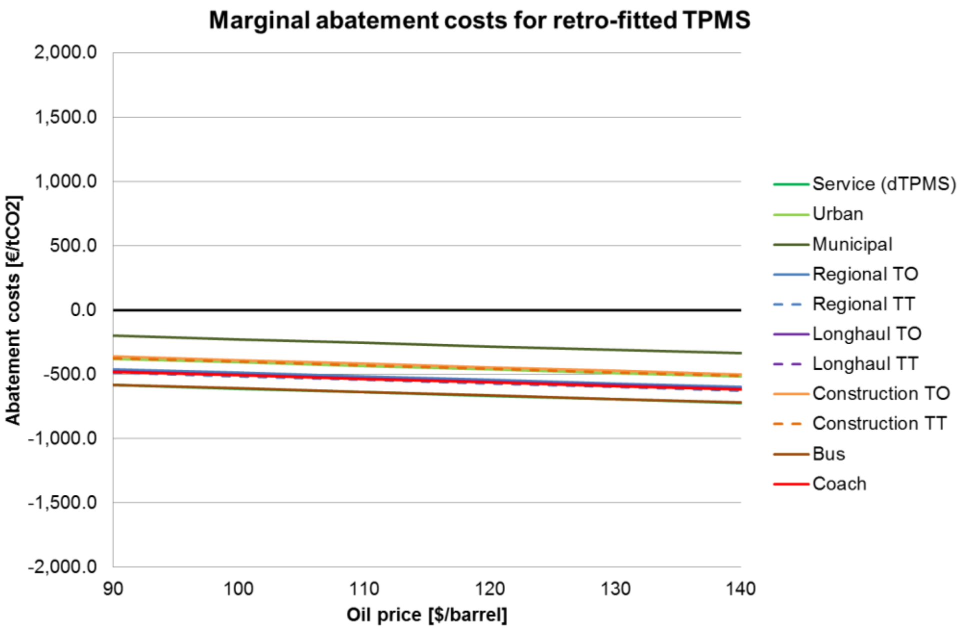

Figure 42: Total cost savings (**"Prospective costs / high savings potential"** scenario) – Marginal abatement costs for an investment in retro-fitted TPMS

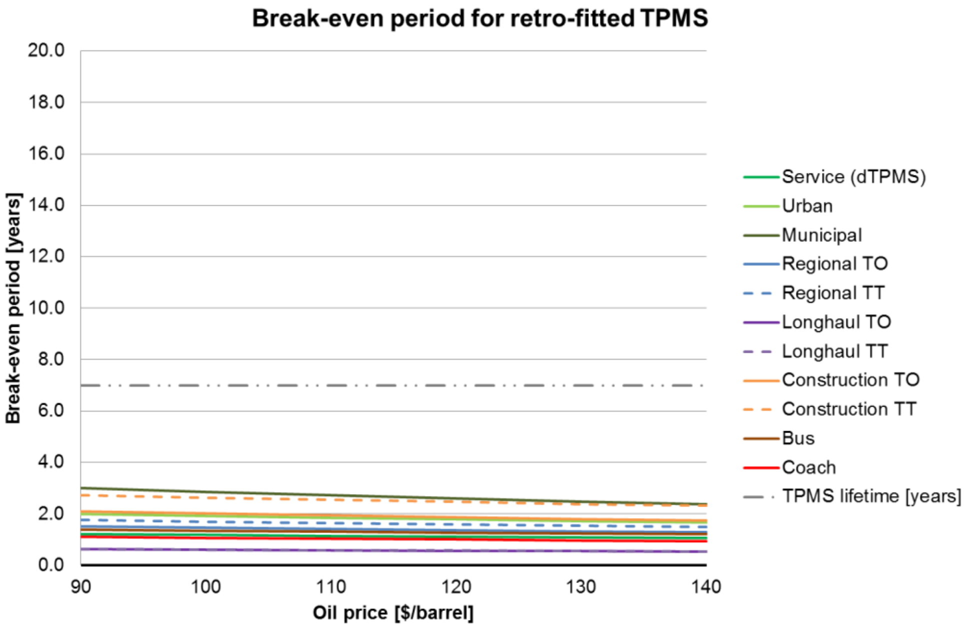

Figure 43: Total cost savings (**"Prospective costs / high savings potential"** scenario) - Break-even period for an investment in retro-fitted TPMS

6.4.2.3 *"Current costs / low savings potential" scenario*

In the "current costs / low savings potential" scenario, the cost effectiveness of OEM- and retro-fitted TPMS strongly depends on the oil price and the vehicle segment. As seen in Figure 44, abatement costs are negative for vehicle segments like service delivery, long-haul TO and TT, as well as for regional TO and TT. TPMS solutions for coach, construction and municipal delivery vehicles are not cost-effective from a societal perspective at any given oil price.

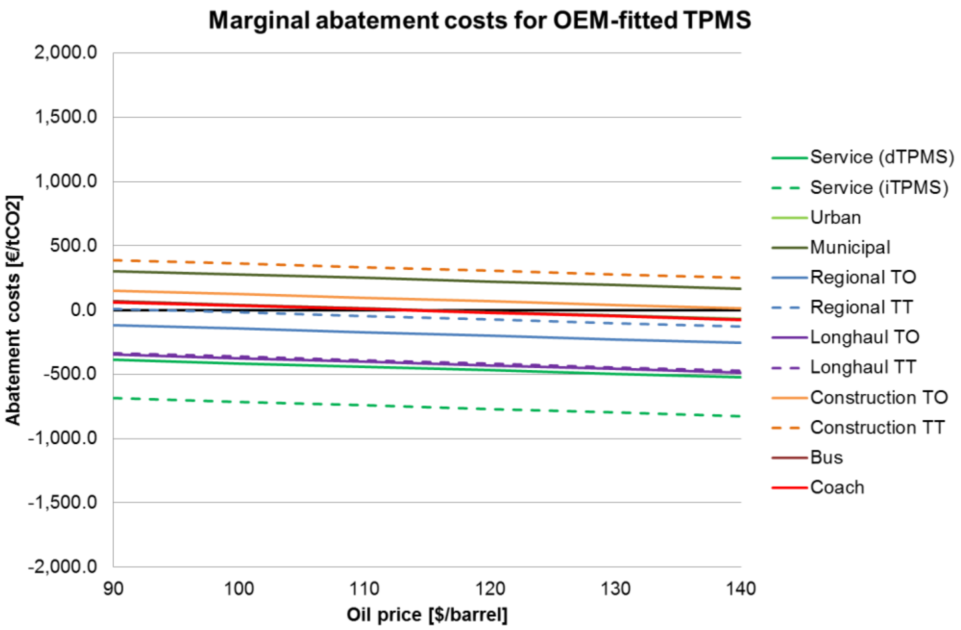

Figure 44: Total cost savings (**"Current costs / low savings potential"** scenario) – Marginal abatement costs for an investment in OEM-fitted TPMS

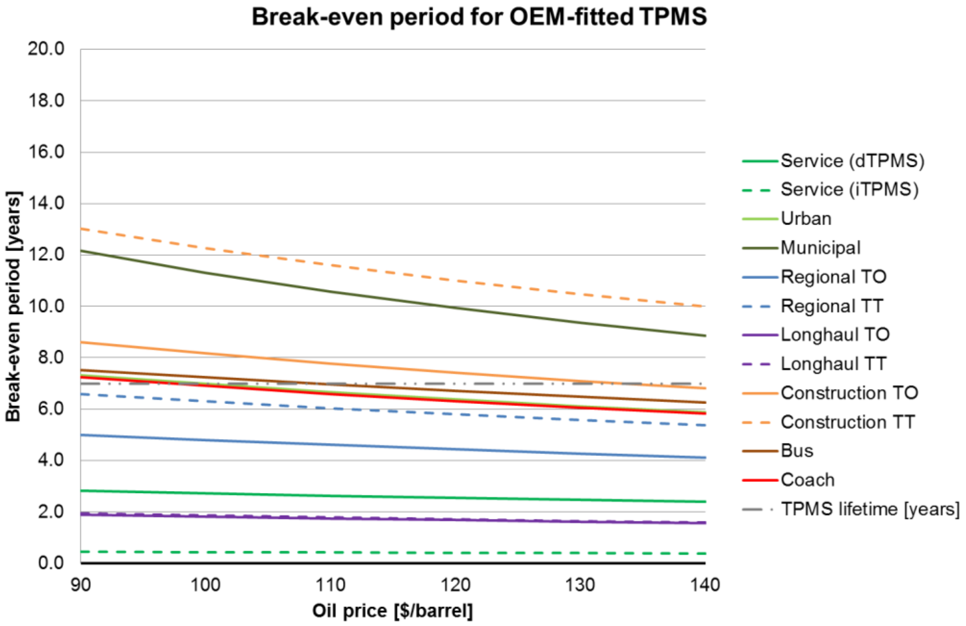

Figure 45: Total cost savings (**"Current costs / low savings potential"** scenario) - Break-even period for an investment in OEM-fitted TPMS

Apart from all the vehicle segments for which OEM-fitted TPMS is cost effective from a societal perspective, TPMS is also cost effective from an end-user perspective (see Figure 45) for bus, coach and urban vehicles depending on the oil price. For construction and municipal vehicles, the break-even period is larger than the product lifetime.

For retro-fitted systems TPMS on long-haul and service delivery vehicles is cost-effective from a societal perspective (Figure 46) at all oil prices. For all other segments abatement costs are positive for all oil prices.

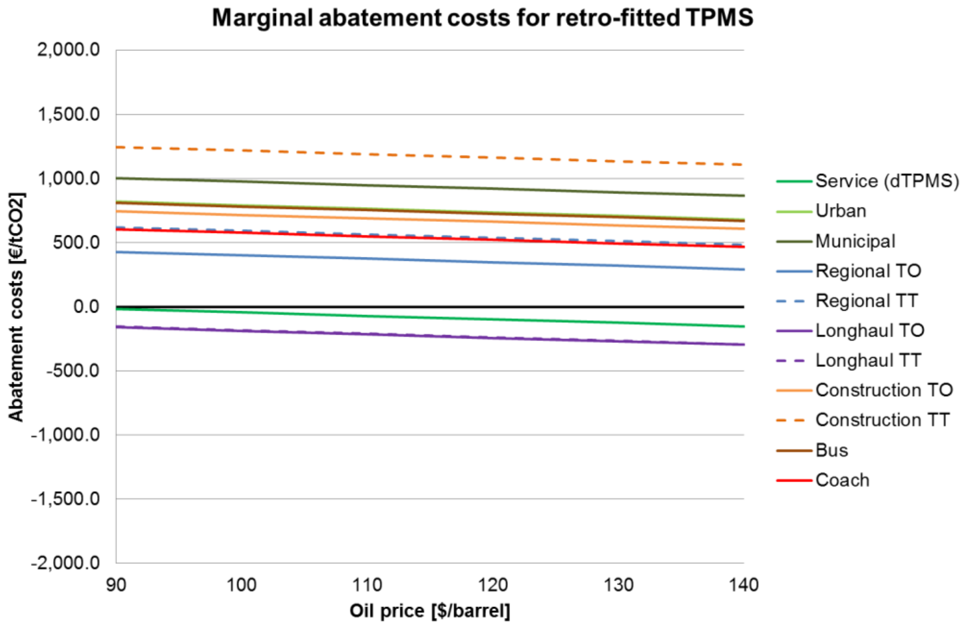

Figure 46: Total cost savings (**"Current costs / low savings potential"** scenario) – Marginal abatement costs for an investment in retro-fitted TPMS

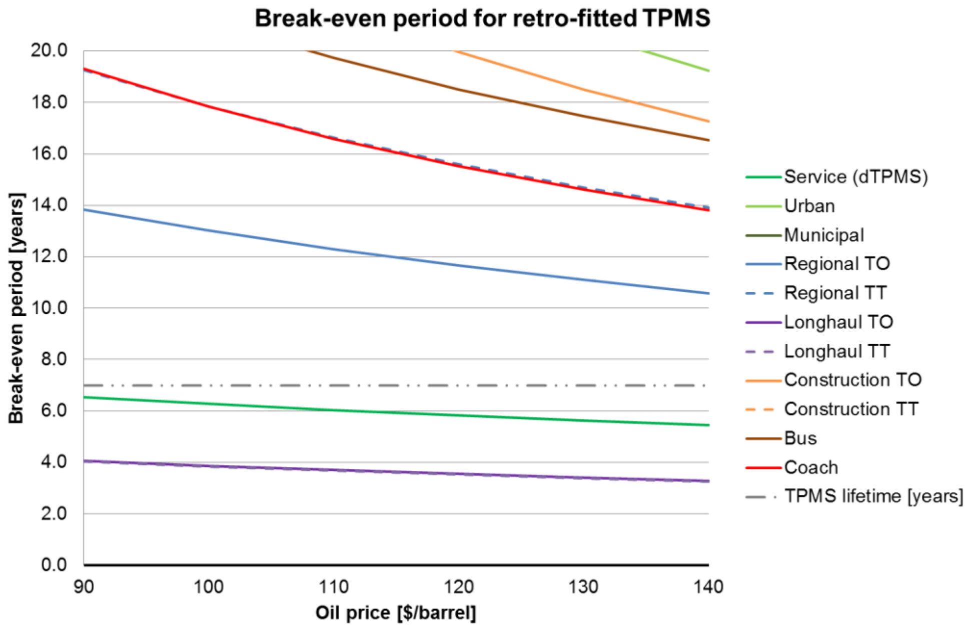

Figure 47: Total cost savings (**"Current costs / low savings potential"** scenario) - Break-even period for an investment in retro-fitted TPMS

From an end-user perspective (Figure 47), retrofit TPMS in long-haul and service delivery vehicles is cost-effective (break-even period smaller than product lifetime) for all given oil prices. In other vehicles retrofit TPMS have much longer break-even periods than the TPMS lifetime and can therefore not be considered cost-effective.

6.4.2.4 "Prospective costs / low savings potential" scenario

Even in the "prospective costs / low savings potential" scenario, OEM-fitted TPMS is considered cost-effective in most applications (see Figure 48 to Figure 49).

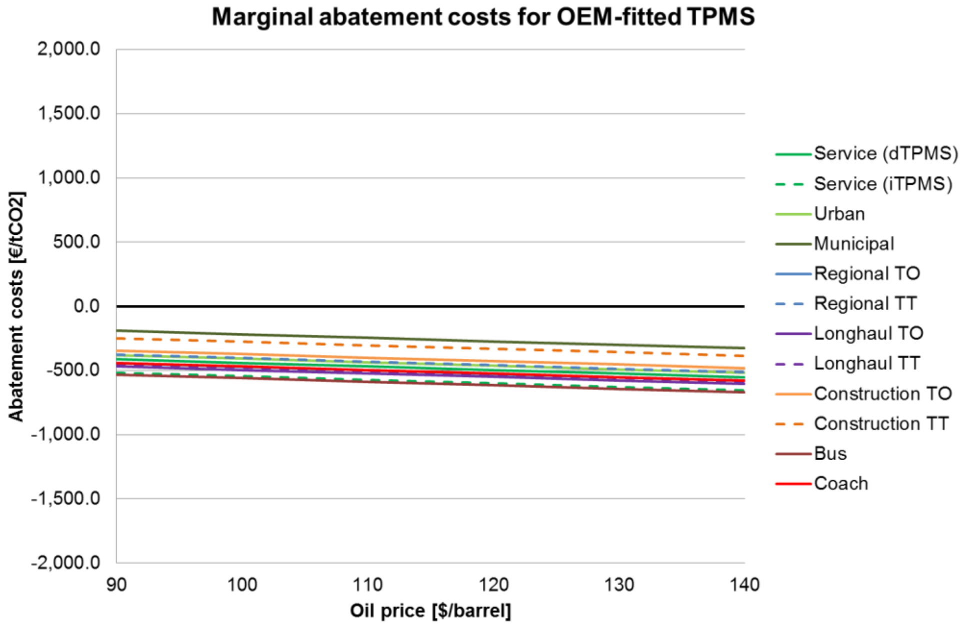

Figure 48: Total cost savings (**"Prospective costs / low savings potential"** scenario) – Marginal abatement costs for an investment in OEM-fitted TPMS

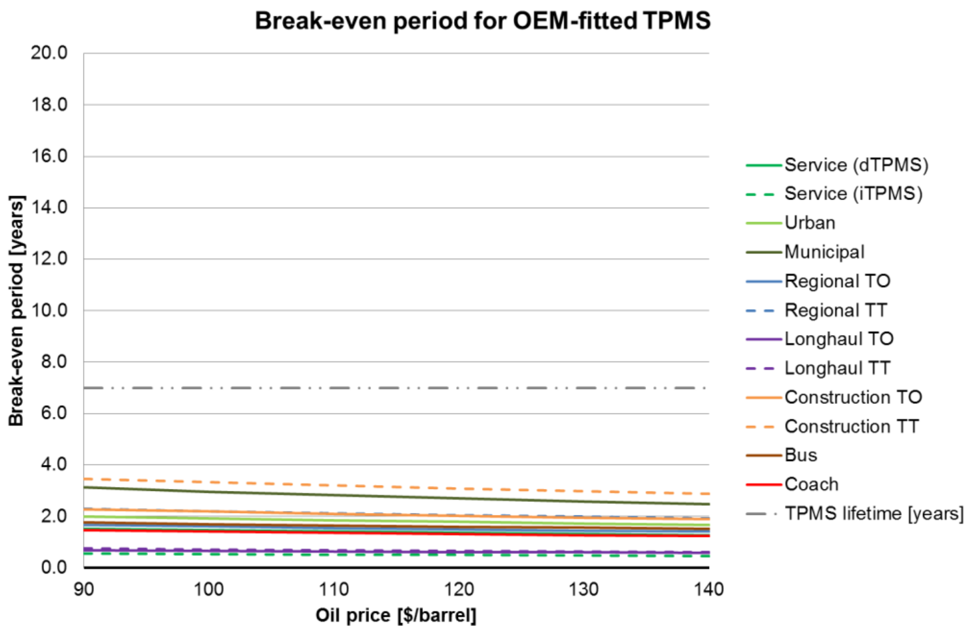

Figure 49: Total cost savings (**"Prospective costs / low savings potential"** scenario) - Break-even period for an investment in OEM-fitted TPMS

Only in the retro-fitted case, TPMS is less cost-effective due to higher investment costs. However, most cases still have negative abatement costs and low break-even periods. This can be interpreted that even if user-compliance is low, TPMS can still be cost-effective.

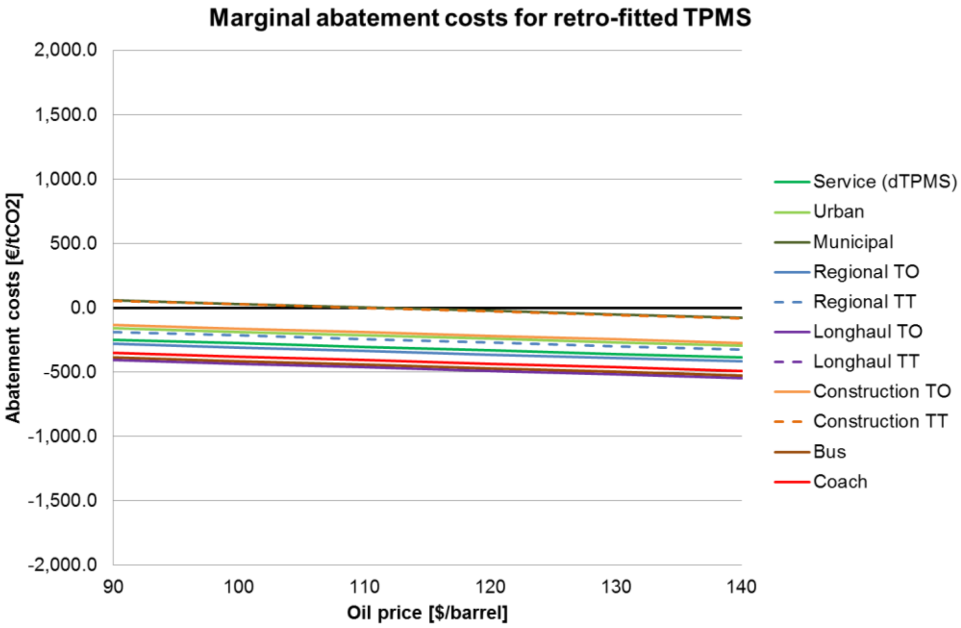

Figure 50: Total cost savings (**"Prospective costs / low savings potential"** scenario) – Marginal abatement costs for an investment in retro-fitted TPMS

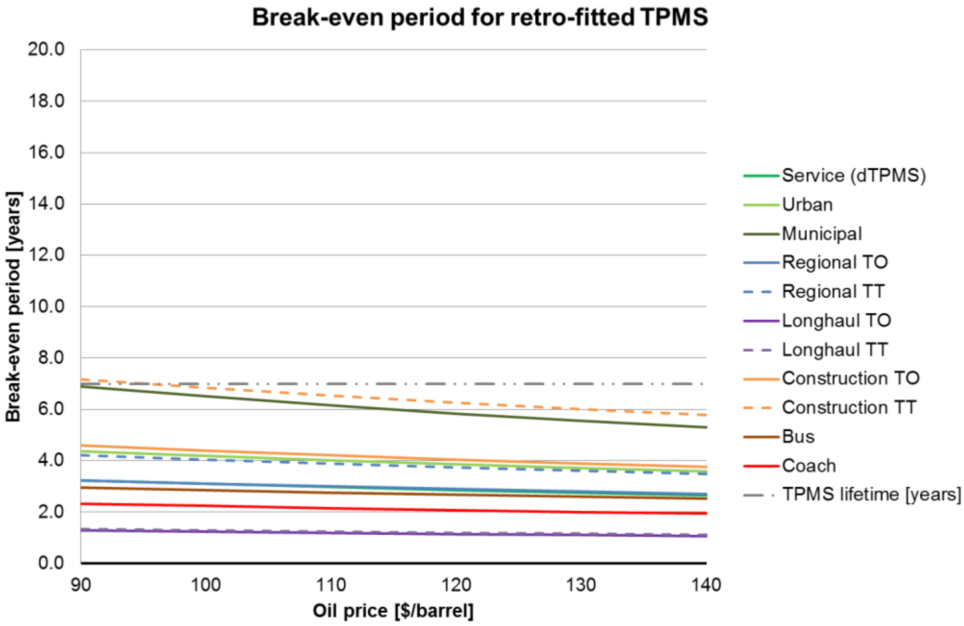

Figure 51: Total cost savings (**"Prospective costs / low savings potential"** scenario) - Break-even period for an investment in retro-fitted TPMS

6.5 Influence of individual cost factors

Below overviews (separately for the societal and end-user perspective) are shown for the costs of OEM-fitted TPMS in the ”current cost / high savings potential” scenario when taking into account of all possible cost savings.

Table 47 shows all costs and cost savings from the societal perspective. When summing up all costs and cost savings, the total is in all cases below zero (which indicates that the implementation of TPMS leads to a net cost saving for society).

From an end-user perspective, the result is not much different (Table 48). The total of the sum of investment minus cost savings remains negative.

Table 47: Changes in annual costs per vehicle for OEM-fitted TPMS from a **societal perspective**, with cost assumptions according to the **“current cost / high savings potential”** scenario, assuming an oil price of 100 $/barrel

Societal perspective	**Invest. costs**		**Operational costs**				**External costs**		
	OEM investment cost (ex VAT)	**Annuity**	**Fuel savings (ex VAT)**	**Extended lifetime of tyres**	**Change in check frequency**	**Reduced break-down**	**Reduced accidents**	**Reduced emissions**	**TOTAL costs**
Vehicle segment	**[€]**	**[€]**	**[€]**	**[€]**	**[€]**	**[€]**	**[€]**	**[€]**	**[€]**
Service/delivery (indirect TPMS)	8	1	-11	-20	+12	-12	-4	-1.8	-36
Service/delivery (direct TPMS)	44	7	-11	-20	+12	-12	-4	-1.8	-30
Urban	164	27	-22	-29	+12	-12	-4	-2.8	-31
Municipal utility	195	32	-23	-18	+12	-12	-3	-2.2	-14
Regional TO	173	29	-30	-44	+12	-12	-6	-3.2	-54
Regional TT	314	52	-43	-88	+24	-12	-6	-4.6	-78
Long haul TO	185	31	-85	-95	+12	-12	-14	-4.2	-168
Long haul TT	338	56	-156	-191	+24	-12	-14	-7.6	-301
Construction TO	234	39	-28	-37	+12	-12	-5	-3.1	-35
Construction TT	395	66	-35	-73	+24	-12	-5	-3.9	-40
Bus	174	29	-19	-37	+12	-12	-5	-1.3	-33
Coach	209	35	-28	-38	+12	-12	-6	-0.9	-38

It is seen that cost savings for an increased tyre lifetime is identical from a societal and an end-user perspective. This has to do with the fact that companies can claim back VAT on these products.

Table 48: Changes in annual costs per vehicle for OEM-fitted TPMS from an **end-user perspective**, with cost assumptions according to the **"current cost / high savings potential"** scenario, assuming an oil price of 100 $/barrel

End-user perspective	Invest. costs		Operational costs				External costs		
	OEM investment cost (ex VAT)	Annuity	Fuel savings (ex VAT)	Extended lifetime of tyres	Change in check frequency	Reduced break-down	Reduced accidents	Reduced emissions	TOTAL costs
Vehicle segment	[€]	[€]	[€]	[€]	[€]	[€]	[€]	[€]	[€]
Service/delivery (indirect TPMS)	8	1	-17	-20	+12	-12	n/a	n/a	-36
Service/delivery (direct TPMS)	44	8	-17	-20	+12	-12	n/a	n/a	-29
Urban	164	31	-34	-29	+12	-12	n/a	n/a	-32
Municipal utility	195	37	-35	-18	+12	-12	n/a	n/a	-17
Regional TO	173	33	-46	-44	+12	-12	n/a	n/a	-57
Regional TT	314	60	-67	-88	+24	-12	n/a	n/a	-83
Long haul TO	185	36	-131	-95	+12	-12	n/a	n/a	-191
Long haul TT	338	65	-240	-191	+24	-12	n/a	n/a	-354
Construction TO	234	45	-44	-37	+12	-12	n/a	n/a	-35
Construction TT	395	76	-54	-73	+24	-12	n/a	n/a	-39
Bus	174	33	-28	-37	+12	-12	n/a	n/a	-32
Coach	209	43	-43	-38	+12	-12	n/a	n/a	-38

In both cases, from an societal as well as from an end-user perspective, the most cost-effective application for TPMS is in a long-haul truck + trailer vehicle.

The overviews in Table 47 and Table 48 also clearly show that cost savings due to extended tyre lifetime are a determining factor in the cost effectiveness of TPMS. They are of the same order of magnitude as the fuel cost savings, and largely explain the differences in cost-effectiveness between the assessment on the basis of investments and fuel cost savings only and the assessment on the basis of all cost factors included in the tables.

The effect of including cost savings due to extended tyre lifetime is somewhat dampened by the extra costs due to increased check frequency.

Other costs have a limited impact on the cost-effectiveness. Especially the external costs savings related to reduced accidents and pollutant emissions turn out to be negligible.

6.6 Conclusions and recommendations

A cost-benefit analysis has been carried out from a societal perspective as well as an end-user perspective.

In the assessment of cost-effectiveness the investment costs, fuel cost savings and reduced accident costs are based on the detailed assessments made in this study. For the other cost factors more indicative estimates have also been derived.

Cost-effectiveness has been estimated for OEM-fitted and retrofit systems and for different LCV and HDV applications separately. Results have been calculated as function of the oil price (through a direct relation between oil price and diesel price). A sensitivity analysis has been carried out by assessing cost-effectiveness for different combinations of scenarios for the costs of TPMS and the potential fuel savings. Furthermore cost-effectiveness has been assessed taking account of all the above-listed cost factors as well as on the basis of TPMS investment costs and fuel cost savings only.

- TPMS is considered cost-effective from an end-user perspective when the payback time is shorter than the average TPMS lifetime of 7 years, determined from supplier responses to the questionnaire.
- If CO_2 abatement costs are negative, TPMS is definitively cost-effective from a societal point of view. But TPMS can also be considered cost-effective from a societal point of view if the abatement costs are positive. This depends on the level of CO_2 abatement costs that is considered acceptable in view of a CO_2 reduction target to be achieved or in comparison with other CO_2 reduction options.

Cost-effectiveness of OEM-fitted TPMS in the “current cost / high savings potential” scenario

As a starting point for the assessment of cost effectiveness the **“current cost / high savings potential”** scenario is taken, which represents the current situation in terms of TPMS production volumes and voluntary adoption.

For OEM-fitted TPMS in a “current cost / high savings potential” scenario the sum of all costs and cost savings, from a societal perspective, is below zero for all applications, which indicates that in this scenario the implementation of TPMS leads to a net cost saving for society. From an end-user perspective, the result is not much different. The total of the sum of investment minus cost savings remains negative.

The fuel price has an influence on cost-effectiveness but under the assumptions made in the “current cost / high savings potential” scenario and taking account of all relevant cost factors OEM-fitted, TPMS is cost-effective for all considered applications from a societal as well an end-user perspective irrespective of assumptions regarding the price of fuel.

In both cases, from a societal as well as from an end-user perspective, the most cost-effective application for TPMS is in a long-haul truck + trailer vehicle.

It was also clearly shown that cost savings due to extended tyre lifetime are a determining factor in the cost effectiveness of TPMS. They are of the same order of magnitude as the fuel cost savings, and largely explain why an assessment of cost-effectiveness on the basis of investments and fuel cost savings only would lead to a significantly less favourable result. The effect of including cost savings due to extended tyre lifetime is somewhat dampened by the extra costs due to increased check frequency.

Other costs have a limited impact on the cost-effectiveness. Especially the external costs savings related to reduced accidents and pollutant emissions turn out to be negligible.

Robustness of the cost-effectiveness of OEM-fitted TPMS to scenario variations

Besides a **“current cost / high savings potential”** scenario, additional scenarios have been evaluated to provide insight into the impact of a lower cost scenario and of scenarios with lower savings potential:

- **“Prospective costs / high savings potential”**: This scenario can be thought to e.g. represent a situation in which TPMS application is mandated (leading to high production volumes and therefore low investment costs) and user response to TPMS signals is high.
- **“Current costs / low savings potential”**: This scenario is used as a worst case scenario. It may represent a future situation in which investment cost remain high while TPMS only results in low savings potential. But it also can be considered representative for a current situation in which TPMS application leads to a reduction of tyre over-inflation, which partly counteracts the estimated savings due to full prevention of under-inflation.
- **“Prospective costs / low savings potential”**: This scenario could e.g. occur in a situation in which TPMS application is mandated (leading to high production volumes and therefore low investment costs) but where user response to TPMS signals is low and/or systems are tampered with. It also caters for the possibility that TPMS application leads to a reduction of tyre over-inflation, which partly counteracts the estimated savings due to full prevention of under-inflation.

For all scenarios cost-effectiveness has also been evaluated on the basis of investment costs and fuel cost savings only, in addition to the above described case in which a range of cost impacts is taken into account.

<u>Taking all cost factors into account</u> the following conclusions can be drawn from the scenario analyses:

- In the **“prospective costs / high savings potential”** scenario, the cost-effectiveness of OEM-fitted TPMS is better than in the ”current cost / high savings potential” scenario. Payback times are generally 2 years or less, and abatement costs are even more negative (order of magnitude -500 €/tonne).
- In the **“current costs / low savings potential”**, with 50% lower fuel savings potential, OEM-fitted TPMS is only cost-effective from an end-user point of view for application in service/delivery vans, regional trucks and long haul trucks. Abatement costs are negative for these applications too, with the exception that for regional trucks with TPMS on truck and trailer this is only the case for oil prices above 115 €/barrel.
- In the **“prospective costs / low savings potential”** scenario, payback times for OEM-fitted systems are generally 3.5 years or less. Abatement costs are negative (order of magnitude -200 €/tonne or less).

When cost-effectiveness is based on <u>TPMS investment costs and fuel cost savings only</u>, payback times are significantly longer and abatement costs higher.

- In the **“prospective costs / high savings potential”** scenario payback times are still below 7 years (lifetime direct TPMS) for all applications, while abatement costs are negative for almost all vehicle categories.
- In the **”current cost / high savings potential”** scenario payback times are above 7 years for construction vehicles (TPMS on truck and trailer) and, in case of low oil prices, also for buses and municipal utility trucks.
- In the **“current costs / low savings potential”** abatement costs are below zero only for long haul trucks and for service/delivery vans with indirect TPMS. Payback times are only below 7 years for long haul applications and for service/delivery vans with indirect and direct TPMS.
- In **“prospective costs / low savings potential”** scenario payback times are below 7 years in most applications and abatement costs are negative. Exceptions are construction vehicles with truck-trailer configuration, for which abatement costs and break-even period are only favourable for higher oil prices.

Cost-effectiveness of retrofit TPMS

Due to the higher investment costs the cost-effectiveness of retrofit TPMS systems is worse than that of OEM-fitted systems.

Taking all cost factors into account retrofit TPMS is cost-effective for:
- all applications in the **“prospective costs / high savings potential”** scenario;
- most applications in the **“current costs / high savings potential”** scenario, with the exception of e.g. service/delivery vans, municipal trucks and construction vehicles with TPMS on truck and trailer. Abatement costs are always below zero only for long haul applications, regional trucks and truck & trailers and service / delivery vans and around zero for a few other applications;
- long haul applications only in the **“current costs / low savings potential”** scenario.
- most applications in the **“prospective costs / low savings potential”** scenario, except for construction TT and municipal vehicles, for which cost-effectiveness depends on the oil price. Above 110 $/barrel, both societal and end-user costs are favourable.

When cost-effectiveness is based on TPMS investment costs and fuel cost savings only, retrofit TPMS is only cost-effective for:
- all applications in the **“prospective costs / high savings potential”** scenario;
- long haul applications, regional truck & trailers and service / delivery vans in the **“current costs / high savings potential”** scenario, with abatement costs below zero only for long haul trucks;
- long haul trucks in the **“current costs / low savings potential”** scenario, when viewed from an end-user perspective. Abatement costs are above zero for all applications.
- long haul trucks, coaches and service delivery vehicles in the **“prospective costs / low savings potential”** scenario, when viewed from an en-user perspective. Abatement costs are below zero only for long haul trucks and coaches for all oil prices.

6.7 References

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7 Task 6 – Rationale for public/legislative intervention

7.1 Introduction

In chapter 6 it was shown that in the “current cost / high savings potential” scenario, and taking into account all considered impacts on operational and external costs, OEM-fitted TPMS is cost-effective for all considered LCV and HDV applications from a societal as well as an end-user perspective. Nevertheless, as described in chapter 4, suppliers expect that autonomous adoption of TPMS will be slow and that market shares will remain small in the coming years, even though TPMS for LCVs and HDVs can be considered a mature product. This may be a motivation for implementing policy measures to promote the uptake of TPMS.

Based on “prospective costs” TPMS is cost-effective for (almost) all applications, regardless of the assumptions on the fuel savings potential or the fuel price. This strengthens the rationale for stronger policy measures such as mandatory fitment, as these would lead to higher production volumes which will result in costs going down from the current level to the estimated prospective costs. For LCVs and long haul applications cost-effectiveness is robust to all considered scenario variations, including the combination of current costs with a low savings potential.

Whether and which policy instruments will be needed for promoting the widespread uptake of TPMS, will depend on the one hand on the size of the economic benefits identified for end-users (long payback periods will not be a strong motivation and require stronger incentives to promote application) and on the other hand on various non-financial barriers which need to be identified.

Possible options that could accelerate the market uptake of TPMS in LCVs and HDVs can be categorised in five policy categories:
- Baseline solution: Do nothing and allow the market to take the initiative.
- Stimulation measures – information
- Stimulation measures – financial
- Voluntary agreements with the sector
- Regulation (mandatory fitment)

For the various options pros and cons and potential impacts are analysed in a qualitative assessment. Based on this analysis a short list of most promising options are identified.

7.2 Evaluation of policy options

The following policy categories have been identified and are discussed in detail in Table 49.

Baseline solution
- Do nothing and allow the market to take the initiative.

Stimulation measures - information
- TPMS performance standard
- Labelling
  - Presence of TPMS visible in tyre labelling scheme

  - In the case of introduction of an HDV CO_2 labelling, the effect of TPMS influences the vehicle's CO_2 score or could be made explicit in the label
- Information campaigns to better disseminate insights in end-user benefits to
  - Dealers
  - Fleet managers

Stimulation measures - financial

- Dedicated fiscal incentives or subsidies (generally at Member State level)
  - Purchase incentive aimed at end users / fleet managers
  - Incentives aimed at vehicle manufacturers or tyre manufacturers
- Broader economic instruments promoting fuel saving and CO_2 reduction
  - E.g. CO_2 tax on fuels or inclusion of HDVs in the EU-ETS

Voluntary agreements with sector

- TPMS-specific voluntary agreement with OEMs and/or the transport sector
  - Stakeholders may agree to implement one or more of the above-mentioned information-related stimulation measures
  - Stakeholders may agree to achieve certain levels of TPMS penetration in targets years
- Broader / generic voluntary agreement with OEMs and/or the transport sector
  - Stakeholders may agree to achieve a certain CO_2 emission reduction in target years, with increased use of TPMS as one of the reduction measures

Regulation (mandatory fitment)

- Regulation for mandatory fitment
  - Regulation may be aimed at vehicle OEMs or tyre manufacturers
  - TPMS performance standard necessary to define minimum requirements for operation, malfunction, warning and pressure range
- Classify TPMS as "eco-innovation" in a possible future CO_2 regulation for HD vehicles

Table 49: Policy options

Measure	Pro	Con	Impact on TPMS penetration	Considerations
Baseline scenario				
Do nothing and allow the market to take initiative	– No government actions required (and no expenses)	– Missed economic benefit due to increased tyre lifetime	0	Cost-benefit analysis has shown that the business case is (on average) positive if all benefits are taken into account, but CO_2 reduction potential is small. The latter could be a motivation for not taking policy action.
Stimulation measures - information				
TPMS performance standard	– More transparency for end-users: – objective assessment of the fuel savings potential – clear benchmark allows easier comparisons between products	– None	+	The LCV and HDV market for TPMS is currently unregulated. Availability of objective information is believed to promote the autonomous market uptake of TPMS.
Labelling: Presence of TPMS visible in tyre labelling scheme	– More transparency for end-users	– None	++	Requires TPMS performance standard
Labelling: In the context of introduction of an HDV CO_2 labelling	– More transparency for end-users	– None	++	The effect of TPMS does not influence the vehicle's CO_2 score directly but a default reduction could be subtracted from the CO_2 score or the presence of TPMS could be made visible in the label. Requires TPMS performance standard
Information campaigns aimed at dealers	– Increases awareness of availability and end-user	– No control over content of information to end-users	+	Retailers should be educated on recent developments in tyre and

Measure	**Pro**	**Con**	**Impact on TPMS penetration**	**Considerations**
	benefits of TPMS – Limited number of stakeholders to be targeted by communication – Low costs			TPMS technology.
Information campaigns aimed at end users / fleet managers	– Increases awareness of availability and end-user benefits of TPMS – Good control over content of information to end-users – Low costs	– Larger number of stakeholders to be targeted by communication	+	Educating fleet managers may increase voluntary uptake of TPMS.
Stimulation measures – financial				
Dedicated fiscal incentives or subsidies (generally at Member State level): Purchase incentive aimed at end users	– Also promotes application of retrofit systems, which may lead to faster increase in overall fleet share – Also promotes TPMS application in replacement tyres	– Large costs to government: administrative costs may be high compared to subsidy as well as end-user benefits – Due to long payback time of retrofit TPMS, financial incentives may need to be large – Significant risk of "free riders" – Risk of varying policies in different Member States	++	Financial stimulation measures are not an obvious candidate, as it is very likely that TPMS is cost-effective for many or all applications. The financial business case at the end-user level does not seem the main barrier for widespread uptake of TPMS.
Dedicated fiscal incentives or subsidies (generally at Member State level): Incentive aimed at vehicle manufacturers	– Promotes most cost effective solutions (OEM-fitted TPMS less expensive than retrofit) – Technology neutral: vehicle	– Targets new vehicles only – No control over TPMS application in replacement tyres – Large costs to government	++	See comment for "Purchase incentive aimed at end users". Is it possible for the EU / EC to provide subsidies to OEMs?

Measure	Pro	Con	Impact on TPMS penetration	Considerations
	OEMs can fit direct or indirect systems	– Significant risk of “free riders” – Negative impact on TPMS price development: necessity for TPMS costs reductions is taken away – Member States unlikely to sponsor application of TPMS on HDVs sold in other countries		
Dedicated fiscal incentives or subsidies (generally at Member State level): Incentive aimed at tyre manufacturers	– Promotes most cost effective solutions (OEM-fitted less expensive than retrofit) – Also promotes application in replacement tyres	– Targets new tyres only – Not technology neutral as tyre manufacturers can only apply direct systems – Large costs to government – Risk of “free riders” – Member States unlikely to sponsor application of TPMS on tyres sold in other countries	++	See comment for “Purchase incentive aimed at end users”. Is it possible for the EU / EC to provide subsidies to OEMs?
Broader economic instruments promoting fuel saving and CO_2 reduction: e.g. CO_2 tax on fuels or inclusion of HDVs in the EU-ETS	– No specific policy instruments for TPMS necessary – No costs to governments	– High CO_2 price needed for significant effect. Other more cost-effective measures likely to be taken first. – Long lead time for introducing broader economic instruments	0/+	From Figure 21 and Figure 19 it can be concluded that a fuel price increase of around 0.40 €/liter reduces the payback time for OEM-fitted systems by 0.5 to 5 years, depending on the application. 0.40 €/liter is equivalent to a CO_2 tax level or CO_2 price under EU-ETS of 150 €/tonne. For retrofit systems a given CO_2 price reduces the payback time by about

Measure	Pro	Con	Impact on TPMS penetration	Considerations
				twice as much as for OEM-fitted TPMS. But payback time needs to be reduced by several years to improve attractiveness of retrofit systems.
Voluntary agreements with sector				
TPMS-specific voluntary agreement with OEMs and/or the transport sector: agreement on measures	– No or limited government action needed – Also promotes TPMS application in replacement tyres is agreement is with tyre manufacturers also – Promotes collaboration between vehicle and tyre manufacturers	– No certainty of reaching desired TPMS penetration – Requires monitoring system – No control over TPMS application in replacement tyres if agreement is with vehicle OEMs only	++	Stakeholders may agree to implement one or more of the above-mentioned information-related stimulation measures. Given the small reduction potential of TPMS care should be taken not to trade in other potentially more effective options for an agreement on TPMS.
TPMS-specific voluntary agreement with OEMs and/or the transport sector: agreement on penetration target	– Freedom for targeted stakeholders to choose most cost-effective TPMS promotion measures – No or limited government action needed – Promotes collaboration between vehicle and tyre manufacturers	– More certainty of reaching desired TPMS penetration than agreement on measures – Requires monitoring system	++	Stakeholders may agree to achieve certain levels of TPMS penetration in targets years. See comment under "agreement on measures"
Broader / generic voluntary agreement with OEMs and/or the transport sector: agreement on overall CO_2 reduction target	– Freedom for targeted stakeholders to choose most cost-effective CO_2 reduction measures – No or limited government action needed	– No control over TPMS penetration levels – Requires complex monitoring system for assessing CO_2 reduction and contribution of	++	Stakeholders may agree to achieve a certain CO_2 emission reduction in target years, with increased use of TPMS as one of the reduction measures.

Measure	**Pro**	**Con**	**Impact on TPMS penetration**	**Considerations**
		stakeholder measures to this		
Regulation (mandatory fitment)				
Regulation for mandatory fitment by vehicle manufacturers	– Certainty of reaching desired TPMS penetration levels – Experience with other similar regulation in EU – Technology neutral: vehicle OEMs can fit direct or indirect systems – Stimulates cost reductions of TPMS	– Targets new vehicles only – Impossible to discriminate between applications with high and low cost-effectiveness – No control over TPMS application in replacement tyres	+++	TPMS performance standard necessary to define minimum requirements for operation, malfunction, warning and pressure range. Mandatory fitment for LCVs only could be considered as cost-effectiveness for this application is robust to all considered scenario variations.
Regulation for mandatory fitment by tyre manufacturers	– Certainty of reaching desired TPMS penetration levels – Experience with other similar regulation in EU – Also promotes TPMS application in replacement tyres – Stimulates cost reductions of TPMS	– Targets new tyres only – Not technology neutral as tyre manufacturers can only apply direct systems – Impossible to discriminate between applications with high and low cost-effectiveness	++++	TPMS performance standard necessary to define minimum requirements for operation, malfunction, warning and pressure range.
Classify TPMS as “eco-innovation” in a possible future CO_2 regulation for HD vehicles	– OEM will only apply TPMS when cost-effective – Eco-innovation credits can be based on assessment made in this report and can be application specific.	– Requires HDV CO_2 regulation to be established first – No control over TPMS application in replacement tyres	++/+++	TPMS performance standard necessary.

7.3 Conclusions and recommendations

Not taking any policy action is an option to be considered, as the relative CO_2 emission reduction potential TPMS is estimated to be less than 0.5%. Other technical options and improvements in the logistics system offer far greater reduction potentials.

Information campaigns seem a no regret option. The focus should in that case not only be on fuel cost savings but also on the benefits of increased tyre life and reduced costs due to tyre blow-outs and other tyre-related incidents. Including TPMS in tyre labelling schemes or in the context of introduction of an HDV CO_2 labelling are feasible and attractive options.

Financial stimulation measures are not an obvious candidate, as it is very likely that TPMS is cost-effective for many or all applications. The financial business case at the end-user level does not seem the main barrier for widespread uptake of TPMS. Due to the relatively small investment costs and savings involved, financial stimulation measures also run the risk of having administrative costs outweighing the potential benefits.

Promotion by the sector of the application of TPMS could be part of a voluntary agreement between the European Commission or a Member State government and the European or national logistics sector. Voluntary agreements are usually the result of negotiations between government and sectoral stakeholders in which it is agreed that the sector takes certain actions in return for a promise by the government not to implement possible government interventions, that are considered undesirable by the sector. Given the relatively small reduction potential of TPMS, care should be taken not to trade in potentially more effective options for voluntary TPMS application.

Regulation for mandatory fitment could be justified if OEM-fitted TPMS is cost effective for most or all applications in the scenarios that could occur in the case of mandatory fitment. When TPMS application is made mandatory through regulation, production volumes will increase significantly, what might lead to lower prices as in the “prospective cost” scenario. Analysis for the combination of the “prospective cost” scenario with scenarios for high resp. low fuel savings potential show that OEM-fitted TPMS could be cost effective for cases in the “prospective cost / high savings potential” scenario and in some of the “prospective cost / low savings potential” scenario. Therefore mandatory fitment of TPMS on new vehicles could lead in the described cost-effective scenarios to benefits for users as well as society. Given the current low market penetration of TPMS for HDVs, a regulation could accelerate mass production and reduce TPMS costs, and thereby could contribute to the materialization of appropriate cost benefits.

Mandatory fitment for LCVs only could be considered as cost-effectiveness for this application is robust to all considered scenario variations. The latter is also true for long haul applications, but as this application is difficult to define from a vehicle regulations point of view, mandating TPMS for long haul HDVs seems not feasible.

Classification of TPMS as “eco-innovation” in a possible future CO_2 regulation for HD vehicles has the advantage that it promotes OEMs to implement this option only in applications where the business case is considered profitable.

Given the uncertainties in the assessment of cost-effectiveness no recommendations are formulated for preferable policy options.

8 Signature

Delft, 29 July 2013

Placeholder

Sam van Goethem
Project leader

Stephan van Zyl
Author

A List of associations & manufacturers contacted during the study

During the project, main market players in the sales of TPMS have been contacted. Below is shown a list of these associations & manufacturers. A copy of the questionnaires is given in the following section(s).

A.1 List of associations & manufacturers contacted

- Before contacting various actors to fill in the questionnaire on TPMS, a categorization and selection was made based on their position in the value chain (from raw material to end product): Sensor manufacturers
- TPMS manufacturer
- Tyre manufacturer
- Vehicle manufacturer
- Fleet Management

Questionnaires sent out: 50
Replies received: 9
Participation rate: 20%

Since not all categories are associated in the sales of TPMS systems, another selection was made in who to contact for input to the questionnaire. Sensor manufacturers and Fleet Management firms were hereby not taken into account. The full list of all associations and manufacturers that contacted for input on the questionnaire is given below (see **Error! Reference source not found.**). Contact details were partly gathered from known contacts in the industry and further completed by research on the internet.

Table 50: List of associations (in bold) and manufacturers (regular print) contacted throughout the study

#	Association / Manufacturer	Contact details
	Sensor	
1	BOSCH	Christian.Hoenicke@de.bosch.com
	TMPS	
2	CLEPA (European Association of Automobile Suppliers)	P.Laurent@clepa.be; L.Holmqvist@clepa.be; a.distefano@clepa.be
3	Stack	sales@stackltd.com
4	TRW Automotive	louise.colledge-contr@trw.com
5	Nira-Dynamics*	jorg.sturmhoebel@niradynamics.se
6	Continental*	ingo.sczesny@continental-corporation.com, eva.appold@continental-corporation.com, frederick.wilde@continental-corporation.com
7	Orange	info@orange-electronic.com

#	Association / Manufacturer	Contact details
8	Schrader*	oe.info@schrader.fr, resale.info@schrader.fr
9	LDL Technologies	info@ldl-technology.com
10	HUF group (prev. BERU)	ralf.kessler@huf-group.com
11	Pacific industries	hsales@pacific-ind.co.jp
12	Delphi	info@tyrepal.com
13	Chongqing Sanxin	info@cccme.org.cn
14	SmarTyre	customerservice@bendixcvs.com
15	Hella	info@hella.com
16	Johnson Control A	info@johnsoncontrols.com
17	Visityre*	info@etv.com.au
18	Actsensor	info@actsensor.com
19	P-Eye	info@peye.nl
20	Impaqed products*	info@impaqedproducts.nl
21	Steel-Mate	info@steel-mate.co.uk
22	WABCO vehicle control systems*	Christoph.adam@wabco-auto.com
23	DORAN	ormsby_ross@doranmfg.com, demis_lee@doranmfg.com
24	Tyrepal	john@tyrepal.co.uk
	Tyre	
25	ETRMA (European Tyre & Rubber Manufacturers' Association)*	Fazilet Cinaralp (Secretary General): f.cinaralp@etrma.org
26	Bridgestone*	Neil.PURVES@bridgestone.eu
27	Michelin	Christophe Penant (in charge of standards&regulations): christophe.penant@fr.michelin.com, Florence Doucy (Public Affairs): florence.doucy@be.michelin.com
28	Goodyear Tyre & Rubber Company	Martina Shchuryk (manager government affairs): martina_shchuryk@goodyear.com
29	Continental GmbH**	rachel.harrison@continental-corporation.com
30	Sumitomo Rubber Industries	info@srigroup.co.jp
31	Pirelli*	info@pirelli.com
32	Yokohama Rubber Company	Sjef de Laat <Sjef@yokohama.nl>
33	Hankook Tyre	a.van.es@hankooktyre.nl
34	Cooper Tyre & Rubber Company	info@coopertyre.com
35	Cheng Shin Rubber Ind.	dquillian@csttyres.com
	Vehicle	
36	ACEA (European Automobile Manufacturers' Association)	Paul Greening: pg@acea.be
37	OICA*	Olivier FONTAINE <ofontaine@oica.net>
38	Fachverband der Fahrzeugindustrie	kfz@wko.at

#	Association / Manufacturer	Contact details
	Österreichs (FFÖ)	
39	Agoria	annie.luchie@agoria.be
40	Chambre Syndicale National des Carrossiers et Constructeurs de Semi-Remorques et Conteneurs (CARSERCO)	
41	Verband der Automobilindustrie e.V. (VDA)	hoeke@vda.de
42	Association of Vehicle Chassis and Body Manufacturers	info@temax.gr
43	Associazione Nazionale fra Industrie Automobilistiche (ANFIA)	a.demaria@anfia.it
44	RAI-Vereniging	r.tekstra@raivereniging.nl
45	Federation of Norwegian Industries	knut.solem@norskindustri.no
46	Associaçao Nacional do Ramo Automóvel (ARAN)	secgeral@aran.pt
47	Asociación Española de Fabricantes de Remolques, Semiremolques, Cisternas y Vehículos análogos (ASFARES)	asfares@terra.es
48	Lasrfordongsgruppen (LFG)	lfg@teknikforetagen.se
49	TREDER Treyler Imalatcilari Dernegii (Association of Trailer Manufacturers)	osmans@tirsan.com.tr
50	The Society of Motor Manufacturers and Traders Ltd. (SMMT)	rdickeson@smmt.co.uk

*Replies received to questionnaire

B Questionnaire

B.1 Definitions & Boundaries

In the questionnaire, the following **definitions and boundaries** are handled:

- TPMS (Tyre Pressure Monitoring System) as defined in Regulation 661/2009. This means that Central Tyre Inflation Systems are not included.
- EU, in specific EU-27. Throughout this study, the focus lies on the EU. Other markets around the world are not included.
- Vehicles: Throughout this study, when referring to vehicles, only LCVs & HDVs are considered. The following definitions are handled:
    - LCVs (N1 vehicles and N2 and M2 with reference mass not exceeding 2610 kg),
    - HDVs (vehicles of class N2 and M2 that are not LCVs and M3 and N3 vehicles).

EU class	Example
M2	
M3	
N1	 
N2	 
N3	

1 Technology

Question 1.1 – Does your company apply TPMS?

In the configuration of tyres, does **your company** make use of TPMS technology? Please tick the box below.

- If the answer is No, you can skip the following questions and return the survey.

Yes	No

Question 1.2 – Types of TMPS used in different vehicle classes

What kind of TPMS technology does **your company** use for LCVs & HDVs? In the following list, please provide product name and supplier of the technology.

- If you have a factsheet of your TPMS system(s) you can share with us, please provide a copy of it in your response.
- If different technologies are used for different vehicle models / variants within the same vehicle class, please feel free to add lines and indicate the various systems applied.

		TPMS technology								
	EU class	**Supplier**	**Product name**	**System type** (direct / indirect)	**Sensor type** (pressure / temperature / both)	**Sensor position** (on rim/in tyre/on valve)	**Display type** (dashboard / handheld / on wheel /PC via satellite)	**Display functions** (bars & ˚C / % deviation from nominal / only alerts)	**Technical life time** (in months)	**Compatible with how many wheels?**
LCVs	**M2 (<2.61t)**									
	N1									
HDVs	**M2 (>2.61t)**									
	M3									
	N2									
	N3									

Other comments?

Question 1.3 – Suppliers & Technologies

Which suppliers does **your company** see as the main market players for TPMS systems (TOP 5)? What is the name of the product / technology?

TOP 5	Supplier	Product name
1		
2		
3		
4		
5		

Other comments?

Question 1.4 – Current experience

What is your current experience with TPMS systems (e.g. largest benefits & shortcomings)?

Question 1.5 – Future developments

What does **your company** consider to be the next technological steps for improving TPMS system technology? Please specify:

Question 1.6 – Costs

What are the additional costs associated for a vehicle configuration with your TPMS system?

- Once again, if different technologies are used for different vehicle models / variants within the same vehicle class, please add lines and indicate the various systems applied.

		TPMS technology	
	EU class	Additional costs [€]	Additional costs [%]
LCVs	M2 (<2.61t)		
	N1		
HDVs	M2 (>2.61t)		
	M3		
	N2		
	N3		
AVERAGE			

Other comments?

Question 1.6 – Costs (Amendment)

in order to get a more specific result for the cost-benefit calculation, we have further split up the EU vehicle classes into vehicle types (see table below). The main difference of this split lies in the axle configuration for n2 & n3 trucks (i.e. 2, 3, 4 à meaning 4,6,8 wheels). Where possible, we kindly ask you to fill in the costs for these configurations, respectively.

EU vehicle class	vehicle type		TPMS price (ex VAT) [in €]
N1	Light Commercial Vehicles		e.g. 20-50€ (see questionnaire)
N2 <=7.5t	Truck 2-axles	4x2 Rigid < 7.5t	Etc.
N2 >7.5t		4x2 Rigid + (Tractor) 7.5-10t	
N2 >7.5t		4x2 Rigid + (Tractor) > 10-12t	
N3		4x2 Rigid + (Tractor) > 12-16t	
N3		4x2 Rigid > 16t	
N3		4x2 Tractor > 16t	
N3		4x4 Rigid 7.5-16t	
N3		4x4 Rigid >16t	
N3		4x4 Tractor >16t	
N3	Truck 3-axles	6x2/2-4 Rigid All Weights	
N3		6x2/2-4 Tractor All Weights	
N3		6x4 Rigid All Weights	
N3		6x4 Tractor All Weights	
N3		6x6 Rigid All Weights	
N3		6x6 Tractor All Weights	
N3	Truck 4-axles	8x2 Rigid All Weights	
N3		8x4 Rigid All Weights	
N3		8x6/8x8 Rigid All Weights	
M2	Bus / Coach	Minibus	
M3		City Class I	
M3		Interurban Class II	
M3		Coach Class III	

Market

Question 2.1 – Share of TPMS: OEMs & retrofits

To your knowledge, considering the range of TPMS systems that are sold on a yearly basis in the EU …

a) what is the share of TPMS sold by OEM vehicle manufacturers [**in %**]?
b) what is the share of TPMS sold by retailers [**in %**], for retrofit applications ?
c) If applicable, what is the share of TPMS systems sold by other parties that do not fall under the categories above [**in %**]?

		TPMS market composition		
	EU class	**a) TPMS sold by OEMs [%]**	**b) TPMS sold by retailers [%]**	**c) TPMS sold by others [%]**
LCVs	**M2 (<2.61t)**			
	N1			
HDVs	**M2 (>2.61t)**			
	M3			
	N2			
	N3			
AVERAGE				

Other comments?

Question 2.2 – Share of TPMS in your company's sales

Considering the range of tyres that **your company** sells on a yearly basis in the EU, what is the share of tyres (for LCVs & HDVs) that are being equipped with TPMS [**in %**]?

		Share of tyres sold with TPMS by your company in the EU [%]		
	EU class	**2010**	**2011**	**2012**
LCVs	**M2 (<2.61t)**			
	N1			
HDVs	**M2 (>2.61t)**			
	M3			
	N2			
	N3			
AVERAGE				
		Sales past 3 years		

Other comments?

Question 2.3 – Expected share of TPMS retro-fits

To your knowledge, considering the range of vehicles that **your company** sells on a yearly basis in the EU, what is the share of tyres (originally not equipped with TPMS) that are retro-fitted with TPMS **[in %]**?

		Share of tyres sold without TPMS by your company & retrofitted with TPMS in the EU[%]		
	EU class	**2010**	**2011**	**2012**
LCVs	**M2 (<2.61 t)**			
	N1			
HDVs	**M2 (>2.61 t)**			
	M3			
	N2			
	N3			
AVERAGE				

Sales past 3 years

Other comments?

Question 2.4 – Overall market share of TPMS

To your knowledge, considering the range of tyres that are sold **in TOTAL** on a yearly basis in the EU, what is the share of tyres that are equipped with TPMS **[in %]**?

		TOTAL share of tyres with TPMS sold in EU [%]		
	EU class	**2010**	**2011**	**2012**
LCVs	**M2 (<2.61t)**			
	N1			
HDVs	**M2 (>2.61t)**			
	M3			
	N2			
	N3			
AVERAGE				
		Sales past 3 years		

Other comments?

Question 2.5 – Autonomous market trends in the absence of additional policy measures

Which trends, and associated threats or opportunities do you observe in the market for TPMS systems (TOP 5)? In the box below, please specify:

TOP 5	Trends	Threats / Opportunities
1		
2		
3		
4		
5		
Example	TPMS prices are dropping. In the last ten years cost price dropped by 50%	Thread: price competition shifts production to lower wage countries. Opportunity: the system can earn itself back in a shorter amount of time

Other comments?

Question 2.6 – Projections

How do you expect the trends specified above to influence the share of TPMS systems sold on tyres for LCVs & HDVs for **your company**? How is this projected in the expected sales of tyres with TPMS **[in % of total tyres sold]** on a short term basis (in 2 years) and on a long term basis (in 6 years)?

		Projected market share of tyres for LCVs & HDVs with TPMS sold by your company in EU [%]					
	EU class	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
LCVs	**M2 (<2.61t)**						
	N1						
HDVs	**M2 (>2.61t)**						
	M3						
	N2						
	N3						
AVERAGE							
			…in 2 years				**…in 6 years**

Other comments?

Safety

Question 3.1 – Share of tyre failures attributed to incorrect tyre pressure

To your knowledge and for the specified vehicle categories, …

a) what is the share of accidents occurring due to tyre failures in general?
b) what is the share of tyre failures due to incorrect tyre pressure?

	EU class	a) Share of accidents attributed to tyre failures [%]	b) Share of tyre failures attributed to incorrect tyre pressure [%]
LCVs	M2 (<2.61t)		
	N1		
HDVs	M2 (>2.61t)		
	M3		
	N2		
	N3		
AVERAGE			

Other comments?

Question 3.2 – Types of accidents related to tyre failure

To your knowledge, what type of accidents result from tyre failure? Please fill in and indicate percentage:

- The table below is not complete. Room is left for further additions in types of tyre failures and accident type. If you perceive other types, please specify below.

	Share of tyre failure related accident for different accidents types [%]				
Accident type	**Share due to tyre blow out**	**Share due to too low pressure**	**Share due to too high pressure**	**If other, please specify.**	**…**
Rollover					
Spin out					
Collision					
Jack-knife					
If other, please specify.					
…					
TOTAL (=100%)					

Other comments?

Question 3.3 – Acceptable tyre pressure variation

What range of tyre pressure variation do you consider acceptable?

- Tyre pressure variation is here expressed as deviation from the defined nominal value for specific vehicle load conditions.

		Acceptable tyre pressure variation [%]	
	EU class	**Lower limit**	**Upper limit**
LCVs	**M2 (<2.61t)**		
	N1		
HDVs	**M2 (>2.61t)**		
	M3		
	N2		
	N3		
AVERAGE			

Other comments?

Potential for reduction in fuel consumption and CO_2 emission

Question 4.1 – Share of kilometres driven with under-inflated tyres

To assess the possible effect of TPMS on fuel consumption and CO_2 emissions, an assessment is needed on the actual share of LCVs & HDVs running on the road with under-inflated tyres. To your knowledge, what is the share of kilometres [% of vehicle-km] driven with under-inflated tyres?

- If possible differentiate according to ranges of under-inflation [% under-inflation]. For example, in a certain EU class: 60 [% of vehicle-km] drive with 0 to 10 [% under-inflation], 20 [% of vehicle-km] drive with 10 to 20 [% under-inflation], 5 [% of vehicle-km] drive with 20 to 30 [% under-inflation] & 5 [% of vehicle-km] drive with >30 [% under-inflation].
- Here, it is assumed that the range of under-inflation is dictated by the tyre with the largest deviation from nominal pressure. For example, a vehicle with 4 wheels/tyres and one tyre at 25 [% under-inflation] is considered as a whole vehicle with 25 [% under-inflation]. If this differs from your assumptions, please specify.

		Share of kilometers driven with under-inflated tyres [% of vehicle-km]			
	EU class	**0 to 10 [% under-inflation]**	**10 to 20 [% under-inflation]**	**20 to 30 [% under-inflation]**	**>30 [% under-inflation]**
LCVs	**M2 (<2.61t)**				
	N1				
HDVs	**M2 (>2.61t)**				
	M3				
	N2				
	N3				
AVERAGE					

Question 4.2 – Impact of under-inflation on rolling resistance and fuel consumption

To assess the potential of TPMS for LCVs & HDVs, an assessment is needed on …

a) how under-inflation affects the rolling resistance coefficient (RRC) of the tyres.
b) how under-inflation affects the fuel consumption or CO_2 emissions of the vehicle.

Please write your references below (% values preferred, if absolute reduction values are given, please provide the base value too):

a) Suggestions for **literature or own equations** to calculate the reduction in RRC as function of under-inflation in tyres?

Example of estimation: % reduction of RRC = % under-inflation * x

b) Suggestions for **literature or own estimations** to calculate the additional fuel consumption or CO_2 emissions as a function of under-inflation in tyres (% values preferred, if absolute reduction values are given, please provide the base value too):

Example of estimation: % reduction in fuel consumption or CO2 emission = % under-inflation * x

C State-of-the-art technology

In this annex, several technologies of TPMS are discussed in detail. Examples are shown of direct systems and indirect systems. However, since indirect systems are expected only play a limited role in the application with LCV and HDV vehicles, only one indirect system is discussed. An overview of the discussed products are shown in Table 51.

Table 51: Overview of currently available technologies

	Direct TPMS								**Indirect TPMS**	
Group	Battery-powered						Batteryless			
Sensor position	On valve / in tyre					On valve				
Supplier	Schrader	Bridgestone	Pirelli	Wabco	Continental	P-eye	Stack	VisiTyre	SRI/DunlopTECH	NIRA Dynamics

A differentiation is made between direct systems and indirect systems. Within these two categories another split is made between:

- Direct: battery-powered & battery-less systems, as well as
- Indirect: 1st generation & 2nd generation systems

Further on, each system is discussed in detail.

C.1 Schrader LCV/HDV TPMS

Type	Direct	
Performance	Range:	0-10 bar
	Resolution:	n/a
	Lifetime:	[10 yrs]
Particular features	Autolocation	
	Load detection	

Schrader Electronics is by far the largest worldwide supplier of Direct TPMS sensors/systems for passenger cars & light trucks. On the top of that, Schrader Electronics is expanding its product range to Direct TPMS sensors/systems for HDV & Buses.

Below, in Figure 52, is given an overview of the Schrader TPMS system. It consists of three main system components:

- TPMS pressure/temperature sensor (valve mounted or tyre mounted)
- TPMS ECU
- TPMS Active Antenna (ALM)

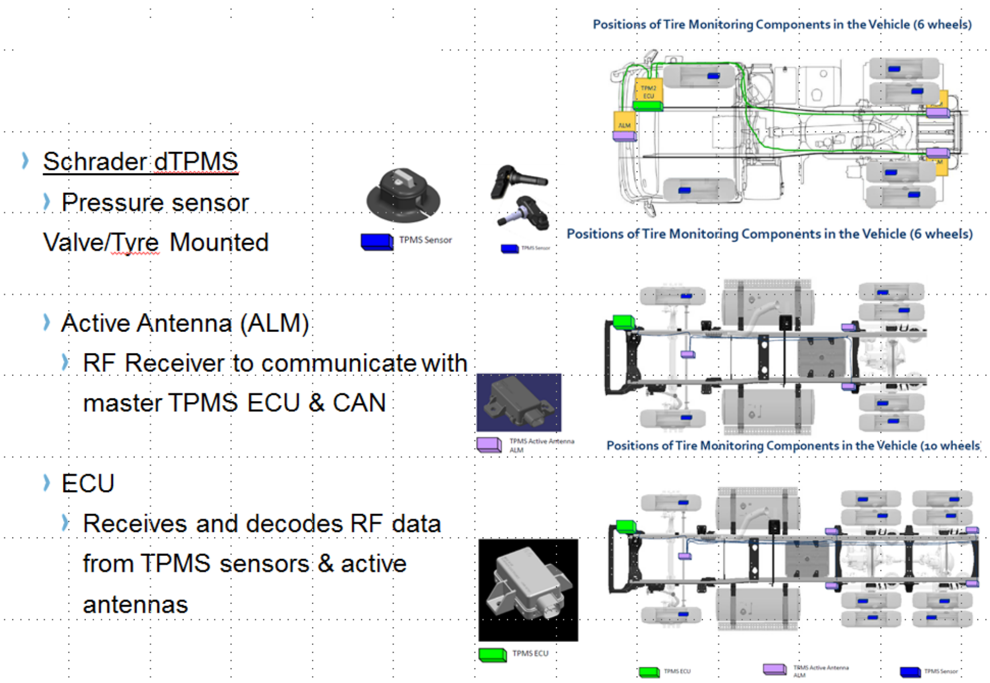


Figure 52: Schrader LCV/HDV TPMS [Schrader, 2013]

TPMS pressure/temperature sensor

- **Valve mounted** sensors: basic functionality of measuring pressure/temperature, detects motion and direction of rotation of wheel, transmits information to TPMS ECU or Active Antennas via RF
- **Tyre mounted** sensors: additional functionality of detecting tyre load, tyre ID, revolution count (tyre life)

TPMS ECU

- Receives and decodes RF data from the TPMS Sensors and optionally data from the various TPMS Active Antennas
- Contains all TPMS software logic such as:
  - Warning Strategy
  - Auto-Learn & Locate
  - Failure Manager etc.
- Provides HMI control via CAN TPMS ECU

TPMS Active Antenna (ALM)

- External slave RF Receiver
- Communicates with Master TPMS ECU via LIN or CAN

The combination of these system components varies per vehicle categories and depends on the vehicle setup, the vehicle length and the number of wheels to be monitored. A vehicle that already includes a RF receiver for other purposes (RKE, passive entry,…) does not require a TPMS ECU. TPMS ALM is needed to bridge large distances from TPMS sensor to TPMS ECU and therefore depends on the vehicle length and number of wheels positions.

C.2 Bridgestone TPMS

Type	Direct	
Performance	Range:	0-12 [bar]
	Resolution:	+- 0.1 [bar]
	Lifetime:	3 [yrs]
Particular features	Tyrematics applied for Total Fleet Management	

Bridgestone Europe have developed its own system aimed at controlling pressure on contracted fleets (where Bridgestone has a contract to maintain the tyres). The solution has 3 valve mounted sensor variants to fit to all wheel positions and a gate system located on the fleet. Data is automatically sent from the gate to a central system where it is analysed and if any deviation outside the defined pressure limit an e-mail is automatically sent to the fleet and service provider so the issue can be resolved.

The TPMS system that Bridgestone is introducing across Europe features a patented valve with a unique Radio Frequency (RF) unit. Specific valves are available for commercial vehicles and passenger cars. These RF units emit the tyre pressure, temperature and unique identification number every 4s, giving the unit a lifespan of a minimum of 3 years. The system is rolling out as a tool within Bridgestone’s Total Fleet Management package which provides full tyre maintenance services within a fleet. Using either detector gates mounted at the fleet premises or handheld data-collection units, vehicle maintenance managers are able to receive targeted pressure alerts so they can quickly react before a low pressure turns into a tyre failure.

The system comprises an external valve-mounted sensor (1), a receiver gate mounted at the fleet site (2), a cloud-based data system and the tyre service provider (3), see Figure 53 [BS, 2013].

The small sensor uses patented low power technologies that enable it to send out a signal every 6 seconds while giving it a battery life of at least 3 years. Three versions have been developed to allow optimal fitment whatever the wheel position on the truck or bus. The sensor sends pressure and temperature data as well as an ID allowing the corrected pressure to be attributed to the specific vehicle and wheel position.

The gate receiver consists of 4 towers that are wirelessly connected and battery powered (with solar panel charger). When a vehicle equipped with Bridgestone TPMS sensors drives through the gate, the towers capture the tyre data and then send it on a regular basis to the Bridgestone database. If a very low pressure is detected the data is sent instantaneously.

A handheld receiver allows TPMS to function with the Bridgestone T2i system; especially useful for locations where a gate may be impractical. The central T2s data system receives data from the gate or T2i and then matches the sensor ID to the specific fleet, vehicle and wheel position data to determine the recommended pressure. The pressure measurement will indicate whether the tyre needs a regular maintenance or urgent action.

In the case of an urgent action status (e.g. pressure lower than 20% below recommended), an automated message is sent to the fleet and service provider who then coordinate to ensure that the vehicle is stopped and an investigation made. The service provider of the Bridgestone fleet is trained to manage the incoming messages and make the relevant actions in a correct and timely manner.

Figure 53:   Bridgestone TPMS with Tyrematics [BS, 2013]

C.3 Pirelli Cyberfleet/TMS

Type	Direct	
Performance	Range:	0-12 [bar]
	Resolution:	+- 0.25 [bar]
	Lifetime:	4 [yrs]
Particular features	Cyberfleet	

Cyberfleet is a fleet management system for commercial vehicles such as trucks, trailers and busses. From a partnership of Schrader Electronics and Pirelli, cyberfleet is a fleet management system which combines state of the art track&trace feature together with robust and market proven tyre pressure monitoring system (TPMS), also see Figure 54 below [Pirelli, 2013].

Figure 54: Cyberfleet [Pirelli, 2013]

C.4 WabCo-Auto iVTM

Type	Direct	
Performance	Range:	n/a
	Resolution:	n/a
	Lifetime:	8 [yrs]
Particular features	TrailerGUARD™ Telematics	

WABCO's Integrated Vehicle Tyre Pressure Monitoring system (IVTM) is especially developed for commercial vehicles. IVTM provides the driver with constant updates of tyre pressures directly from each monitored wheel. In combination with TrailerGUARD telematics (see Figure 55), IVTM also reports the tyre pressures to a web portal and warns the fleet manager or dispatcher via SMS or e-mail [WabCo, 2013].

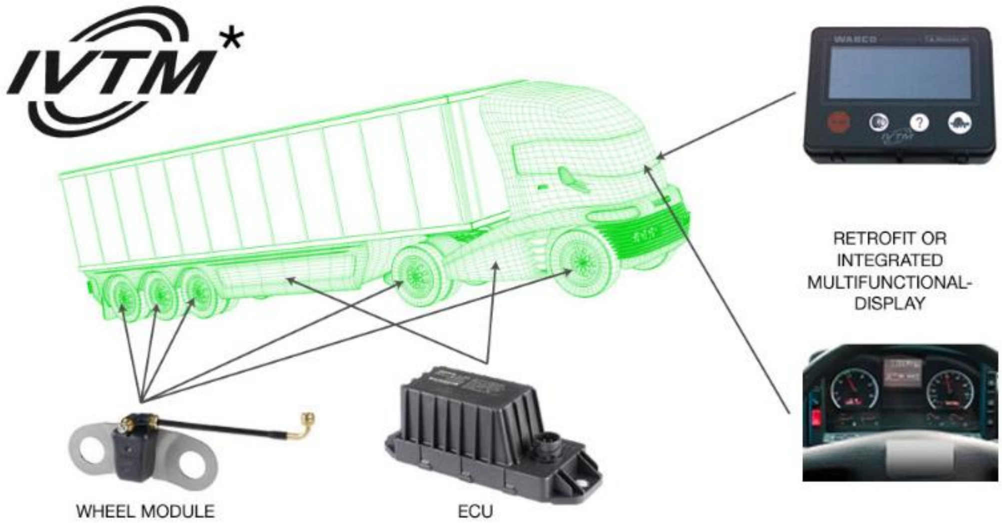


Figure 55: WabCo-Auto iVTM [WabCo, 2013]

C.5 Continental ContiPressureCheck (CPC)

Type	Direct	
Performance	Range:	n/a
	Resolution:	n/a
	Lifetime:	6-8 [yrs]
Particular features	Rim mounted or tyre mounted TPMS	
	LocSync	

Continental's ContiPressurceCheck is an aftermarket – retrofit solution that was launched on market in January 2013. It is a direct measuring system that is mounted into the tyre [Conti, 2013].

A schematic overview of the system is shown in Figure 56. A sensor in the tyre measures the pressure and temperature (1). The signal is wirelessly transmitted to the receiver ECU (2), where the signal is processed and analysed. The absolute pressure values are displayed (3) on a handheld device to the chauffeur in the cabin. In case the pressure drops below a certain threshold, a warning is given to the chauffeur.

Conti also able to offer automatic localization in the future (LocSync) - further offering lower cost for the localization function (today done by expensive additional antennas) on both the HW side and also on time saved in learning the sensor positions manually.

Figure 56: Continental ContiPressureCheck (CPC) [Conti, 2013]

C.6 P-eye dTPMS

Type	Direct	
Performance	Range:	n/a
	Resolution:	pre-defined alarm at 8.5 [bar]
	Lifetime:	limited to battery lifetime prone to damage, since externally mounted
Particular features	External device, easily installed & removed	

Working principle of P-eye is as follows: The valve cap is replaced by the P-Eye. If the tyre pressure drops below the pre-determined alarm pressure, the pressure switch passes a signal to a LED light which starts to flash. The driver or vehicle fleet owner can now see (visually) that the tyre pressure has dropped below the pre-determined level. The P-Eye can be easily removed. As soon as the tyre has the right pressure, the P-Eye can be put back in place. When the tyre has the right pressure, the LED will stops flashing [P-eye, 2013].

The P-EYE works with a mechanical switch. This switch is actuated by a bellow. This bellow will be convex when it is pressurized. When de pressure drops the bellow will be flat. The switch makes contact with the surface. Now you get a working circuit and the LED will flash (see Figure 57) [P-eye, 2013].

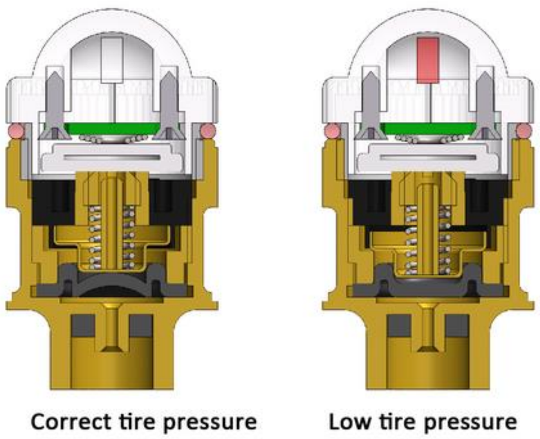


Figure 57: P-eye [P-eye, 2013]

C.7 Stack TPMS PRO system

Type	Direct	
Performance	Range:	0-10 [bar]
	Resolution:	+-0.017-0.069 [bar]
	Lifetime:	in theory unlimited since battery-less
Particular features	Battery-less TPMS	

System uses patented Surface Acoustic Wave (SAW) sensing technology to dynamically measure tyre pressures and temperatures. The SAW sensor elements require no supporting electronics or battery. When the system is not in use, the TPMS sensors are completely passive, i.e. not emitting any RF signal [Stack, 2013].

An illustration of the technology is shown in (Figure 58). Each TPMS sensor (A) is mounted internally within the tyre, either on the rear of the valve stem, or directly on the wheel rim. A central module (B) ‘interrogates’ each wheel sensor in turn, by transmitting an RF ‘power’ signal. Three SAW elements inside the TPMS sensor each re-transmit a specific RF frequency, corresponding to the pressure and temperature inside the tyre. The interrogator (C) receiver picks up the SAW RF signals and converts them into pressure and temperature data, which are transmitted on a CAN bus for use by a data logger and/or driver display [Stack, 2013].

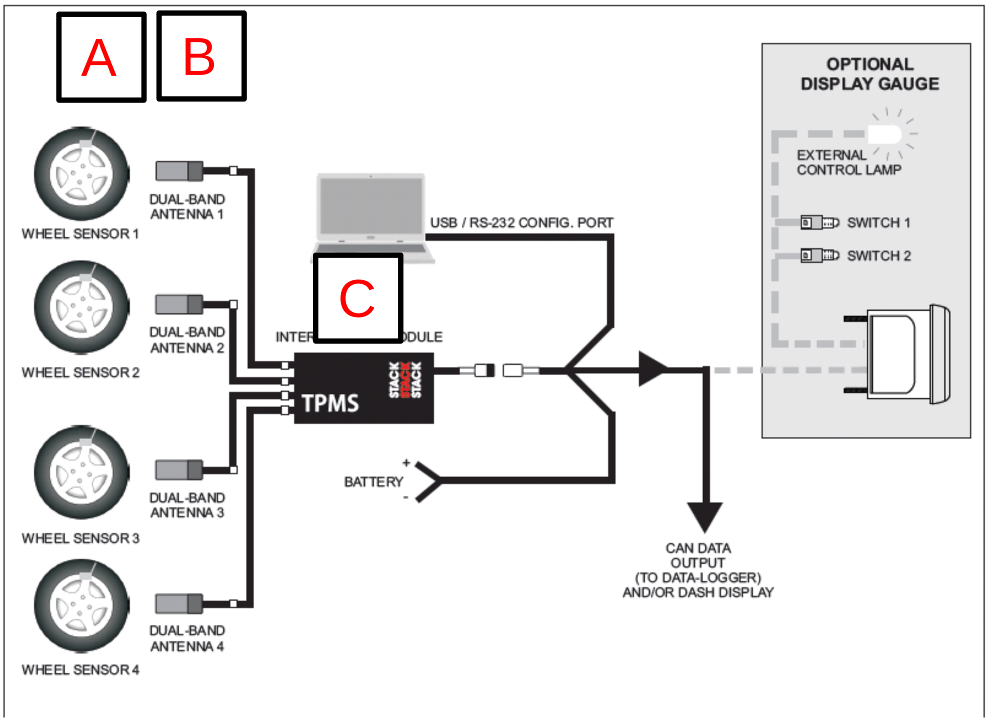


Figure 58: Stack TPMS PRO system [Stack, 2013]

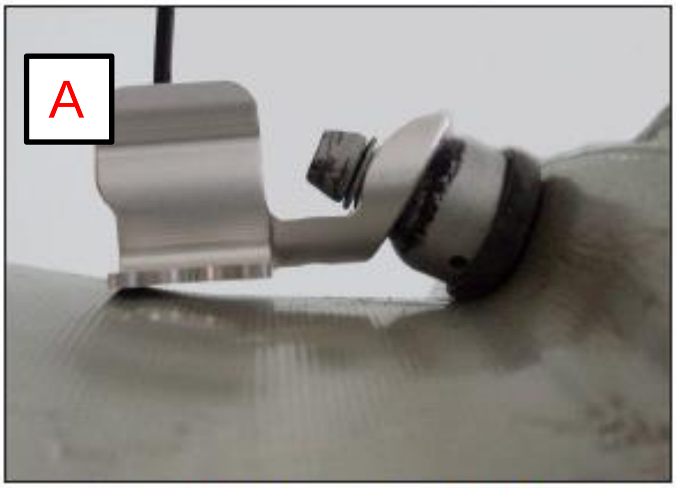


Figure 59: A TPMS sensor is mounted internally within each tyre either on the rear of the valve stem or directly onto the rim [Stack, 2013]

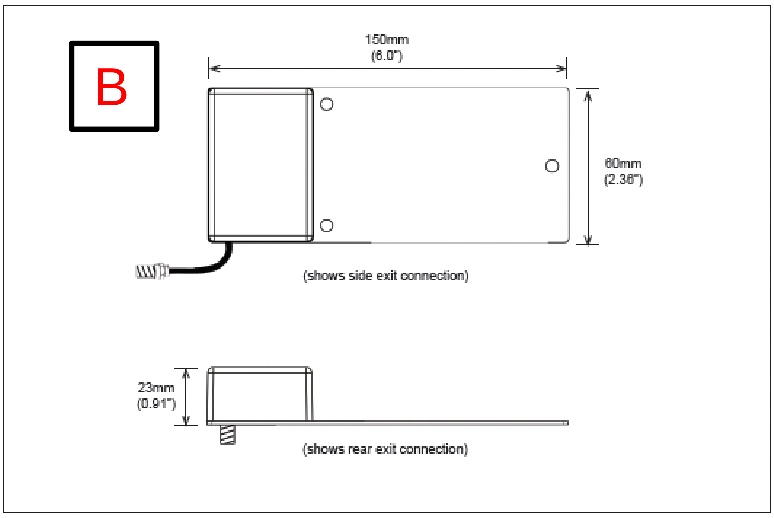


Figure 60: Dual band Antenna: 4 antennas are each mounted locally to each wheel (within approx. 0.5m of the wheel) and connected to the interrogator module via a RF cable [Stack, 2013]

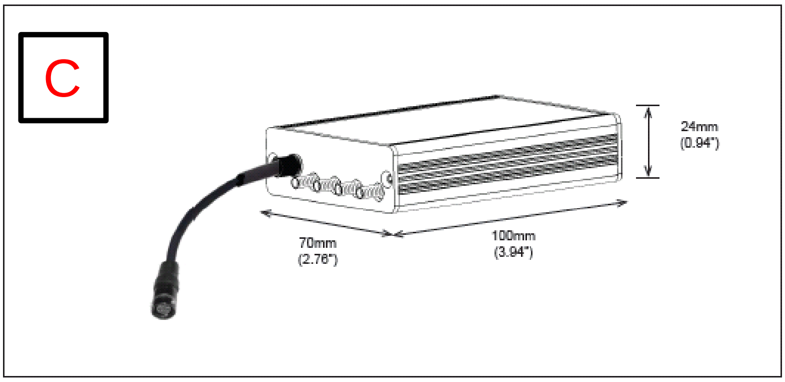


Figure 61: Communication CAN DATA logger (if you want to read out on PC i.e. via USB or RS232). The interrogator CAN bus is used to transmit pressure and temperature data to the Stack TPMS gauge / an external data logging system / dash display module [Stack, 2013]

C.8 VisiTyre Batteryless TPMS

Type	Direct	
Performance	Range:	0.5 [bar] to 6.4 [bar]
	Resolution:	+-0.07 [bar]
	Lifetime:	in theory unlimited, since battery-less
Particular features	Battery-less TPMS	
	Possibility to combine with telematics	

VisiTyre is a Battery-Less Tyre Pressure Monitoring System featuring inductively coupled circuits for the non-contact transmission of power and data across a vehicle's rotating wheel chassis boundary. The system's unique electromagnetic coupling obviates the need for any wheel module sensor batteries and allows instant monitoring and reporting of every tyre's status immediately the vehicle's ignition is switched on. VisiTyre's sensor power is derived from an electromagnetic coupling which effectively eliminates the need for a sensor battery, see Figure 62 [VisiTyre, 2013].

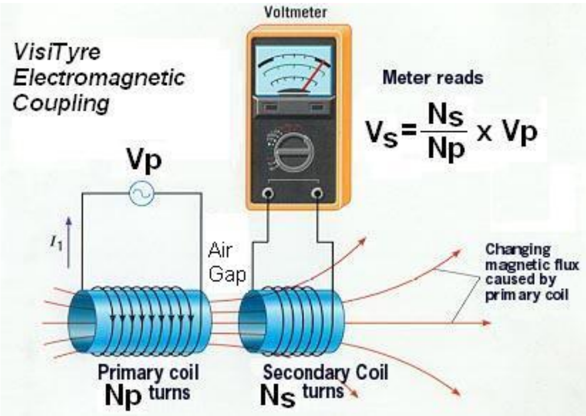


Figure 62: Working principle VisiTyre: Wireless power is transmitted to TPMS pressure sensor via electromagnetic coupling [VisiTyre, 2013]

The VisiTyre Electronic Control Unit is a microprocessor controller unit which interfaces the brake calliper mounted reader Coils - and a spare wheel mounted reader Coil - to the vehicle's instrument cluster display system. This is a chassis mounted electronic module powered from the vehicle's battery. The module's software receives and analyses tyre data for Pressure and Temperature activation floor threshold alarm conditions. [VisiTyre, 2013].

Each VisiTyre Caliper Coil is energized in sequence by the VisiTyre Electronic Control Unit in order to supply energy to its adjacent rim coil over the air gap which exists at the rotating wheel chassis boundary. Each VisiTyre Rim Coil supplies inductively coupled energy from its adjacent caliper coil to its respective rim sensor. VisiTyre's Rim Sensor is a high accuracy pressure and temperature sensor subsystem based on micro-machined silicon technology. It has a digital core with a 2-terminal interface for the simultaneous supply of power and transmission of data. A simple Twisted Pair Wiring Harness is used to connect the VisiTyre Enabled Brake Caliper mounted Coils to the VisiTyre Electronic Control Module [VisiTyre, 2013].

C.9 DUNLOP TECH Warnair

Type	Indirect	
Performance	Range:	from 2.0 [bar] to 3.5 [bar]
	Resolution:	-15 [%] wrt. cold inflation pressure
	Lifetime:	n/a
Particular features	Autolocation by use of spectral analysis	

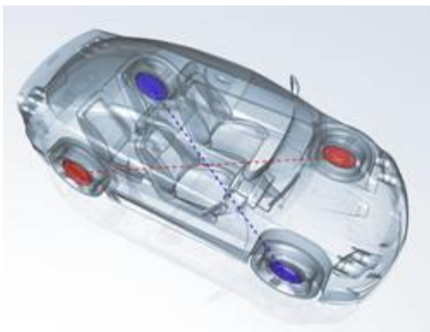
DUNLOP TECH develops and applies the software of the DUNLOP TECH Warnair tyre pressure loss detection system for passenger cars and light commercial vehicles (categories M1 and N1) [DUNLOP, 2013].

DUNLOP TECH Warnair is an indirect measuring system, i.e. it does not require any components inside the tyre or on the wheel. It monitors the change in tyre characteristics with changing tyre pressure by using the signals and measuring parameters already available within the vehicle solely by software. For this reason, both its manufacture and in-vehicle operation are to be considered as CO2 neutral The DUNLOP TECH Warnair System is an integrated component of selected BOSCH ABS and ESP systems. While BOSCH is responsible for the production and adjustment of the ABS/ESP components, DUNLOP TECH takes care of the application of the WARNAIR functions in vehicles manufactured in Europe. In the USA this task is assumed by Sumitomo Rubber Industries Automotive Technology (SRIAT) and in the Asian market by patent owner Sumitomo Rubber Industries Ltd. (SRI). [DUNLOP, 2013].

DUNLOP TECH Warnair is based on the comparison of the four wheel rotational speed signals to one another as well as to reference data which are made available by the ABS/ESP systems. DUNLOP TECH Warnair detects losses in pressure "indirectly", i.e. due to the changes of rolling circumference resulting from a tyre losing air. Second-generation Warnair (DDWS) uses - beside the evaluation of the rolling circumference - further possibilities for the detection of changes in tyre characteristics as they occur when the tyre is losing air. For instance, a frequency analysis of the tires is carried out while in transit. This allows for the detection of any losses in tyre pressure and other changes in the condition of the tyre. [DUNLOP, 2013].

A manual calibration is required by pressing a switch or a corresponding menu selection in HMI [DUNLOP, 2013]:

- after changing a tyre (e.g. breakdown, replacement, tyre change summer/M&S)
- after a wheel position change (e.g. swapping front axle/rear axle tires)
- after a tyre pressure change occasioned by the driver (e.g. partial load/full load)
- after repair shop works on the chassis



After the start of calibration DUNLOP TECH Warnair will be fully operational again within a few minutes' journey under normal driving conditions.

C.10 NIRA Dynamics TPI

Type	Indirect	
Performance	Range:	n/a
	Resolution:	-20 [%] in 15 [min] driving time
	Lifetime:	unlimited
Particular features	Autolocation by use of spectral analysis	
	Load detection	

Indirect TPMS like TPI are integrated into ABS/ESC systems, 100% software based and require no additional hardware whatsoever. TPI is included in ND4 Suite, which is a software package of safety enhancement functions for passenger cars, light trucks and SUVs with an anti-locking brake system. Figure 63 below illustrates a typical integration of the ND4 Suite software into the ESC in a vehicle. The ND4Suite software utilizes signals from the wheel speed sensors and from different sensors and systems connected to the CAN bus. The user can interact with the system through menu options in the onboard computer or through a special calibration or reset button. Warning messages or warning symbols are shown on the dashboard or in the onboard computer display [ND2, 2013].

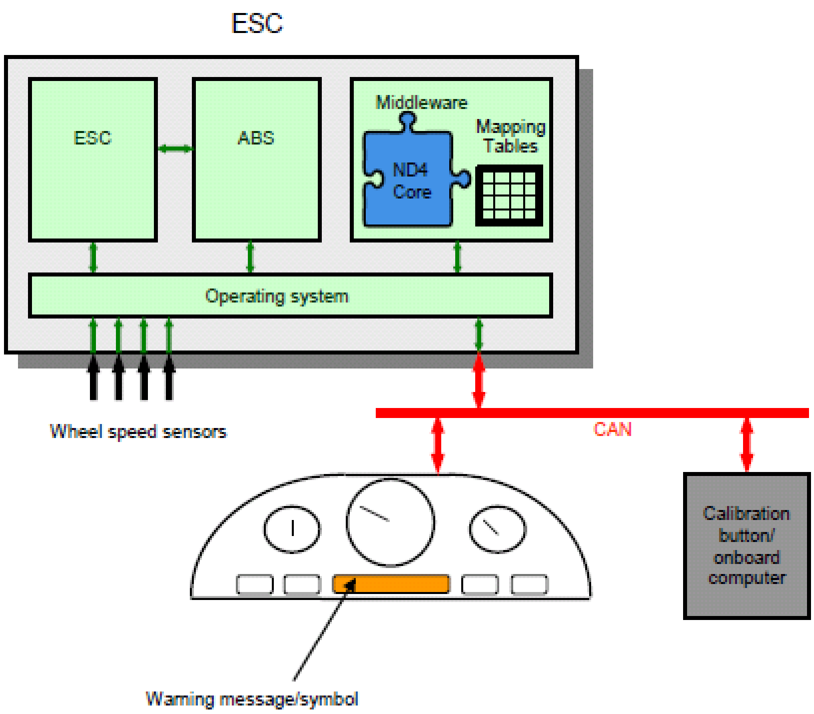


Figure 63: NIRA Dynamics integration into ND4 suite

TPI is an OEM solution exclusively, but can be used on most aftermarket tyres and rims as well.

TPI is a modern 2nd generation indirect TPMS that uses so-called spectrum analysis to monitor certain tyre-pressure-dependent oscillations. This is done individually for each wheel, thus enabling a comprehensive monitoring for all four wheels

(Autolocation). The new EU legislation already provides respective tests. Indirect systems can detect a pressure drop of 20% on all four wheels in about 15 [min] driving time. This is four times quicker than legally required and also works well at high speeds. A flat tyre is detected in about 10 [s]. According to NIRA Dynamics, a finer resolution than 10% (or 0.2 [bar]) makes no sense in practice since ambient and tyre temperature variations can cause up to 0.5-0.6 [bar] of tyre pressure variations. In addition, the risk of warnings being ignored is high if thresholds are set too tight [ND, 2013].

An advantage of TPI is that it is tuned to work optimally with all the original tyres. Furthermore, they are tested with a variety of popular aftermarket tyres to make sure that the drivers do not run into trouble with them later on. In contrast, direct TPMS with the sensors mounted on the rim do not always fit to aftermarket rims [ND, 2013].

Modern indirect systems have mechanisms for load compensation which are able to distinguish load difference of 250 [kg] [ND, 2013].

TPI, as all other current indirect TPMS solutions is not yet applicable for vehicles with more than 4 wheel positions or without ABS/ESC [ND, 2013].