AN ASSESSMENT OF $PM_{2.5}$ REDUCTIONS AS A RESULT OF TRANSPORT FLEET AND FUEL POLICIES ADDRESSING CO_2 EMISSIONS AND CLIMATE CHANGE

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ABSTRACT

This paper addresses the co-benefits of climate change mitigation policies to reduce $PM_{2.5}$ pollution for passenger cars (PCs) using a scenario-based approach in Ireland. To analyse future scenarios (2015–2035), estimation was initially conducted in COPERT software. Emissions estimation was improved using an add-on module to the COPERT model that was capable of considering a range of future vehicle technologies and the contribution of additional non-exhaust $PM_{2.5}$ emissions from road abrasion. A fleet, disaggregated at major fuel type, and at the level of newly registered and survived PCs, was required for this add-on module. The module was developed based on the concept, emission factors and fuel efficiency improvement factors from a number of previous research papers, and COPERT output, to estimate fuel-based emissions e.g. exhaust and non-exhaust $PM_{2.5}$ and CO_2 emissions. Three additional estimations were conducted in the add-on module: a baseline scenario that was similar to COPERT but accounted for a different disaggregation of the PC fleet, and two alternative scenarios. The two alternative scenarios were developed using an approach previously developed by the authors that addressed the existing Electric Vehicle (EV) policy in Ireland, and a possible ban on the sale of conventional vehicles powered by gasoline and diesel fuel in the future (in line with the planned actions of a number of EU cities). The results revealed that CO_2 emissions continuously decreased in the projection period, however, reductions of $PM_{2.5}$ reversed from the year 2028 due to increases in the non-exhaust component of $PM_{2.5}$ emissions. Under alternative scenarios, a 57–69% reduction of CO_2 could be possible whereas a 9-15% reduction for $PM_{2.5}$ could be achieved in 2035. Non-exhaust $PM_{2.5}$ was found to have a larger share (as much as 35 times that of exhaust emissions) in 2035 where alternative PCs such as EV represented a major share in the fleet. The research also provided a methodology capable of detailing the CO_2 and $PM_{2.5}$ emissions in future scenarios for a range of PC technologies.
Keywords: passenger car, policy analysis, CO_2, $PM_{2.5}$, co-benefit.

1 INTRODUCTION

Previous investigations have highlighted the lack of integration of air pollution and climate change policy in the EU [1]. Several climate change policies have been shown to have negative impacts on air pollution and vice versa, and thus their integration is crucial to avoid unintended consequences. Air pollutant reductions may accelerate the increase in global mean temperature in the short term, however, eventually, contribute to long-term climate stabilization [2], [3]. In addition, reduction of air pollution will immediately improve the air quality and thus, will reduce negative consequences on population health. In Ireland, the reduction of $PM_{2.5}$ concentrations is one of the key challenges identified by the Irish EPA [4]. However, $PM_{2.5}$ does not receive much attention in the policy arena for a quantitative reduction of mass in comparison to heavily regulated pollutants like CO_2. Rather, $PM_{2.5}$ is a policy concern from the perspective of air quality and health.

$PM_{2.5}$ has been noted in the literature for its significant health impacts [5], and it is becoming a cause for concern because of relatively short, but high exposures, to a major share of the population during their movements. The transport sector in Ireland contributed

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15.4% of the total emissions of $PM_{2.5}$ in 2015, with >92% of this coming from road transport [6]. An investigation in the road transport sector in 2014 has highlighted that private passenger vehicles contribute the largest proportion (56%) to $PM_{2.5}$ of all vehicle categories [7]. Emissions of $PM_{2.5}$ from Passenger Cars (PCs) were estimated to increase to a 63% share of total road transport emissions by 2035 [7]. The projection was conducted using the COPERT model and the national road transport emissions database in 2014. COPERT is widely used in the European Union to calculate real-world air pollutant and GHG emissions from road transport for existing and historic years [8] and many investigations [9]–[11] also used the COPERT model or a modified COPERT methodology to estimate future emissions. COPERT reports non-exhaust $PM_{2.5}$ emissions together, excluding emissions from road abrasion. However, a detailed distribution of $PM_{2.5}$ according to the brake, tyre wear, road abrasion and exhaust $PM_{2.5}$ emissions may be necessary to provide a better understanding of the extent of contributing sources for the future transport fleet. Such methodological improvement may also be needed to cover a number of modern vehicles, e.g. Fuel Cell Vehicle (FCV) which is not included in COPERT. Such methodological improvements will also affect the estimation of other pollutants like CO_2.

CO_2 is the primary Greenhouse gas (GHG) which is directly related to fuel consumption, unlike $PM_{2.5}$. Reduction of CO_2 is crucial in meeting the global 2°C temperature stabilization targets. In Ireland, 18.7% of total CO_2 at national level originated from PCs in 2015 [6] and the policies that are currently in place and directly relevant to PCs are the bio-fuel policy and Electric vehicle (EV) policy [12], [13]. This investigation addressed these policies and relevant policies that were currently in consideration in different EU countries to estimate the likely co-benefits in $PM_{2.5}$ reduction. A scenario-based approach is presented in this paper using an improved methodology to quantify $PM_{2.5}$ and CO_2 from PCs in Ireland. Similar scenario based co-benefits analysis was conducted in a number of recent investigations that accounted for both $PM_{2.5}$ and CO_2 [14]–[16]. Different methodologies were applied. Lott et al. [14] applied a bottom-up techno-economic energy systems model for all sectors and accounted for both exhaust and non-exhaust emission, however, a detailed segregation of the future vehicle class was not the prime focus of the study. Pathak and Shukla [15] applied an energy-based model for all road transport, where exhaust and non-exhaust $PM_{2.5}$ emissions and a segregation of vehicle fleet were not emphasised. Xia et al. [16] estimated CO_2 and $PM_{2.5}$ in alternative scenarios, primarily based on the changes in vehicle kilometres travelled. A combination of models was applied in that study for all road transport that also included exhaust and non-exhaust emissions, however, a detailed segregation of vehicle class was not included.

The scenarios analysed here are of a relevance to a number of existing policies, both nationally and internationally, such as the CAFE Directive (2008/50/EC), proposed targets in the EU National Emissions Ceiling Directive (2001/81/EC), and the Gothenburg protocol.

2 METHODOLOGY

2.1 Methodological framework

The current national emissions projection system in Ireland is based on three fuel types: gasoline (fossil and biofuel), diesel (fossil and biofuel) and Liquefied Petroleum Gas (LPG). It is also based on three default PC technologies i.e. gasoline, diesel, and LPG, however, the hybrid gasoline and Compressed Natural Gas (CNG) PC technologies were not included [6]. In order to produce a baseline scenario for this analysis a modification of the national emissions inventory model was developed in COPERT. Here Hybrid Electric Vehicle (HEV)

PCs powered by Gasoline were separated from the aggregated gasoline PCs in the national emissions inventory model following Alam et al. [10], [11], as it was a considerable category in terms of its share in the fleet. This scenario was run with similar mileage as gasoline PCs for HEV with additional an amount of bio-fuel (6.8% up to 1990 and then 12% until 2035) for all road transport vehicle categories [10], [11]. Results from this COPERT scenario were only collected for PCs and labelled as "COPERT Scenario", processed and entered into an add-on module to create a "Baseline Scenario" for this study. Two different alternative scenarios (EV Policy Scenario and Non-conventional PC Scenario) were then run in the add-on module to compare against the Baseline Scenario. To develop a fleet composition for alternative scenarios, a fleet scenario tool developed by Alam et al. [10], [11] was also applied for the period 2015 to 2035. In the alternative scenarios, the addition of modern technologies to the fleet was taken into account.

An add-on module for COPERT was developed that provided emissions projections segregated according to exhaust, and non-exhaust emissions and its subdivisions. The add-on module estimated energy consumption for a wide range of PC categories using fuel efficacy uplift multipliers for alternative PC technologies e.g. FCV from a number of previous investigations [17]–[19]. The total emission in this study was calculated based on the estimated fuel demand [19], [20] as well as total mileage by the add-on module for exhaust and non-exhaust emissions [21]. Although the total mileage between COPERT outputs and the add-on module remained the same, the fuel demand varied due to changes in vehicle technologies in different scenarios. Implied emission factors from COPERT were included in the add-on module to facilitate $PM_{2.5}$ exhaust calculation, which was considered as fuel based. Emission factors for exhaust $PM_{2.5}$ is difficult to obtain as it was not directly related to fuel consumption, rather engine technology and exhaust system, e.g. particulate filters play a role in the amount of $PM_{2.5}$ emission exhausted [21]. For $PM_{2.5}$ exhaust and different non-exhaust emission factors of new PC technologies, e.g. FCV that were not available as implied emission factors, were directly obtained or estimated from a number of previous investigations [22]–[24]. Where implied emission factors for CO_2 were not available, e.g. CNG PCs, fuel demand was calculated based on the fuel efficacy and default emission factor based on the carbon concentration [20]. Like CO_2 and exhaust $PM_{2.5}$, non-exhaust emissions were segregated into brake, tyre and road abrasion, and varied according to the distribution of mileage in different vehicle technologies. Road abrasion $PM_{2.5}$ was not reported under COPERT and was calculated using EMEP/EEA recommended emissions factors [22].

The data, however, could not directly be transferred from COPERT to the add-on module. Both fleet data and implied emission factors required pre-processing before feeding to the add-on module. The add-on module required vehicle information disaggregated between fuel technologies and at the level of newly registered and survived vehicles, according to their different years. Thus, the PC technologies at EURO standard were required to be aggregated at fuel technology level and disaggregated using the survival rate.

The fleets for the Baseline Scenario and EV Policy Scenario were obtained from the author's previous study at this disaggregated level [10], [11]. A similar estimation was conducted for the Non-conventional PC Scenario using a scenario development approach [10], [11]. The add-on module takes a detailed breakdown of the fleet categories according to the major fuel types that are segregated into newly registered and survived vehicles. It then applies improvements in their fuel efficiency (where applicable) along with fuel based mileage distribution to calculate fuel demand for the same amount of mileage projected in an initial estimation by COPERT. It is capable of estimating both $PM_{2.5}$ and CO_2 emissions in accordance with the mileage efficiency improvements for different vehicle fuel technologies. The methodology of the study is presented in Fig. 1.

2.2 Add-on module

The add-on module was developed with gasoline, diesel, HEV (gasoline and diesel), Plug-In Hybrid Vehicles (PHEV) for both gasoline and diesel, EV, FCV, CNG and LPG PC categories. PHEV was assumed to be driven by electricity for 40% of its mileage. The module applied two separated methodologies for exhaust and non-exhaust $PM_{2.5}$ and CO_2 emissions. For non-exhaust emissions, the add-on module calculated emissions from mileage, implied emissions factor (g/km) and PC population according to the category distribution. As implied emission factor was selected for exhaust emission, the fuel efficiency in the add-on module has not been considered in fuel demand estimation except in CO_2 estimation for CNG and LPG PC which applied carbon content based emission factors. The implied factors were both weighted by engine size and euro technology with efficiency improvement. Although COPERT did not account for euro technology beyond Euro 6 [25], fuel efficiency at the add-on module could be applied to include the impact of beyond EURO 6 technology. Thus, the estimation based on implied emission factors has room for further improvement. Currently, the add-on module considered zero efficiency improvement in future years in fuel demand for estimating exhaust $PM_{2.5}$ (all categories) and CO_2 (all except CNG and LPG) emission to adjust with the efficiency weighted implied emission factors.

2.2.1 Emission factors

Non-exhaust emission factors (2015–2035) for brake wear, tyre wear and road abrasion were obtained from COPERT data. EV implied emission factors for non-exhaust were estimated from COPERT output and using the results of Timmers and Achten [23]. It was found that EV emission factors were 21.6% and 18.4% higher than conventional gasoline and diesel vehicles for tyre and road abrasion, because of vehicle weight. The brake wear emission factor was zero [23]. FCV emission factors were assumed to be similar to EV. All $PM_{2.5}$ emission factors for CNG were assumed similar to the LPG PC.

Similarly, exhaust $PM_{2.5}$ implied emission factors for gasoline, diesel and LPG were obtained from COPERT data processing, for the years 2015 to 2035. In comparison to the conventional PC, Ciborowski et al. [24] estimated a 42.9% and 64.3% reduction in exhaust $PM_{2.5}$ emissions in HEV and PHEV (where PHEV was driven 40% mileage by wind generated electricity). This reduction rate was applied to the $PM_{2.5}$ implied emission factors

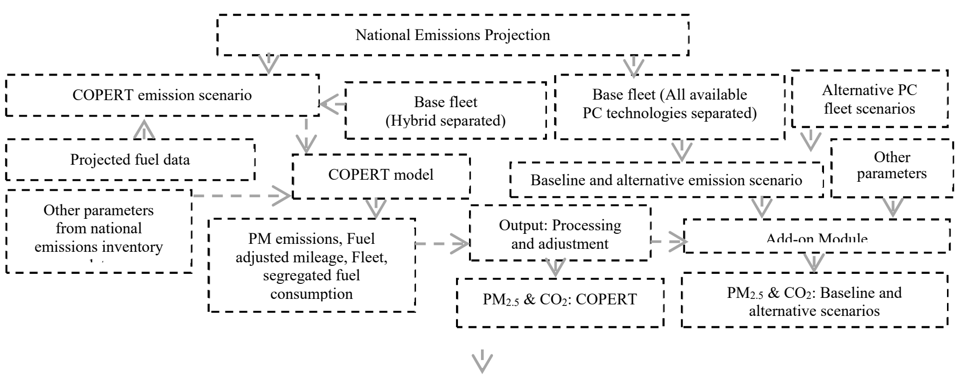

Figure 1: Research methodology.

of gasoline and diesel PCs to represent HEV (Gasoline and Diesel) and PHEV (gasoline and diesel) in the current study. $PM_{2.5}$ exhaust implied emission factors and CO_2 for EV and FCV were set to zero. CO_2 implied emission factors for gasoline and diesel PCs were obtained from COPERT data.

In order to obtain implied emissions factors from COPERT, fuel adjusted mileage (km), exhaust PM (tonne), total $PM_{2.5}$ (tonne), total CO_2 emissions (tonne), fuel consumption (tonne) and PC fleet disaggregated by fuel and euro emission technologies were estimated. Disaggregated fuel consumption was converted to the energy consumption using fuel to energy conversion factors [26] and bio-fuel blends. The fuel efficiency (MJ/km) was derived at the disaggregated level. An average fuel efficiency (MJ/km) for gasoline, diesel, LPG and HEV was derived from 60 categories of PCs. The disaggregated mileage was also aggregated into the four categories (i.e. gasoline, diesel, LPG and HEV) and adjusted by using ratios of aggregated total fuel consumption and fuel consumption derived by original mileage, population and with average fuel efficiencies.

Exhaust PM, total $PM_{2.5}$, and total CO_2 emissions were also aggregated into these four PC categories. The exhaust PM was considered as exhaust $PM_{2.5}$ [22], [25], and thus, total non-exhaust $PM_{2.5}$ was separated from total $PM_{2.5}$, which was aggregated from tyre and brake wear [25]. The yearly non-exhaust $PM_{2.5}$ implied emission factors (g/km) were calculated using mileage data. The distribution between tyre and brake wear were calculated based on the percentage distribution of the emission factors of brake and tyre wear from EMEP/EEA [22]. These factors for the brake and tyre wear were calculated from the emissions factor for total suspended solids (TSP) and its particle size distribution. To calculate road abrasion, the emission factor (g/km) from EMEP/EEA [22] was applied with mileage. Implied emissions factors (g/MJ) for exhaust $PM_{2.5}$ and total CO_2 emissions were calculated using the corresponding energy consumption.

2.2.2 Mileage

To distribute total mileage among different PC categories, a weighting matrix was developed where the primary input was PC mileage per year per vehicle for gasoline, diesel, HEV and LPG from the COPERT Scenario. A similar mileage of CNG to LPG, PHEV (gasoline) to HEV (gasoline), HEV (diesel) and PHEV (diesel) to diesel and EV/FCV to gasoline, was assumed. The weightings matrix was calculated in each year as: (mileage × available fleet) / (sum of the mileage from available fleet).

2.2.3 Fuel demand and emission

Fuel demand was calculated for exhaust emissions. Fuel efficiency, fuel efficiency uplift multipliers, PC population and mileage were required for this calculation. The fuel efficiency data (km/MJ) in Table 1 was mostly obtained from COPERT for the year 2015. Fuel efficiency for alternative PC technologies were derived from Table 2. In addition, improvement in the average fuel efficiency of some PCs was calculated from Table 1.

Table 1: Fuel efficiency data for each fuel and vehicle type.

	Diesel	Gasoline	CNG	LPG
Fuel efficiency (km/MJ) in 2015	0.4075	0.3661	0.3840*	0.3923
Average improvement rate** 2016–2030 for CO_2	0.0%	0.0%	1.30%	1.30%
Average improvement rate** 2031–2035 for CO_2	0.0%	0.0%	1.12%	1.12%

*[18], [19].
**No average improvement rate 2016–2035 for $PM_{2.5}$.

Table 2: Fuel efficiency uplift for low-carbon vehicles over conventional vehicles.

FCV	EV	HEV (gasoline and diesel)	PHEV (gasoline and diesel)	LPG/CNG
2*	2.9*	1.9***	1.9***	1**

*[17].
**[19].
***COPERT.

Using Tables 1 and 2 in relation to the vehicle population and mileage data the total energy demand (MJ) was calculated using eqn (1). Finally, the total emissions were calculated using implied emission factors for exhaust $PM_{2.5}$ and CO_2.

$$F_{t,i} = \left(P_{k,t} * Eff_{i,t} + P_{s,(t-1)} * Eff_{i,(t-1)} + P_{s,(t-2)} * Eff_{i,(t-2)} + \cdots . + P_{s,(t-n)} * Eff_{i,(t-n)}\right) * A_{i,t}. \quad (1)$$

Here, $F_{t,i}$ = Energy demand in year t for PC technology i; $P_{k,t}$ = Newly registered PC in year t; $P_{s,(t-n)}$ = Estimated survived PC population in the previous years (n = 1, 2, …, n); $A_{i,t}$ = Mileage for PC technology i in year t; $Eff_{i,(t-n)}$ = Fuel efficiency which was subject to the yearly efficiency improvement and also efficiency uplift for some technologies.

For non-exhaust emissions, the estimation process was a multiplication of total mileage in a category by the corresponding emission factors (eqn (2)).

$$E_{non,i,j} = P_i * A_i * EF_{non,i,j}. \quad (2)$$

Here, $E_{non,i,j}$ = Non-exhaust emission j for PC technology i, P_i = Total population for PC technology i in a year; A_i = Total mileage population for PC technology i in a year, $EF_{non,i,j}$ = emissions factor for non-exhaust emission j for PC technology i.

2.3 Fleet and scenarios

The fleet for Baseline Scenario and EV Policy Scenario were obtained from the COPERT Scenario [10], [11], however, all subclasses of HEV and PHEV were aggregated in this study. The EV Policy Scenario addressed the existing Electric Vehicle policy in Ireland. The Non-conventional PC Scenario represented a possible ban on the sale of conventional vehicles powered by gasoline and diesel in the future. Total mileage and the total number of PCs were the same between all emissions scenarios.

In EV Policy Scenario, sales for different technologies were determined by the current national policy regarding EVs. The PC technologies were considered similar to the disaggregated Baseline Scenario except for a higher proportion of EVs and PHEVs. A total of 50,000 EVs and PHEVs by 2020 were modelled in line with national policy targets. Its growth after 2020 was calculated based on a modelled growth curve ($y = 25422ln(x) + 531$, where x = year started from 2014 and y = EV and PHEV numbers). This curve was selected as it gave an acceptable share of the EVs and PHEVs by 2035 (51% of the total sales). The split between EV and PHEV in the calculation was considered, based on their share in the disaggregated Baseline Scenario. The sales for other PC technologies were assumed similar to the baseline. In this scenario, only vehicles currently available PC technologies were considered.

For the Non-conventional PC scenario, the shares of the sales for different low carbon technologies were gradually increased. New sales of conventional PCs powered by gasoline and diesel fossil fuel were phased out by 2030. The concept followed a recent trend of banning fossil fuelled PCs, e.g. the Netherlands is in the process of banning new sales of conventional PCs by 2025 [27]. Similarly, Norway is proposing to ban gasoline vehicles and move to 100% green energy for PCs by 2025 [28]. In this scenario, a penetration of CNG was considered from the year 2025 as a recent policy paper on energy indicated a building of CNG filling stations would commence from 2025 [13] in response to European legislation (Directive 2014/94/EU). FCV were also considered from the year 2030 onwards. The total cumulative sales for all new technologies between the years 2015 and 2035 were segregated according to the Table 3. The share of the cumulative sales was assumed or estimated by the authors in light of the policies, and the current vehicle penetration trends [11].

For the yearly distribution of new car sales, the above vehicle categories were aggregated based on their existing market share and future market penetration capabilities (see Table 4), later disaggregated and adjusted for fleet EV Policy Scenario and Non-conventional PC Scenario, following the same approach described in [10], [11]. The distribution was conducted following a fitted curve (eqn (3)) and using the parameter values in Table 4.

$$CFleet_y = m * \frac{C_{2015-2035}}{1+e^{-k(y-y_{mid})}}. \tag{3}$$

Here, $CFleet_y$ is the cumulative fleet distribution for the year y; $C_{2015–2035}$ is the cumulative total of new sales from 2015–2035 for a group; $\underline{k}$ = the steepness of the curve, in a standard S-curve k = 1; y_{mid} is the year when half of the total cumulative sales are expected to be distributed between initial year and y_{mid}; m is a multiplier used to raise curves which is the ratio of the actual cumulative value and cumulative value of the first iteration.

Table 3: Penetration of different PC technologies in different scenarios.

Assumption for 2015–2035	Baseline [10], [11]	EV Scenario [10], [11]	Non-conventional PC Scenario
Gasoline	31.86%	13.09%	6.00%
Diesel	67.53%	45.80%	7.00%
EV	0.12%	39.73%	24.00%
HEV (gasoline)	0.45%	1.00%	13.00%
HEV (diesel)	0.00%	0.01%	18.00%
PHEV (gasoline)	0.00%	0.14%	10.00%
PHEV (diesel)	0.00%	0.14%	12.00%
LPG	0.04%	0.08%	5.00%
CNG	0.00%	0.00%	1.00%
FCV	0.00%	0.00%	4.00%

Table 4: Parameter values in the eqn (1) for EV Policy Scenario and Non-conventional PC Scenario.

Group	Remarks	Technology	EV Policy Scenario^	Non-conventional PC Scenario
1	Healthy market share	Gasoline and diesel	y_{mid} = 2022; k = 0.1; m = 2.1	y_{mid} = 2016; k = 0.4; m = 1.4
2	Shows promising growth	HEV and PHEV	y_{mid} = 2035; k = 0.18; m = 2.09	y_{mid} = 2015; k = 0.29; m = 1.10
3		EV and FCV	--	y_{mid} = 2035; k = 0.29; m = 2.1 y_{mid}* = 035; k* = 0.5; m* = 2.14
4	Very low market share	FCV and CNG	y_{mid}* = 2035; k* = 0.5; m* = 2.01 (CNG); 2.1 (FCV)	y_{mid}* = 2035; k* = 0.5; m* = 2.01

^[10], [11].
*Applicable for CNG and FCV.

3 RESULTS

3.1 Fleet

The fleet in the disaggregated Baseline Scenario in Fig. 2 shows all the available technologies except FCV and CNG which were not present in Ireland in 2015. In this scenario, gasoline and diesel PCs dominated the fleet having similarity to the historic years [7]. The PC shares in 2035 were 35% and 63% for gasoline and diesel PCs respectively. According to the estimation in this study, 3.1 million new PC sales will enter the Irish market in the 2015 to 2035 period. Approximately 32% and 67% of the new sales will be entered in the Baseline Scenario as gasoline and diesel PCs.

An assumption was made of having a higher EV penetration than the current national EV policy in the EV Policy Scenario. This resulted in a share of gasoline, diesel and EV PCs at 13%, 39% and 47% respectively in 2035 (Fig. 3). This was because of 13%, 46% and 40% penetration of new sales of gasoline, diesel and EV PCs in the projection period. In the Non-conventional PC Scenario, the penetration of new gasoline and diesel was designed to end in 2030 which resulted in a very low share (6% gasoline and 5% diesel) of conventional vehicles by 2035 (Fig. 4). In this scenario, 6% and 7% of the 3.1 million new PC sales were distributed in 2015-2030 as gasoline and diesel respectively. The largest and the second largest shares were EV and HEV at 30% and 28% in 2035. This was the result of penetration of 24% and 31% of the new sales of EV and HEV in the period of 2015 to 2035.

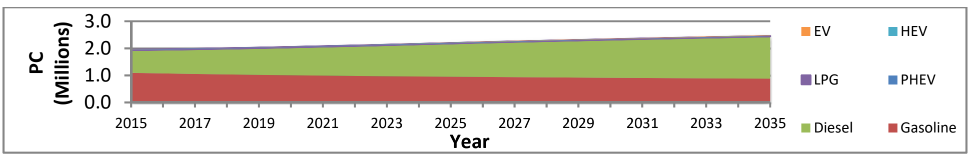

Figure 2: Total disaggregated Baseline fleet.

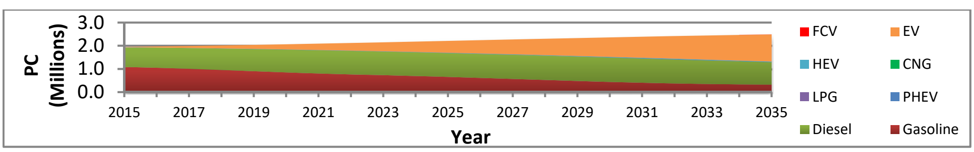

Figure 3: Fleet in EV Policy Scenario.

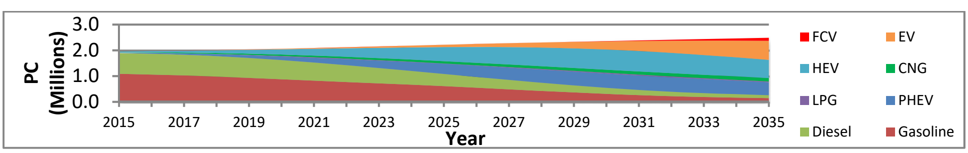

Figure 4: Fleet in Non-conventional PC Scenario.

3.2 CO_2 emissions

CO_2 emissions in the EV Policy Scenario and Non-conventional PC Scenario were much lower than the Baseline Scenario in Fig. 5. Baseline CO_2 emissions were 7186.7 kt in 2035 whereas 3417.6 kt and 2223.1 kt of CO_2 emissions were produced in 2035 under EV Policy and Non-conventional PC Scenarios. The highest level of reduction was 69% in 2035 from 2015 level in Non-conventional PC Scenario.

3.3 Exhaust $PM_{2.5}$ and non-exhaust $PM_{2.5}$

The total $PM_{2.5}$ emissions reduced until 2028 in all scenarios and gradually increased in the rest of the projected period (see Fig. 6). The baseline $PM_{2.5}$ emission was 767.9 tonnes in 2028 and this was 33% lower than total $PM_{2.5}$ in 2015. The total reduction was 26% from 2015 to 2035, from 1144.1 tonnes in 2015 to 845.9 tonnes in 2035. The estimated total $PM_{2.5}$ emissions in EV Policy and Non-conventional PC Scenarios in 2035 were 773.1 tonnes and 718.1 tonnes respectively. The poorest $PM_{2.5}$ emissions reductions occurred in EV policy Scenario throughout the time series and the reduction was 26% by 2035. EV Policy Scenario had a higher penetration of EVs and produced higher amounts of non-exhaust tyre wear and road abrasion $PM_{2.5}$ because of their comparatively higher vehicle weight than that of conventional gasoline or diesel PCs.

The comparison of total $PM_{2.5}$ emissions figures in 2015 and 2035 in Fig. 7 showed that the most notable reduction occurred in the exhaust emissions for all the scenarios. On the other hand, non-exhaust emissions except brake wear increased from 2015 to 2035 due to an increase of overall mileage in all scenarios. Both EV Policy Scenario and Non-conventional PC Scenario had lower exhaust $PM_{2.5}$ emissions in comparison to the baseline due to fuel efficiency improvements and penetration of alternative vehicles. However, Non-conventional PC Scenario had a greater reduction in exhaust $PM_{2.5}$ than that of emission EV Policy Scenario throughout the time series as a result of a lower penetration of gasoline and diesel vehicles (11% of the total sales between 2015 and 2035).

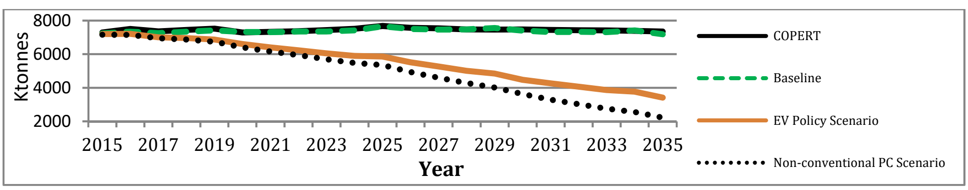

Figure 5: Total CO_2 from all the scenarios.

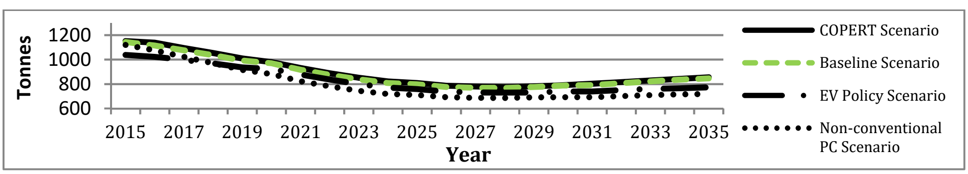

Figure 6: Total $PM_{2.5}$ from all the scenarios.

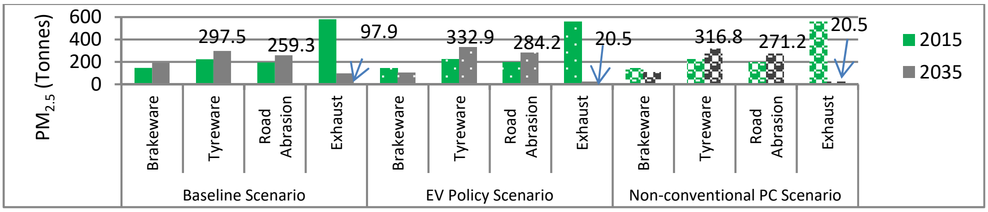

Figure 7: Breakdown of $PM_{2.5}$ emissions.

Tyre wear emissions increased the most (42%) followed by a 39% increase in road abrasion $PM_{2.5}$ emissions in 2035 in the Non-conventional PC Scenario, as a result of higher weightier EV penetration. Non-exhaust brake wear $PM_{2.5}$ emissions from EV Policy Scenario was lower than that of Non-conventional PC Scenario due to a higher total mileage of EV. This was the result of higher penetration of EV (40%) in EV Policy Scenario in comparison to Non-conventional PC Scenario (24%). Brake wear emissions from EVs and FCVs were assumed zero because of improvements in their braking systems which was consistent for both scenarios.

The ratio of total exhaust to total non-exhaust $PM_{2.5}$ in 2015 were 0.97 for both COPERT and Baseline Scenario and 1.01 for both EV Policy Scenario and Non-conventional PC Scenario in Fig. 8. However, the ratios changed to 7.5, 7.56, 34.9 and 33.9 in 2035 for COPERT, Baseline, EV and Non-conventional PC Scenario respectively.

3.4 CO_2 emission vs. $PM_{2.5}$

CO_2 emissions reductions were 47% and 69% in EV Policy and Non-conventional PC Scenarios respectively, in comparison to the Baseline Scenario in 2035 (Fig. 9). In comparison, $PM_{2.5}$ emissions reduction percentages were 9% and 15% in 2035.

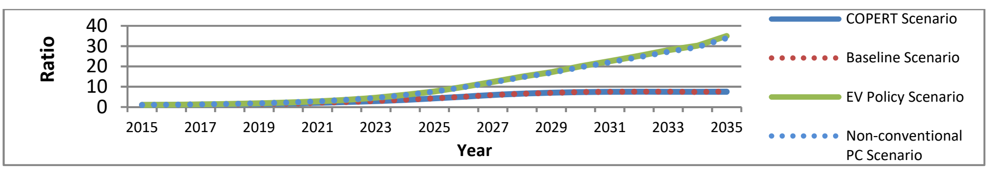

Figure 8: Non-exhaust to exhaust ratio.

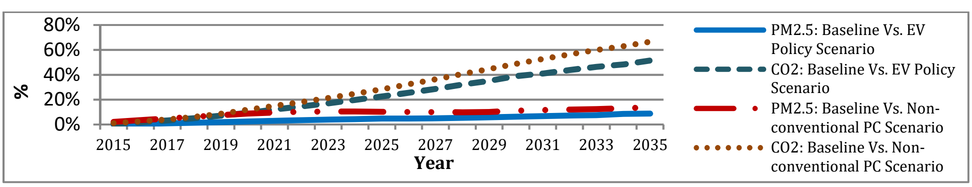

Figure 9: Emissions reduction for all the scenarios (CO_2 vs. $PM_{2.5}$).

4 DISCUSSION

This study provided likely future $PM_{2.5}$ scenarios under the current vehicle trends and various policy options. In addition, this study included alternative PC technologies in these future scenarios. The Baseline Scenario resulted in a 26% reduction of $PM_{2.5}$ emissions in 2035 from the 2015 level, whereas the reduction figure for CO_2 in the same period was less than 1% despite the increase of fuel and mileage use. Where alternative fleet technology is concerned, CO_2 emissions reduction is the highest in Non-conventional PC Scenario (69% lower in 2035 from 2015) in comparison to $PM_{2.5}$ (36% lower in 2035 in comparison to 2015). In addition, total $PM_{2.5}$ trends showed an upward tendency after 2028 which is similar to a finding in a recent UK study by Lott et al. [14], while total CO_2 emissions continuously went down.

This work highlights that co-benefits can be achieved for both air pollutant (i.e. $PM_{2.5}$) and GHG emissions (i.e. CO_2). However, the level of benefit is restricted to some extent for particulate air pollutants due to the non-exhaust component, and these resulted in an upward emissions trend. This is because of the nature of the emission sources where air pollutants are associated with both fuel and mileage, unlike GHGs, which is dependent on fuel consumption. While considering health effects near roads, the increase in mileage also contributes to the re-suspension of $PM_{2.5}$ regenerated by turbulence and tyre wear of the vehicle from road dust. Along with road transport, the source of the road dust includes nearby vegetation, corrosion of street furniture and human activities such as industry. The resuspension $PM_{2.5}$ is almost two times higher than combined exhaust and non-exhaust $PM_{2.5}$ for EVs and is similar to conventional vehicles on a kilometre basis according to Timmers and Achten [23].

This study highlights that national emissions inventories using the COPERT methodology do not accurately capture future technologies and importantly may not fully account for the impact of non-exhaust emissions in their assessments of environmental impacts and policy. As is clearly shown here, the expected increasing demand for travel (i.e. mileage) in future and the comparatively higher weight of EVs results in significantly more $PM_{2.5}$ non-exhaust emissions. This study also highlights that policy heavily incentivising the use of alternative fuels and technology will result in significant CO_2 savings but may not result in significant particulate matter reductions. Thus the importance of the integration of air pollution and climate change policy, as highlighted by many authors recently, is shown to be very important in this context [1]. In the coming years, fuel consumption related emissions will likely be reduced gradually with the increase of tighter emissions control for regulated gases/pollutants. Non-regulated exhaust pollutants will also decrease in the process due to increased fuel efficiency. However, non-exhaust emissions must also be reduced to improve air quality. In order to do that, travel demand for PCs (in terms of mileage) must be replaced with sustainable and smarter travel options such as walking and cycling. In the long term, non-exhaust $PM_{2.5}$ will become a larger threat to health and will adversely affect the success of governmental efforts. A reduction of non-exhaust emissions immediately will also help attaining the $PM_{2.5}$ emissions reduction target under the Gothenburg protocol.

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