EU road vehicle energy consumption and CO2 emissions by 2050 – Expert-based scenarios

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A R T I C L E   I N F O

Keywords:
Road transport
CO2 emissions
Electrification
Decarbonisation
Modelling
Expert discussion

A B S T R A C T

To inform long-term policies on transport decarbonisation, the present paper analyses European road transport CO2 emission reduction options by 2050. The investigation focuses on measures improving plant to wheel vehicle efficiency, but takes into account upstream emissions of electric vehicles. Measures for vehicle efficiency improvement, transport smoothing, and transport reduction, as well as possible 2050 road vehicle fleet compositions have been quantified through expert group discussion and combined with fleet impact modelling to calculate scenario results.

Outcomes show that to wheel road transport CO2 emission reductions up to 90% versus 1990 could be achieved by 2050 through strong fleet electrification and if all measures achieve their best potential. Under ambitious fleet electrification scenarios, CO2 reduction of more than 60% is reached without measures, but causes substantial additional demand for low-carbon electricity, the availability of which is not covered in this paper. It is likely that policies will be a prerequisite for fleet electrification and efficiency increases of the order of magnitude assumed. Moreover, upstream CO2 emissions of electricity for battery and plug-in hybrid electric vehicles could add up to 40% of to wheel emissions, suggesting that complementary policies are needed to avoid shifting transport emissions to other sectors.

1. Introduction

The transport sector is confronted with the challenge of reducing emissions while transport demand grows at the same time. Road transport is currently the second largest source of CO2 emissions in the European Union (EU), accounting for around a quarter of total emissions (EEA, 2018). About 94% of EU transport energy needs are covered by oil as of today (EC, 2016a). In the absence of ambitious steps towards decarbonisation, the 2016 EU Reference Scenario highlights that by 2050 road transport could account for the largest share of CO2 emissions (EC, 2016c). This is partly due to a projected growth in transport demand of 40% for passenger transport and nearly 60% for freight transport between 2010 and 2050, according to the EU Reference Scenario.

Such trends contrast with the long-term goal to limit global warming to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C, as embraced by the EU with the ratification of the Paris agreement in 2016 (EC, 2016b). Recently, the European Commission has reinforced the commitment to transport decarbonisation with its Communication on a low-emission mobility strategy (EC, 2016a), which emphasizes the need to increase the efficiency of the transport system, deploy low-emission alternative energy for transport, and move towards low- and zero-emission vehicles. The

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https://doi.org/10.1016/j.enpol.2019.111224
Received 18 January 2019; Received in revised form 15 December 2019; Accepted 26 December 2019
Available online 19 February 2020

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EU has recently decided on post-2020 CO₂ standards for passenger cars and vans and the first European CO₂ standards for new trucks. Despite the clear need and political intention to move towards a low-carbon transport sector, efforts are hampered by uncertainty on key aspects such as necessary enabling conditions and technology options available. One key uncertainty for transport electrification is battery development and related prices. Recent findings have shown that battery costs may be declining more strongly than previously anticipated (Nykist and Nilsson, 2015; Bloomberg, 2017). Edelenbosch et al. (2018) find that electric vehicle market penetration strongly depends on battery costs, with uptake scenarios ranging from insignificant towards near-full 2050 electric vehicle market penetration in the absence of climate policy, depending on the battery cost trajectory.

Such uncertainties are reflected in the wide range of future market uptake scenarios of electrified powertrains found in literature. The European Climate Foundation (2016) showed a range of scenario assumptions on 2030 advanced electric vehicle sales shares from 15% to 85%. Recent EU policy has narrowed down the 2030 range at the lower end, setting benchmarks of 35% of zero- and low-emission vehicles for cars and 30% for vans in the 2030 new vehicle fleet (EU, 2019), whereas in 2016, battery electric vehicles and plug-in hybrids represented only 1.1% of the new EU car fleet (EC, 2017). There is still a lot of uncertainty with regard to the further development throughout 2050. Siskos et al. (2018) present energy system model scenarios for reaching a 60% transport greenhouse gas reduction in the EU by 2050. They show that 2050 electric car shares (battery electric, plug-in hybrid and fuel cell electric vehicles combined) would be 70% of car stock in an optimal trajectory, but would have to be higher than 90% if sluggish uptake occurs in the decade to come. Similarly, the EU28 decarbonisation scenario presented by Karkatsoulis et al. (2017) shows a 70% stock share of battery and plug-in electric cars by 2050. While strong electrification is an option considered for light duty vehicles, studies find that ambitious truck decarbonisation remains challenging throughout 2050 (Dray et al., 2012; Siskos et al., 2018; Karkatsoulis et al., 2017).

The objective of the present paper is to provide an assessment for the CO₂-reduction potential of vehicle technology and operation measures as contribution to a 2050 low-emission road transport system, aiming to contribute to the understanding of technically feasible solutions and of the relative effects of different measures. Intentionally, these investigations focus on vehicle technology and operational aspects primarily influencing the tank to wheel part of energy consumption and related CO₂ emissions. Upstream emissions of electricity production for electric vehicles are also calculated, using conventional knowledge. For the different scenarios and technologies considered, the study provides an overview on the amounts of electricity and chemical energy carriers needed to operate a 2050 low-emission road transport vehicle fleet. The question if, how, and to what extent electricity and chemical energy carriers can be provided on a low carbon or even zero carbon basis is beyond the scope of the present investigation.

The approach is based on vehicle technology modelling techniques complemented by and interlinked with experts’ knowledge of technologies and trends in vehicle technology and transport today. Baseline fleet specifications are taken from a fleet impact model, and expert group assessment is used to specify different feasible 2050 scenarios with regard to vehicle efficiency, transport demand and flow, as well as fleet composition. Fleet impact modelling is employed to assess scenario impacts on energy consumption, CO₂ emissions, and the degree to which policy targets can be fulfilled. This approach allows identifying main drivers of transport decarbonisation, to quantify and compare their impacts, separately as well as combined, and to point out major sources of uncertainty as well as research and development needs at an early stage. Results can inform policy with regard to feasible long-term targets, strategies to achieve them, and existing knowledge gaps.

In literature, fleet scenarios are typically model outputs, driven for example by past trends (e.g. Zachariadis et al., 1995), assumed policies, price development or infrastructure availability. They can result from energy system models (e.g., EU reference scenario 2016 (EC, 2016c), EUCO27 and EUCO30 Scenarios (E3MLab & IIASA, 2016), systems dynamics models (e.g., Harrison et al., 2016a; Harrison and Thiel, 2017; Pasaoglu et al., 2016; Shafiei et al., 2012), simulation models (Kloess and Müller, 2011), or user choice models (Kihm and Trommer, 2014). In other cases, assumptions are made based on a what-if approach (Thiel et al., 2014; Pasaoglu et al., 2012) or derived via extrapolation techniques (Sorrentino et al., 2014). The present analysis, which is strongly based on the assessment of available options and their technical and market potentials and combines them with engine and vehicle modelling, complements previous analyses by investigating technical feasibility and boundaries. The main focus of the paper is therefore on technical measures and their tank to wheel impacts on energy consumption and emissions.

The paper is structured as follows: Section 2 explains the methods and data employed and the modelling approach, covering baseline settings, scenario development, and energy consumption and CO₂ emission calculation methodology. Section 3 presents the results regarding 2050 fleet activities, energy consumption and mix, and CO₂ emissions in different scenarios. The paper then concludes, outlines the study’s scope and policy implications as well as need for further research in Section 4.
2. Methodology and data

In this section, the research methodology and the inputs used are described. First, an overview of the building blocks of the analysis and their interaction is given, followed by two sub-sections describing the methods and data employed to define the baseline and develop the scenarios, respectively. Two further sub-sections explain the fleet energy consumption and emission calculation from a tank to wheel perspective and the approach for estimating well to tank emissions of electrified vehicles.

2.1. Overview of the approach

The study addresses road transport in 2050 with regard to vehicle fleet composition options, the efficiency of different vehicle technologies, and vehicle activities. This is done by defining a baseline scenario for 2050, then making scenario assumptions on measures that could be employed and their impacts as well as fleet penetration potential, and finally calculating 2050 road transport energy consumption and emissions under the different scenario settings. This is done by combining the baseline of the DIONE fleet impact model with assumptions derived from expert group discussion.

Fig. 1 depicts the building blocks of the analysis: Inputs from the DIONE fleet impact model are indicated by the blue shading of most bubbles and define baseline conditions. Expert group assessment, indicated by red shading, is employed for defining scenarios on vehicle efficiency, transport efficiency, and selected activity reduction measures (red box on the left hand side) as well as road vehicle fleet composition in 2050 (red box and the right hand side). These inputs are combined through fleet impact calculations, indicated by the grey boxes, mathematically described in the Annex (A.3). Key inputs are described in detail in the following sections.

The DIONE fleet impact model (see Thiel et al., 2016; Harrison et al., 2016b) is developed and run at the European Commission’s Joint Research Centre (JRC). It is based on the software Sibyl (Katsis et al., 2012), which has been developed from an earlier model version (“ForeMove”, see Zachariadis and Samaras, 1999; Samaras et al., 1999). It is a road transport fleet projection tool that allows analysing scenarios of road vehicle stock, activity, energy consumption and CO₂ as well as air pollutant emissions up to 2050.

Expert group discussion was employed to derive consensus stakeholder assessment for key input parameters, and was held within the European Road Transport Advisory Council’s (ERTRAC¹) CO₂ working group, which offered a unique opportunity to establish a long-term, thorough group discussion process involving experts from industry, research and public authorities as well as different disciplinary backgrounds. The list of group members and their affiliations, as well as details on the group discussion process, are available in Annex 1.

2.2. Baseline definition

The elements of the baseline, i.e., fleet composition and activities, fuel and energy consumption are described in the following sections.

2.2.1. Vehicle types, stock and activity

In the present study, four vehicle categories are differentiated with regard to energy consumption, i.e.,

- 2-wheelers; Small/medium size cars
- Large cars and SUVs, LCVs, Delivery vans <7.5t

¹ ERTRAC is the European Technology Platform for road transport, which was set up to develop a common vision for road transport research in Europe, see https://www.ertrac.org/.
Table 1
2050 Baseline Vehicle Activities, absolute values (trillion vkm) and changes compared to 2016 (% of 2016).

| Baseline | trillion vehicle kilometers | versus 2016 |
|----------|----------------------------|-------------|
| Cars, LCVs & 2wheelers | 4549 | 112% |
| Trucks, Vans, Buses | 582 | 147% |
| Total Road | 5131 | 115% |

Fig. 2. Baseline 2050 road transport activity shares (% of vehicle-kilometres) by vehicle segment.

- City buses, MDT <12t
- Trucks >7.5 t; Long distance buses

Each vehicle type can be either a conventional vehicle (CV, with spark ignition or compression ignition powertrain), or an advanced electrified vehicle (xEV), which comprises plug-in electric vehicles (PHEV), battery electric vehicles (BEV) and fuel cell hybrid electric vehicles (FCHEV). For each vehicle category and powertrain, fuel or energy consumption is specified for three driving profiles, i.e., urban, rural and highway operation conditions.

For the present study, 2050 total road vehicle fleet activity and stock was calibrated with the EU Reference Scenario 2016 (EC, 2016c), which is based on the assumption that the EU greenhouse gas and renewable energy targets for 2020 will be met and takes into account all policies agreed until 2014. The resulting 2050 baseline road transport activity amounts to a total of 5.1 trillion vehicle kilometres, which implies an increase by around 15% compared to today’s road vehicle activity. Activity increases much more strongly in freight transport than in passenger transport (see Table 1).

Total activity is distributed to the vehicle categories based on the 2050 DIONE baseline activity distribution, shown in Fig. 2. Nearly three quarters of total vehicle kilometres driven in 2050 are covered by passenger cars. A similar approach was followed for vehicle stock.

2.2.2. Baseline fuel consumption of conventional vehicles
For conventional vehicles, it was assumed that 2050 baseline average fuel consumption of each vehicle type would be the same as the consumption of a 2015 new vehicle of the same type. This represents a diffusion of today’s state of the art technology over the complete fleet by 2050, but no further efficiency improvement.

Present new conventional vehicle fuel consumption by driving profile (urban, rural and highway) was taken from DIONE and is based on the COPERT® road transport emission inventory software. Using driving profile shares available from DIONE, given in Table 3, weighted averages of fuel consumption for each vehicle type can be calculated. CO2 emissions are derived using present fuel emission factors. The resulting baseline 2050 specific real-world fuel consumption and CO2 emissions are shown in Table 2.

2.2.3. Baseline energy consumption of advanced electrified vehicles
Similar to the approach followed for CV, energy consumption of present new xEV was used as a baseline for 2050 xEV fleet energy consumption, representing no further improvement. Their present energy consumption was calculated using a computational model available at BMW, and then confirmed in the expert group. The key vehicle specifications for BEV and FCHEV and the resulting energy consumption are shown in Table 4.

For Plug-in Hybrid Electric Vehicles (PHEV), fuel and energy consumption of the respective CV and BEV of the same segment were used for conventional mode and electric mode operation, respectively. The share of electric system operation per driving mode (urban, rural, highway) was estimated based on the assumptions that each trip will start in electrical mode and that urban trips are 100% electric. The remaining operation was assigned to combustion engine mode.

2.3. Scenario development

Departing from the baseline, different scenarios are defined to explore the impact of measures on vehicle efficiency, transport efficiency, and activity, and of road vehicle fleet electrification by 2050, as specified in the following.

2.3.1. Vehicle and transport measures
Different options exist to improve the efficiency of vehicles or of the transport system throughout 2050. In the present study, different measures were identified by the expert group, and their potential impacts by 2050 were quantified, based on quantitative modelling and expert knowledge.

To capture uncertainty, for each measure, vehicle type, and drive profile, optimistic as well as pessimistic 2050 scenarios were developed. Optimistic represents the upper limit of the effect a measure could have according to the experts, and pessimistic gives the measures’ minimum potentials. Note that the optimistic to pessimistic range for measures is used to cover uncertainty with regard to their potential by 2050 as prevailing according to the experts. The potentials are technical properties of the measures and are independent of the degree of exploitation of the technologies.

The measures for reducing road transport carbon intensity can be bundled in three general categories:

A. Vehicle efficiency improvement
Type “A” measures cover technical improvements that can be employed to increase the efficiency of engines or vehicle systems. For conventional vehicles, the effects of “A” type measures are specified in terms of percent savings in fuel consumption compared to 2015 baseline vehicles, which translates directly into percent CO2 emissions. Measures considered include internal combustion engine efficiency improvement, efficiency improvement for xEV, waste heat recovery, energy management, hybridization, aerodynamics, weight and rolling resistance reductions. In most of these cases it was attempted to base the quantitative assessment of measures on engine and vehicle model calculations. For example, the assessment of combustion engine improvement for

2 This assumption can be seen as a ‘worst case’ estimate. While it could be argued that some improvement over 2015 should occur due to 2021 and 2025/2030 new vehicle CO2 standards already agreed in the EU, it is relatively difficult to predict what effect these targets, defined on the drive cycle, will have on vehicle real world energy consumption throughout 2050.

3 For more information see: http://emisla.com/products/copert.
Table 2
Baseline 2050 conventional vehicle fuel consumption, per vehicle segment and driving profile, and real world CO₂ emissions at present fuel greenhouse gas intensities, tank to wheel.

| Fuel Type                        | Urban Fuel Consumption [l/km] | Rural Fuel Consumption [l/km] | Highway Fuel Consumption [l/km] | Combined Fuel Consumption [l/km] | Combined CO₂ Emissions, TtW [gCO₂/km] |
|----------------------------------|-----------------------------|-------------------------------|-------------------------------|---------------------------------|--------------------------------------|
| 2-Wheeler/Small Car/Medium Car   | GSL 0.07                    | 0.05                          | 0.06                          | 0.06                            | 135                                  |
| Large Car/SUV                    | GSL 0.12                    | 0.08                          | 0.08                          | 0.09                            | 213                                  |
| LCV/Delivery Van                 | DSL 0.10                    | 0.07                          | 0.12                          | 0.10                            | 252                                  |
| Medium Duty Truck                | DSL 0.21                    | 0.15                          | 0.16                          | 0.17                            | 450                                  |
| Long Distance Bus                | DSL 0.43                    | 0.25                          | 0.22                          | 0.26                            | 688                                  |
| Heavy Duty Vehicle               | DSL 0.38                    | 0.25                          | 0.24                          | 0.26                            | 678                                  |

Table 3
Baseline 2050 road type shares per vehicle segment.

| Urban share | Rural share | Highway share |
|-------------|-------------|---------------|
| 2-Wheeler/Small Car/Medium Car | 0.30 | 0.45 | 0.25 |
| Large Car/SUV | 0.30 | 0.45 | 0.25 |
| LCV/Delivery Van | 0.42 | 0.30 | 0.28 |
| Medium Duty Truck | 0.29 | 0.38 | 0.33 |
| Long Distance Bus | 0.12 | 0.59 | 0.29 |
| Heavy Duty Vehicle | 0.12 | 0.25 | 0.63 |

passenger cars involved the design of baseline and scenario engine maps and vehicle simulation in the AVL CRUISE⁴ environment (see Annex A.2a for a detailed description).

The A measures applied on conventional engine operation and to vehicles considered in this study are listed in Table 5, which specifies their energy reduction potentials derived for each vehicle type and drive profile.

For BEV and FCHEV, rather than applying improvement factors, 2050 energy consumption was calculated using the same vehicle modelling approach as for their baseline energy consumption, but improving their weight, aerodynamics and efficiency as specified in Table 6.

B. Improvements in traffic flow

Type “B” measures cover energy consumption or CO₂ reduction, again defined versus a 2015 baseline, due to improvements in driving conditions. The measures analysed were the overall potential for smoothing speed and avoiding stops in real traffic, e.g. through improving green light operation (see Annex A.2b for a detailed description of the modelling employed), and platooning. B measure impacts considered in this study are included in Table 5.

C. Road transport reduction

Reductions in the kilometres driven, or in the numbers of vehicles on the road versus a 2015 baseline, are covered by type “C” measures. Measures considered in this study address reduced parking search traffic, intermodality of freight, coordination systems for freight, and increased truck capacity. The assumptions made for this study are quantified in Table 7. For a discussion of the estimates in the light of literature, see Annex A.2c.

The degree of implementation and the estimates of C measures’ impacts is much less elaborated compared to the efficiency measures. This was primarily due to the fact that projections of changes in the transport system as a whole were beyond the scope of the present exercise. Nevertheless, it is of importance to stress that there is a lack of fact-based research results regarding transport reduction and its consequent effects on CO₂ emissions from the introduction of measures such as ride-sharing, mobility as a service, autonomous vehicles and modal shifts. Therefore these measures were not included in the study due to their inherent complexities and the corresponding high degree of uncertainty. Given the uncertainty in this area, transport reduction potentials were limited to low levels and will be further investigated in a follow-up step of the study.

2.3.2. Fleet compositions scenarios

Three 2050 road vehicle fleet composition scenarios by powertrain were established, varying in their degrees of fleet electrification. They can be described as follows:

i) The High Electrification (HE) scenario describes a situation with maximum market uptake of plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) all experts could agree on.

ii) The High Electrification plus Hydrogen (HEH) scenario also includes fuel cell hybrid electric vehicles (FCHEV) running on hydrogen on top of the options in the HE scenario.

iii) The Mixed (Mix) scenario assumes substantially lower fleet electrification, where combustion-based propulsion dominates in most vehicle segments. No FCHEV are considered. Shares of BEV are relatively modest; shares of PHEV and conventional vehicles are relatively high compared to the first two scenarios.

The HE and HEH scenarios, also named collectively “electrification scenarios” in the following, incorporate the fact that the EC transport white paper (EU, 2011) target of zero-emission urban transport by 2050

Table 4
Baseline 2050 Vehicle Specifications used for BEV and FCHEV and resulting energy consumption.

| Type               | GfA [m²] | Mass [kg] | Powertrain efficiency [%] | Urban Energy Consumption [Wh/km] | Rural Energy Consumption [Wh/km] | Highway Energy Consumption [Wh/km] | Combined Energy Consumption [Wh/km] |
|--------------------|----------|-----------|---------------------------|---------------------------------|---------------------------------|-----------------------------------|-------------------------------------|
| Small car 2015     | 0.32     | 1650      | 85                        | 135                             | 142                             | 204                               | 155                                 |
| (Baseline)         |          |           |                           |                                 |                                 |                                   |                                     |
| Large Car 2015     | 2.5      | 2400      | 84                        | 175                             | 173                             | 236                               | 189                                 |
| (Baseline)         |          |           |                           |                                 |                                 |                                   |                                     |

⁴ https://wwwavl.com/cruise.
is reached. This fosters a combined 100% coverage of BEV, FCHEV and PHEV powertrains in the car segments as well as for urban buses, light commercial vehicles, and medium duty trucks. For heavy duty vehicles and long-distance coaches, apart from PHEV and FCHEV powertrains, hybridized advanced internal combustion engines remain an option throughout 2050. This study considers conventional fuel and liquid natural gas (LNG) versions. Gasoline was assumed to be the conventional fuel utilised for light duty vehicles and diesel for heavy duty.

These assumptions were made purely for simplicity and do not imply that these will be the fuels of choice in the future nor that ICEs are assumed to use only conventional fuels in 2050. In fact, fossil fuels are expected to be replaced by other types of chemical energy carriers such as renewable fuels, power-to-liquid etc. Finally, it was assumed that in 2050, combustion engines will have zero air pollutant emissions in real world driving. 2050 fleet composition for all scenarios is shown in Table 8.

Advanced electrified car shares under the Mix scenario correspond roughly with what has previously been found necessary to reach a 60% decarbonisation of road transport in the EU by 2050 under optimal trajectories (Siskos et al. (2018); Karkatsoulis et al. (2017)), whereas the electrification scenarios HE and HEH show substantially stronger fleet electrification, which could result from a strong decline in battery costs, or else would need to be driven by stringent regulation (Edelenbosch et al. (2018)).

While the 2050 fleet composition scenarios were determined through expert group discussion, Fig. 3 illustrates trajectories of market uptake and stock composition for light duty (a, b) and heavy duty vehicles (c, d) compatible with 2050 fleet composition in the Mix scenario, assuming a roughly linearly increasing trend in BEV market shares and linearly decreasing trend in conventional vehicle shares.

As Fig. 3 (a) shows, the resulting shares of electrified vehicles in 2050 light duty vehicle (LDV) new registrations are 20% BEV and 28% PHEV, thus nearly half of all new 2030 LDV are advanced electrified vehicles (xEV) in the Mix scenario. To reach a 2050 stock composition as in the two electrification scenarios, xEV shares need to be substantially higher, which demonstrates the degree of ambition of the scenarios presented in this study.

2.4. Tank to wheel fleet impact calculations

Calculations of 2050 road vehicle fleet tank to wheel energy consumption, energy mix and CO2 emissions are based on the DIONE fleet impact model. To this aim, baseline fuel and energy consumption, vehicle activities and stock are transformed according to the scenario settings. The scenario-specific energy consumption per vehicle and driving profile is weighted by driving shares and combined with the fleet composition scenarios. The results are the real world energy consumption and mix, as well as tank to wheel real-world CO2 emissions of the 2050 road vehicle fleet, calculated via the application of fuel and energy emission factors. The mathematical documentation of the fleet impact calculations is provided in Annex A.3. A graphical overview of the model inputs, interactions and outputs was shown in Fig. 1.

The approach allows for applying single measures and for combining packages, in their optimistic and pessimistic variants respectively, resulting in a high number of possible scenarios. We limit the subsequent presentation of results to options where, for all three fleet composition scenarios.

- only one measure type (A, B or C) is applied, all optimistic or all pessimistic -> 3 measure types x 2 variants x 3 fleet compositions 18 settings, or
- all measure types are applied, either all of them optimistic or pessimistic -> 2 variants x 3 fleet compositions 6 settings.
Table 6
Vehicle Specifications used for Optimistic and Pessimistic 2050 Scenario BEV and FCHEV and resulting energy consumption.

| Car Type | Cd x A [m²] | Mass [kg] | Power-train efficiency [%] | Urban Energy Consumption [Wh/km] | Rural Energy Consumption [Wh/km] | Highway Energy Consumption [Wh/km] | Combined Energy Consumption [Wh/km] | Reduction over Baseline |
|----------|-------------|-----------|-----------------------------|----------------------------------|---------------------------------|----------------------------------|-----------------------------------|------------------------|
| Small Car 2050, Pessimistic | 0.25 | 1250 | 90% | 94 | 99 | 145 | 109 | 0.30 |
| Small Car 2050, Optimistic | 2.5 | 1000 | 93 | 64 | 67 | 98 | 74 | 0.52 |
| Large Car 2050, Pessimistic | 0.19 | 2000 | 91 | 120 | 123 | 175 | 135 | 0.29 |
| Large Car 2050, Optimistic | 2.7 | 1700 | 94 | 86 | 87 | 125 | 96 | 0.49 |

Table 7
Transport reduction potentials by 2050, versus 2015. Measures C (1) address reductions in activity per vehicle, measures C (2) reductions in the number of vehicles. The table gives 2050 shares of reduction of the activity/number of vehicles over 2015 for each measure separately.

| Type | Measure | 2-W; S/M Cars | L Cars, SUVs, LCVs, Vans <7.5t | City Buses, Trucks <12t | Trucks >7.5 t; Long Dist. Buses |
|------|---------|----------------|---------------------------------|--------------------------|-------------------------------|
| C (1) | Reduced urban parking search traffic | 0.04 | 0.1 | 0.02 | 0.06 | 0 | 0.02 | 0 |
| C (2) | Intermodality of freight | 0.02 | 0.05 | 0.05 | 0.1 | 0.05 | 0.1 |
| C (3) | Coordination systems for freight (logistics) | 0.05 | 0.1 |
| C (4) | Increased truck capacity | |

Table 8
2050 Fleet Composition for the scenarios HE/HEH/Mix (%); Powertrains and fuels: Adv. ICE – Advanced Internal Combustion Engine, PHEV – Plug-in Hybrid Electric Vehicle, BEV – Battery Electric Vehicle, FCHEV – Fuel Cell Hybrid Electric Vehicle, GSL – Gasoline, DSL – Diesel, LNG – Liquid Natural Gas. Light commercial vehicles and delivery vans (up to 7.5t) use the same efficiency as the large car category but have a different fleet composition; Medium duty trucks (MDT, 7.5 to 12t) use the same measure efficiencies as city buses.

| Car Type | Small Car, Medium Van | Large Car, Delivery Van | City Bus / Medium Duty Truck | Heavy Duty, Coach |
|----------|-----------------------|-------------------------|-------------------------------|------------------|
| GSL adv. | 0/0/37.5 | 0/0/20 | 0/0/20 | 0/0/20 |
| ICE | 0/0/15 | 0/0/15 | 0/0/15 | 0/0/15 |
| GSL adv. | 50 | 50 | 50 | 50 |
| GSL PHEV | 50/25/60 | 60 | 60/30/70 | 40/20 |
| DSL PHEV | 40/20/60 | 60/30/70 | 40/20 | 20/20 |
| BEV | 50/50/50 | 60/40/20 | 40/40/15 | 20/20 |
| FCHEV | 0/0/25 | 0/0/40 | 0/0/30 | 0/0/20 |
| LNG | 0/0/50 | 0/0/50 | 0/0/50 | 0/0/50 |

2.5. Well to wheel calculations for BEV and PHEV energy and CO₂

While a full analysis of well to wheel (WtW) energy consumption and emissions for all powertrains is beyond the scope of this paper, a sensitivity calculation is carried out to highlight the order of magnitude of such impacts for BEV and PHEV. On top of battery to wheel electricity consumption addressed in the energy consumption calculation for xEV described in the previous section, electric vehicles require a higher total electricity production due to a series of losses, quantified in Table 9. While power electronics and motor to wheel efficiency are included in the battery-to-wheel calculations, grid to battery losses need to be factored in to calculate grid to wheel efficiencies. They can be derived as the product of grid, inverter and battery charging efficiencies from Table 9. A grid to battery efficiency of 86% is estimated for 2050, which means that total energy required is 1/0.86 – 1.17 times the amount of battery to wheel energy. Similar efficiencies are assumed for BEV and PHEV, and similar 2050 inverter and charging efficiencies for all vehicle segments. With the addition of vehicle to grid or grid-level energy storage, the efficiency could be significantly lower, however these are not accounted for in the present analysis.

To estimate the upstream CO₂ emissions of BEV and PHEV in 2050, the total energy consumption (charging plus losses) is multiplied by projected 2050 electricity carbon intensity. A factor of 0.082 tCO₂/MWh is applied, taken from the EU Reference Scenario 2016 (EU, 2015) and steam and steam production emission intensity according to EC, 2016c.

3. Results and discussion

In this section, the activity of the 2050 road vehicle fleet and its distribution over different powertrains is outlined, followed by a presentation of fleet energy consumption and CO₂ emissions under the different scenarios. Energy and CO₂ results are compared both with present data, as well as to scenario projections under the 2016 EU reference scenario (EC, 2016c) and the EUCO30 scenario (EC, 2016; E3MLab & IILASA, 2016), which is the more ambitious one of two scenarios designed to achieve the EU’s 2030climate and energy targets.

The present approach addresses technical emission reduction potential, with a strong focus on electrification and vehicle efficiency. The investigation of social innovations such as mobility as a service, sharing, or new mobility patterns are beyond the scope of the present paper. Well to wheel impacts or lifecycle implications, which play an important role in particular with view to the strong electrification assumed, cannot be fully covered here and merit further investigation.

3.1. 2050 road transport activity

In the scenarios, baseline 2050 activities as shown in Table 1 apply for the HE, HEH and Mix scenarios. They are lowered if C type measures are taken, which result in a total 2050 fleet activity reduction by 1.8% in the pessimistic to 4.2% in the optimistic C measures case compared to baseline 2050 activity. The impact of C measures on total activity, as well as on light versus heavy duty vehicles separately, is shown in Table 10.

All scenarios constitute a shift towards electrified propulsion, to different extents (see Table 11). The share of total activity covered by
Table 9
Efficiency assumptions for electric vehicles throughout 2050, from grid to wheel. Source: ERTRAC (2017).

|                      | Grid Efficiency | Inverter AC/DC Efficiency | Battery Efficiency (Fast Charge) | Power Electronics Efficiency (DC/DC-AC) | Motor to wheel efficiency (WLTP) | Grid to wheel efficiency |
|----------------------|-----------------|---------------------------|----------------------------------|----------------------------------------|---------------------------------|--------------------------|
| BEV 2015, Range 250 km | 0.95            | 0.95                      | 0.92                             | 0.91                                   | Min 0.86, Max 0.91               | Min 0.65, Max 0.69       |
| BEV 2050, Range 600 km | 0.96            | 0.96                      | 0.93                             | 0.92                                   | Min 0.87, Max 0.92               | Min 0.69, Max 0.73       |

Table 10
2050 Vehicle Activities, with C measures, absolute values (trillion vkm) and changes compared to 2016 (% of 2016).

|                      | C measures, Pessimistic | C measures, Optimistic |
|----------------------|-------------------------|------------------------|
|                      | trill. vkm versus 2016 | trill. vkm versus 2016 |
| Cars, LCVs & 2wheelers | 4500            | 4422                   | 111%                               |
| Trucks, Vans, Buses  | 541             | 496                    | 127%                               |
| Total Road           | 5040            | 4918                   | 113%                               |

Table 11
2050 Fleet Activity distribution by powertrain in the three scenarios.

|       | HE   | HEH  | Mix  |
|-------|------|------|------|
|       | 4.7% | 4.0% | 36.3%|
| Advanced ICE | 16.2% | 8.1% | 33.8%|
| PHEV   | 79.1%| 78.5%| 30.0%|
| BEV    | 0.0% | 9.4% | 0.0% |

Fig. 3. Exemplary market uptake and fleet composition trajectory for the Mix Scenario; for light duty vehicles (LDV - a,b) and heavy duty vehicles (HDV - c,d). Light duty vehicles comprise small cars, large cars, and vans, whereas heavy duty vehicles include buses, coaches, medium and heavy duty trucks.

3.2. Energy consumption and energy mix

Fig. 4 gives an overview of 2050 road transport energy consumption and energy mix under different scenarios. The first 3 bars present references for comparison, the second 3 bars (labelled “Fleet Composition Effect, no measures”) show 2050 road transport energy consumption derived by implementing the fleet composition scenarios only. The final 6 bars (“A&B&C”) show 2050 energy consumption when all measures for efficiency improvement (A type), transport smoothing (B) and transport reduction (C) are implemented, in their optimistic and pessimistic version respectively. Thus, the figure exhibits the bandwidth of development options throughout 2050 covered by this study.

With the assumed fleet composition only and the projected activities, 2050 total road transport energy consumption (tank to wheels) is 1900 and 2000 TWh for the two electrification scenarios HE and HEH. This is xEV, i.e., the sum of PHEV, BEV and FCHEV in 2050 ranges from more than 60% in the Mix scenario to around 95% in the HE and HEH scenarios. BEV alone make up for an activity share of 30–80%.
below what is projected according to the EU reference scenario 2016 and the more ambitious EUCO30 scenario, as well as visibly below 2015 road transport energy consumption. However, the Mix scenario without measures shows a 2050 energy consumption of around 2800 TWh and thus not much lower than under the EU reference scenario 2016. Note that energy consumption is driven by the assumed increase in transport activity throughout 2050. As activity is projected to increase over-proportionally in freight transport (see Table 10), notably in trucks, the Mix base scenario exhibits an energy consumption increase which is higher than average total road transport activity increase.

When all measures are implemented, in the two electrification scenarios, 2050 transport energy consumption tank to wheels can be reduced to 1300 and 1400 TWh in the pessimistic case, and to around 800 TWh if the optimistic version holds, achieving in the best case a reduction of two 75% versus present road transport energy consumption. Again, the Mix scenario remains at substantially higher levels of 2000 (pessimistic) and 1250 TWh (optimistic).

Regarding the energy mix, driven by the fleet powertrain composition, substantially different mixes of chemical fuels, electricity and hydrogen arise. Chemical fuels comprise gasoline (GSL), diesel (DSL), and liquid natural gas (LNG), which can be replaced by alternative fuels of either biofuel or transformed fossil fuel type. Their combined share remains at 85% in the Mix scenario but decreases to around 55% in the HE scenario and to 35% in the HEH scenario. In the two electrification scenarios, the consumption of non-chemical fuels increases strongly: In the HE Base (without measures) scenario, 2050 road transport electricity consumption from battery to wheels is 840 TWh. Although this figure does not include losses from vehicle charging efficiency or energy grid losses, it can be seen that this is significant being equivalent to 30% of EU28 final energy consumption of electricity in 2015 (Eurostat, 2018). In the HEH Base (without measures) scenario, the sum of electricity and hydrogen consumption is even higher, at 1300 TWh. Thus in the absence of further measures to reduce transport energy consumption but with strong fleet electrification, the consumption of electricity and hydrogen by transport can pose a substantial challenge to the energy sector.

Fig. 5 separates the energy consumption impacts of single measure types and of fleet electrification. In the two electrification scenarios, fleet electrification alone leads to an energy consumption reduction of about 40% compared to 2015 (“Fleet composition” effect, blue bars), at the projected 2050 fleet activity, showing that electrification over-compensates the activity increase. This is less pronounced for the Mix scenario, where 2050 energy consumption is roughly 15% lower than in 2015 if no measures are implemented.

For all three scenarios, the total energy reduction achieved by adding all measures (A, B & C, red bars in Fig. 5) yields roughly an extra 30%pts of energy reduction over the fleet composition effect in the optimistic version, or 20%pts in the pessimistic variant. Of the measure types, A measures have the largest impact (roughly 20%pts optimistic/10%pts pessimistic), followed by B (ca. 10%pts/5%pts) and C (5%pts/3%pts) for the two electrification scenarios. In the Mix scenario, the merit order of measures is maintained. Measures, in particular A and B measures, reduce energy consumption more significantly than in the electrification scenarios. Note that the combined potential of A, B and C measures is less than the sum of their separate potentials, due to overlap in the savings addressed.

Upstream electricity losses are addressed Table 12. Grid to battery losses of electric energy for BEV and PHEV are shown in the second column, and grid to wheel electricity consumption is given in column three. By assumption, this is an extra 17% of electricity on top of battery to wheel electricity consumption, which amounts to 30 to 140 TWh under the different scenarios. Compared to total road transport tank to wheel energy consumption, it makes up for an additional 2–7% under the different scenarios.
3.3. 2050 transport CO₂ emissions

With view to the target of mitigating climate change, it is crucial to what extent the CO₂ emissions of transport can be reduced. Note that conventional fuels (GSL, DSL) are treated as 2015 standard fuel mixes and are accounted for with the present conventional fuel emission factors. Resulting emissions from chemical fuel combustion can be considered as an upper limit, as by 2050, these fuels could be substituted by alternative, lower-emission fuels to some extent, such that ICE TtW emissions could be substantially lower.

Fig. 6 shows the bandwidth of road vehicle CO₂ emissions in 2050 resulting from the different scenarios, in terms of tank to wheel (TtW) real-world CO₂ emissions. Emissions caused during extraction, transport or transformation of fuels are not considered. The first 4 bars (“References”) present benchmarks for comparison. The second 3 bars (“Fleet composition effects, no measures”) show 2050 road transport CO₂ emissions resulting from the respective fleet composition scenarios. The final 6 bars (“A&B&C”) present CO₂ emissions when all measures are implemented, in their optimistic and pessimistic versions, respectively.

At first glance, all scenarios reduce road transport CO₂ emissions compared to their 2015 level of 860 MtCO₂, and also compared to the projection within the EU reference scenario 2016 of 740 MtCO₂ in 2050.

However, more ambitious reductions are needed to achieve the EU’s policy targets. The European Commission’s white paper on transport (EU, 2011) has set a 2050 target of reducing transport GHG emissions by 60% compared to 1990, represented by the by the black horizontal line in Fig. 6. Targets set at the same time for aviation (40% sustainable low carbon fuels by 2050) and shipping (50% emission cut) as well as strong CO₂ emission reduction pledges made under the Paris Agreement suggest that road transport will have to reduce its emissions by more than 60%. Thus the White Paper target is not to be understood as the final benchmark for 2050 EU road transport emission reduction, and 2050 road transport emissions will need to stay well below the 280 MtCO₂ indicated.

The HEH scenario is the only one reducing CO₂ emissions to below 200 Mt by 2050 without further measures and reaching a 75% reduction versus 1990. When implementing all A, B and C measures, the two electrification scenarios with optimistic measures show emissions of 80 (HE Opt) and 115 MtCO₂ (HEH Opt), the former of which is a nearly 90% reduction versus 1990. In the pessimistic variant, 2050 emissions are 130 (HEH Pess) and 190 MtCO₂ (HE Pess). The Mix scenario achieves a roughly 60% reduction at 270 MtCO₂ in the optimistic, all measures case, but remains at 440 MtCO₂ (less than 40% reduction) in the pessimistic variant. Thus, even if all measures are employed and can achieve their optimistic potential, moderate fleet electrification as depicted in the Mix scenario is unlikely to be sufficient and would require decarbonisation of the chemical energy sources via introduction of sustainable fuels, e.g. advanced biofuels or fuels derived from renewable electric energy (PtX).

Fig. 7 shows the CO₂ reduction by 2050, compared to 2015, of fleet composition and the individual measure types separately. Differently from the order of magnitude of effects seen with regard to energy consumption in Fig. 5, fleet electrification alone makes a large contribution to CO₂ reduction of 70–80% versus 2015 (which corresponds to 60–75% compared to 1990) in the electrification scenarios, but less than 30% in

### Table 12

|                       | Battery to wheel Electricity Consumption (TWh) | Grid-to-battery Electricity Losses (TWh) | Grid to wheel Electricity Consumption (TWh) |
|-----------------------|-----------------------------------------------|------------------------------------------|--------------------------------------------|
| HE Base               | 842                                           | 140                                      | 982                                        |
| HEH Base              | 763                                           | 127                                      | 890                                        |
| Mix Base              | 430                                           | 72                                       | 501                                        |
| HE Opt                | 346                                           | 58                                       | 404                                        |
| HE Pess               | 565                                           | 94                                       | 659                                        |
| HEH Opt               | 304                                           | 51                                       | 355                                        |
| HEH Pess              | 507                                           | 85                                       | 592                                        |
| Mix Opt               | 185                                           | 31                                       | 216                                        |
| Mix Pess              | 287                                           | 48                                       | 335                                        |

Fig. 6. 2050 road transport real-world tank to wheel CO₂ emissions (MtCO₂), for references and all scenarios, without measures and with all A, B and C measures applied. Scenarios: High Electrification (HE), High Electrification plus Hydrogen (HEH), and Mixed scenario (Mix), with Optimistic (Opt) and Pessimistic (Pess) measure versions. Black line: 60% reduction versus 1990.
in particular the Mix scenario. This is due to the large amount of zero-TtW emission fuels consumed in the electrification scenarios. In contrast, in the two electrification scenarios, single measure types make relatively small contributions of 2–8%pts in most cases. Measure types retain the same merit order as seen with regard to energy consumption reduction, with A measures being more effective than B and B more so than C, but with little margin. The impact of all measures combined varies with the degree of fleet electrification, i.e. they have the highest impact in the Mix scenario (a maximum contribution of about 40%pts in Mix Opt), followed by HE Opt (20%) and HEH Opt (10%pts). In the pessimistic variant, their effect is roughly half of the optimistic version impact.

The fleet calculations also allow analysing CO₂ emissions by vehicle type, providing evidence that HDV will be the main emitters of CO₂ with a contribution between 50 and 80% of emissions by 2050 in the scenarios. More details on vehicle type emissions and the role of engine measures for emission reduction is provided in Annex A.4 to this paper. While the dominant part of conventional vehicle emissions results from burning fuels during use, in the tank-to-wheel perspective xEV are treated as zero-emission. However, important quantities of emissions can be caused by the production of the electricity they use. Table 13 presents upstream emissions from BEV and PHEV, in absolute terms (MtCO₂) as well as relative to the total TtW CO₂ emissions calculated for the respective scenarios. They range from 41 to 80 MtCO₂ for the base scenario versions with no measures applied, and from 18 to 54 MtCO₂ when all measures are applied. As can be seen, upstream emissions from electricity play a significant role in particular in the strong electrification scenarios, and merit further investigation.

Table 13: 2050 BEV and PHEV upstream CO₂ emissions.

| BEV/PHEV grid to wheel electricity CO₂ emissions (MtCO₂) | Share of total scenario tank to wheel CO₂ emissions (%) |
|----------------------------------------------------------|--------------------------------------------------------|
| HE Base                                                  | 80                                                     | 30%                                                   |
| HEH Base                                                 | 73                                                     | 40%                                                   |
| Mix Base                                                 | 41                                                     | 7%                                                    |
| HE Opt                                                  | 33                                                     | 29%                                                   |
| HE Pess                                                  | 29                                                     | 37%                                                   |
| HEH Opt                                                  | 48                                                     | 38%                                                   |
| Mix Opt                                                  | 18                                                     | 7%                                                    |
| Mix Pess                                                 | 27                                                     | 6%                                                    |

4. Conclusions and policy implications

The present study casts light on the technical feasibility of energy consumption and CO₂ emission reductions from EU road transport by 2050 from a tank to wheels perspective. To this aim, a group of experts from automotive industry, research and public authorities has provided a thorough consensus assessment of the potentials of a wide range of vehicle measures, including options to increase vehicle efficiency, smooth transport, and reduce vehicle activity throughout 2050. They have also established three scenarios of road vehicle powertrain composition by 2050. An exemplary analysis of a market uptake trajectory to reach 2050 electrified vehicle stock shares of the least electrified scenario has shown that even this scenario requires nearly 50% of electrified cars and vans in the 2030 new fleet, which demonstrates the degree of ambition underlying the present scenarios. Using these inputs for fleet impact calculations based on the DIONE model, a number of conclusions can be drawn.

Scenario outcomes demonstrate that substantial tank to wheel reductions of CO₂ emissions from road transport are feasible by combining fleet electrification and the three types of measures. In the two more ambitious fleet composition scenarios, summarized as “electrification scenarios”, 2050 emission reductions of more than 70% versus 1990 can be achieved even if all measures perform only at the lower boundary of experts’ expectations (‘pessimistic’ version). With optimistic measure potential and electrification, CO₂ emissions from road transport could be reduced by 85–90% versus 1990. In the Mix scenario, which represents a less rapid uptake of electrified vehicles, a 60% CO₂ reduction versus 1990 can still be reached with optimistic measure potential, but only 40% can be achieved in case the pessimistic assessment holds and there is no decarbonisation of chemical fuel sources such as the introduction of sustainable fuels or PtX. In case of strong electrification, the market uptake of electrified powertrains is the primary driver of CO₂ reduction, and less than 20 percentage points of CO₂ reduction are attributed to the measures.

While CO₂ emissions decrease substantially in all fleet composition scenarios considered even without any measures, energy consumption depends strongly on the successful application of measures. High energy consumption reductions of around 75% versus 2015 in the optimistic or 60% in the pessimistic case can be achieved by combining both ambitious fleet electrification (as in the electrification scenarios) and all measures available. If fleet electrification remains at the more modest level of the Mix scenario, base energy consumption is reduced by 15% over its present level, but a maximum overall reduction of 60% (optimistic) or 40% (pessimistic) can be achieved if all measures are applied.

Both with regard to CO₂ emission and energy consumption reduction, measure types exhibit a clear ranking. Highest benefits are expected from vehicle efficiency improvements, followed by transport smoothing, and finally activity reduction measures. The measure type ranking cannot be considered as fully consolidated. It turned out during expert group discussion that available evidence on the feasibility and impact of transport smoothing and activity reduction measures is limited, thus there were few measures the impact of which could be quantified reliably and no assessment of overall reduction potential of transport demand was attempted. Furthermore, the Delphi approach employed in the study entailed a bias towards technical measures and their emission potentials, where experts involved had very strong expertise. The knowledge base for assessing transport smoothing, in particular transport reduction measures, was comparatively less pronounced. Moreover, the expert group did not address social innovations, behavioural aspects, or potential radical transport system changes which could not be captured by the present approach. More research with regard to these measure types is warranted to complement the present approach, which has been successful in addressing feasibility and boundaries of technical measures for transport energy consumption and CO₂ emissions from a tank/battery to wheel perspective.

This papers’ primary focus is the technical feasibility of strong
vehicle emission reduction, without explicitly investigating the conditions for such a transition. It is likely that policies will be a prerequisite for fleet electrification and efficiency increases of the order of magnitude demonstrated.

Moreover, the present study focused on vehicle technology and operations effects in the transport sector. It is obvious however that any of the scenarios would have major impacts on transport energy consumption. For example, the strongly electrified scenario without measures would cause an electricity consumption from transport (battery to wheels) of the order of magnitude of nearly one third of the present EU28 final electricity consumption, or total present EU28 renewables share in electricity. While in the transport sector, electric energy is counted as zero-emission from a tank to wheel perspective, the energy sector will face a challenge to provide high quantities of low-carbon electricity for transport. Complementary policies would be needed to ensure that transport emissions are not shifted to other sectors. Moreover, a life cycle perspective on vehicle emissions should be added for a full picture of the impacts of road transport electrification.

Another boundary of the present analysis consists of the properties of chemical fuels. It has been assumed that combustion engines consume conventional fuels with today’s properties and emission factors. The present results can thus be seen as an upper boundary of the CO2 the specified fleets could emit. No attempt was made to investigate the availability of alternative, low-carbon synthetic fuels by 2050, which might play an important role for transport decarbonisation in particular within more moderate electrification scenarios. Moreover, this analysis deals with CO2 emissions, but does not consider air pollutant emissions from transport. While in the expert group, there was broad agreement that by 2050, any persisting combustion engines would be near zero-emission with regard to air pollutants, this assumption and its technical implementation merits further investigation.

It can be concluded that ambitious CO2 emission reduction targets are technically feasible by 2050. Fleet electrification has been demonstrated to achieve high tank to wheel emission reductions even in the absence of other measures, but with the consequence of inducing high transport energy consumption. A combined approach fostering both electrification and measures for vehicle efficiency improvement, transport smoothing and transport reduction can limit transport energy consumption and the resulting challenge for the energy sector.

Author contributions

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements/Funding

A part of the investigations has been performed in the framework of the EU Horizon 2020 coordination and support action FUTURE RADAR (contract no. 723970). The financial support from the European Union is highly acknowledged. The European Commission’s Joint Research Centre has funded the open access publication of the paper.

The present paper is based on the intense involvement of experts from automotive industry, research and public authorities. The list of experts is included in Annex A.1.

The scientific output expressed does not imply a policy position of the European Commission, nor a position of any of the institutions where authors are affiliated.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2019.111224.

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