PERSPECTIVE

The hidden cost of road maintenance due to the increased weight of battery and hydrogen trucks and buses—a perspective

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Abstract

Decarbonisation of transport emissions is essential to meet climate targets. For road transport, currently available technologies are battery electric vehicles and hydrogen fuel cell electric vehicles. Battery vehicles are more established than hydrogen; both could deliver the emissions reduction required. However, battery vehicles are considerably heavier than equivalent hydrogen vehicles, which are in turn slightly heavier than internal combustion engine (ICE) vehicles; a heavier vehicle will have a bigger impact on road wear and associated costs. Here we carry out a desk-based analysis, developed in 2021–2022, examining the impact and cost of the increased weight of zero emissions vehicles on road wear in an entire national vehicle fleet. The novelty is in the first quantified application of the long-understood relationship between axle load and road wear to the problem of the additional weight of zero emissions vehicles. This leads to an approximate quantification of additional costs of road maintenance as the vehicle fleet transitions to zero emissions vehicles. We examine these in four scenarios: all battery vehicles; all hydrogen vehicles; a combination; current ICE vehicles for comparison. We find 20–40% additional road wear associated with battery vehicles compared to ICE vehicles; hydrogen leads to a 6% increase. This is overwhelmingly caused by large vehicles – buses, heavy goods vehicles. Smaller vehicles make a negligible contribution. Governmental bodies liable for road maintenance may wish to set weight limits on roads, require additional axles on heavier vehicles, or construct new roads to a higher standard, to decrease road wear.

Graphical abstract
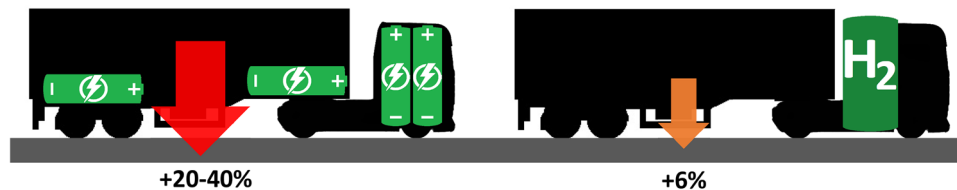
BEV large vehicles create a significantly greater increase in road wear than HFCEV, both compared to ICE

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Introduction

Decarbonisation of energy used in road transport will be essential for the world to meet the necessary reductions in emissions. The two currently commercially available technological solutions for road vehicles are Battery Electric Vehicles (BEV) and Hydrogen Fuel Cell Electric Vehicles (HFCEV) (Robinius et al. 2018). At present, HFCEV vehicles are in their infancy, while BEVs are more established. However, in the UK, Zero Emission Vehicles (ZEV) of any type

have not yet made significant inroads into the hydrocarbon fuelled internal combustion engine (ICE) fleet with less than 1% of the vehicle fleet and about 4.3% of new vehicle sales in 2020 (UK Government 2021a; Scottish Government 2020b).

HFCEV are typically slightly (1–2%) heavier than ICE vehicles; BEVs are usually significantly heavier (10–30%) due to the high weight of batteries (Lombardi et al. 2020). In this paper we apply existing knowledge of the relationship between vehicle weight and road wear to consider the impact of the heavier ZEVs. We do this by assessing the road wear due to the main vehicle classes at present and in the future scenarios of (1) all battery vehicles; (2) all hydrogen vehicles; (3) a combination, and comparing the overall results. A significant increase in wear would lead to a combination of increased maintenance costs, increased particulate emissions, and potentially the need to construct new roads to a higher standard.

We select Scotland as an area of analysis. This allows analysis of a fairly homogenous road construction and vehicle standard (Low et al. 2020). This is also connected with the Scottish Government's commitment to unusually demanding targets for early decarbonisation, with a ban on new hydrocarbon car & LGV sales, and an all-sector emissions reduction of 75% from 1990 levels, to be achieved by 2030, followed by net zero emissions by 2045 (Scottish Government 2019), and also with the Scottish Government's recent announcement of substantial investment in the hydrogen economy (Scottish Government 2020a).

This approach can be applied to other locations, subject to local factors, such as (i) existing road quality and construction standards, (ii) typical vehicle weight, numbers and construction & use regulations, and (iii) an assessment of the local applicability of the method of road wear assessment used (Rhodes 1983).

Context and Literature

There have been several relevant studies investigating the connection between vehicle weight and road wear, starting with seminal work by the American Association of Highway and Transportation Officials (AASHO) in the 1950s (AASHO 1962). This was further developed in the UK by Rhodes (Rhodes 1983) and the Transport Research laboratory (Addis and Whitmarsh 1981), and re-examined by Martin in 2002 with a focus on Australian roads of similar construction (Martin 2002), confirming the relationship first developed.

Nilsson, Svensson and Haraldson (Nilsson et al. 2020) assess the economic impact and life between major restorations of road surfaces subject to different types of loading. However, their results also find additional surface wear due to smaller vehicles. They attribute this to the use of studded snow tyres in their study area, Sweden, which are not used in Scotland.

Gustafsson (Gustafsson 2018), Denby, Kupiainen and Gustafson (Denby et al. 2018) and Stafoggia and Faustini (Stafoggia and Faustini 2018) review the impact and measurement of road wear emissions on public health, within *Non-Exhaust Emissions: an Urban Air Quality Problem for Public Health; Impact and Mitigation Measures* (Fulvio 2018).

This all contributes to the established and widely used principle that relates vehicle axle load to road wear in the 4th power. This is described in more detail in the Method section below.

Lombardi, Triboli, Guandalini and Iora (Lombardi et al. 2020) examine the impact of different drivetrain types, including HFCEV and BEV on the weights of a range of vehicles, as part of their analysis into efficiency.

As the world moves into a transition to zero emissions, new vehicles will require different zero emission drivetrains. At present, available options are either BEV or HFCEV (Robinius et al. 2018). Both of these are heavier overall, with current technology, than existing hydrocarbon ICE drivetrains (Lombardi et al. 2020). Additional road wear is considered in a number of works in the context of particulate emissions (Matthias et al. 2020; Beddows and Harrison 2021), or in BEV specific road design (Börjesson et al. 2021).

Here, then, we take the established relationship between axle load and road wear and apply it to the increased weight of vehicles arising from replacing an existing national vehicle fleet with ZEVs, to arrive at the scale of the increased wear on existing roads, and hence future maintance cost.

The novelty in this paper is that this appears to be the first quantified application of the long-understood relationship between vehicle axle load and road wear to the problem of the additional weight of zero emissions vehicles. This leads to an approximate quantification of the additional cost of road maintenance as the vehicle fleet transitions to zero emissions vehicles, filling that gap in published knowledge. We introduce the new terms Road Wear Potential (RWP) of an individual vehicle, and the Road Wear Impact Factor (RWIF) which reflects the total annual wear caused by a vehicle fleet.

Hypothesis There will be significant and quantifiable additional costs of road maintenance due to the increased weight of ZEVs over ICE vehicles. This will be markedly greater for BEVs than for HFCEVs.

Method

Rhodes (RHODES 1983) (and many others) describes the 4th power relationship between road wear and axle load, developed from the experimental work on the subject by

the AASHO in the 1950s (AASHO 1962). Rhodes introduces the concept of using a Standard Axle as a way of comparing the impact of various vehicle types. The Standard Axle is taken as a single axle imposing a total load of 80kN (equivalent to 8 tonnes); the wear relative to such an axle can be readily calculated using the 4th power to give a number of effective standard axles per actual axle. We express this mathematically in Eq. 1 below.

$$\text{Effective Standard Axles per axle} = (\text{Axle load in kN}/80)^4 \tag{1}$$

This approach allows an assessment of cumulative impact of vehicles of different classes, and is used in other studies into road wear (Nilsson et al. 2020). As road wear is very tightly controlled by axle load, it becomes apparent that larger vehicles such as HGVs and buses will have a much greater impact than cars, relative to the vehicle weight.

Other researchers have developed different relationships—for example the UK Transport and Roads Research Laboratory produced a range of exponential powers between 2.4 and 6.6 depending on a number of factors including existing road condition and construction standard (Addis and Whitmarsh 1981). Johnsson derives a range of powers for Swedish roads between 1.2 and 8.5 (Johnsson 2004). However, for the purpose of this preliminary assessment of the road wear impact by future vehicles, we consider the single 4th power of axle weight to be adequate; this is currently used in UK and many other countries' highways design and maintenance (UK Government 2021b).

Based on this established relationship, we introduce the terms Road Wear Potential (RWP) of an individual vehicle, and the Road Wear Impact Factor (RWIF), reflecting the total annual wear caused, which could apply to each vehicle class, sub-class, or national fleet.

The RWP reflects the potential of a vehicle to wear out the road, without considering the extent to which it is used. It depends on the weight of the vehicle and the number of axles it uses, and uses the above 4th power relationship to determine the number of effective standard axles per vehicle. We assume for these purposes that each axle in a vehicle carries an equal load. In practice this will not be the case; we examine the effect of this in the Sensitivities section.

$$\text{RWP} = (\text{Nr.of axles}) \times (\text{Vehicle Weight}/(\text{Nr.of axles} \times 80))^4 \tag{2}$$

The RWIF for each class (or sub-class) is based on the Road Wear Potential of a typical vehicle of a given class, multiplied by the average distance such a vehicle drives and by the number of vehicles in each class. This gives an overall value for comparison of the road wear associated with an entire vehicle class over the course of a year.

$$
\begin{aligned}
\text{Annual Class RWIF} = {}& \text{RWP(typical in class)} \\
& \times (\text{nr. vehicles in class}) \\
& \times (\text{average annual distance driven})
\end{aligned}
\tag{3}
$$

The Class Road Wear Impact Factors are then summed to create an overall RWIF for each scenario.

The inputs and data sources are as follows:

- The number of vehicles in each standard vehicle class (buses & coaches, cars, motorcycles, HGV and LGV.[1]) (Scottish Government 2020b)
- The typical weight, or range of weights, or fuel-based sub-classes, of ICE vehicles in each class (Scottish Government 2020b).
- The likely change in weight due to a similar vehicle having HFCEV or BEV type fuelling and drive systems (see below for derivation).
- The average annual distance travelled per vehicle by class, in km (UK Government Department of Transport 2019).
- We assume that the wear and tear is directly related to the use made of the roads, i.e. the number, class and weight of vehicles using the roads, and not significantly connected to seasonal, weather and simple aging related impacts alone (Nilsson et al. 2020).
- We use the standard UK government vehicle classes of cars, motorcycles, Light Goods Vehicles (LGV), Heavy Goods Vehicles (HGV),[1] and Buses & Coaches. HGVs are further divided into ten weight-based sub-classes, while cars and LGVs are divided into fuel based, that is petrol (gasoline) and diesel (the number of BEVs is still small enough to be insignificant) sub-classes.

To estimate the applicable vehicle weight, or reference weight, for ZEVs, we make an initial assessment of the increase in vehicle weight due to the two new fuel types, and derive simple formulas that fit data previously identified by Lombardi et al. (Lombardi et al. 2020) and vehicle manufacturers (Mercedes Benz UK 2019).

We calculate the RWP and RWIF for all classes and sub-classes, and hence the nationwide RWIF, for four scenarios:

1. Current situation, vehicle fleet overwhelmingly dominated by ICE vehicles.
2. All BEV—all vehicles replaced in the same numbers and load carrying capacity with BEVs.

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[1] The Scottish and UK Governments use the terms "Goods" and "Light Goods" for goods vehicles above and below 3,500 kg maximum gross weight, respectively. Here, to reduce ambiguity, we use the older common terms Heavy Goods Vehicle (HGV) and Light Goods Vehicle (LGV).

3. All HFCEV—all vehicles replaced in the same numbers and load carrying capacity with HFCEVs.
4. Like for Like—all current diesel vehicles replaced by HFCEVs, and all current petrol vehicles replaced by BEVs.

Results

Initial assessment of vehicle weight and other inputs

Based on Lombardi et al. (Lombardi et al. 2020) for larger vehicles (3500 kg and over), and manufacturers' published data for cars (Mercedes Benz UK 2019), we identify the following equivalent vehicle weights for vehicles of the same carrying capacity:

To get a suitable equivalence from manufacturers' data, it is necessary to identify almost identical vehicles made with different fuel types. The only car commercially available both as an HFCEV and as an ICE vehicle is the Mercedes-Benz GLC (now ceased production), which is a medium-large SUV. The HFCEV version has a larger battery than is usual for an HFCEV (13.5kWh instead of around 1.6kWh (Hyundai UK 2020)), and can be used as a plug in hybrid. It is also available as a BEV (called the EQ-C, with some styling differences)(Mercedes Benz, Mercedes Benz UK 2022). Other vehicles exist as both BEV and ICE, but not HFCEV. For the purposes of consistency in this table, we use the Mercedes-Benz GLC / EQ-C for both ZEV types. We adjust the weight of the GLC Fuel Cell down by 95 kg to reflect the typical extra weight of the larger Li-Ion battery (Jung et al. 2018), to create a more relevant entry for this table.

From this table, we derive a simple relationship between the weight of a BEV and an ICE vehicle of the same carrying capacity based on the trend line function in Microsoft Excel, as follows:

$$\text{BEV Weight (kg)} = (1.0744 \times \text{ICE Weight}) + 430 \qquad (4)$$

and between an HFCEV and an ICE vehicle:

$$\text{HFCEV Weight (kg)} = (1.014 \times \text{ICE Weight}) \qquad (5)$$

Both of these formulas match Table 1 data well, with a very close R^2 value of at least 0.9999.

Given that the lowest data point in the original table still represents a large car, it will be necessary to extrapolate the formula slightly to get a vehicle weight more representative of a smaller one; it may be unrepresentative of motorcycles. However, as it turns out, the RWIF of cars and motorcycles is so low that this immaterial (see below).

For each class or sub-class, we have to estimate a reference vehicle weight. The key factor affecting this for large

Table 1 Gross vehicle weights for equal payload, three fuel types

ICE weight (kg)	BEV weight (kg)	HFCEV weight (kg)
1950	2455	1970
3500	4224	3566
5200	6028	5255
18,000	19,816	18,236
44,000	47,686*	44,760*

*Exceed the maximum allowable vehicle weight of 44,000 kg

vehicles is the proportion of time the vehicles run empty or lightly loaded. This will obviously happen some of the time, with a significant change in weight. Vehicle operators will clearly try to maximise the load in their vehicles, so the actual average weight can be expected to be higher than, for example, a mid-point between empty and full. We expect that buses will run for a higher proportion of the time empty or lightly loaded, as they will be sized for peak demand. However, due to the 4th power relationship described above, the heavier loading will have a proportionately greater impact on road wear.

As a working assumption, we take the reference vehicle weight as the midpoint of the applicable weight range. We examine the implications of inaccuracies in the Sensitivities section below.

The annual distance travelled by each vehicle is taken as the average for the class or sub-class from UK government statistics. There are cases where this data is only available for a group of sub-classes (e.g. all 2- or 3- axle rigid chassis HGVs)—in this case we take the average for all relevant sub-classes. This is also examined in Sensitivities, below.

For some sub-classes of HGV, the regulated maximum weight was exceeded when the modelled ZEV vehicle weight was calculated, as seen in Table 1. In these circumstances, we assume that the maximum weight will not be exceeded, but that instead the affected vehicles will be used for additional trips to reach the same aggregate carrying capacity. We explore the effect of this further in Sensitivities, below.

Road wear potential per vehicle

We examined the wear potential associated with individual vehicles. Figure 1 below shows the relationship between vehicle weight and Road Wear Impact Factor, taken as the number of standard axles per vehicle. This shows the RWP of a vehicle in each sub-class based on its weight and number of axles, for the three fuel types under consideration.

We can see from Fig. 1, the wear potential of a larger vehicle is overwhelmingly greater than that of a smaller one, due to the 4th power law exponentially increasing the effect of greater axle load. We also see a significant increase
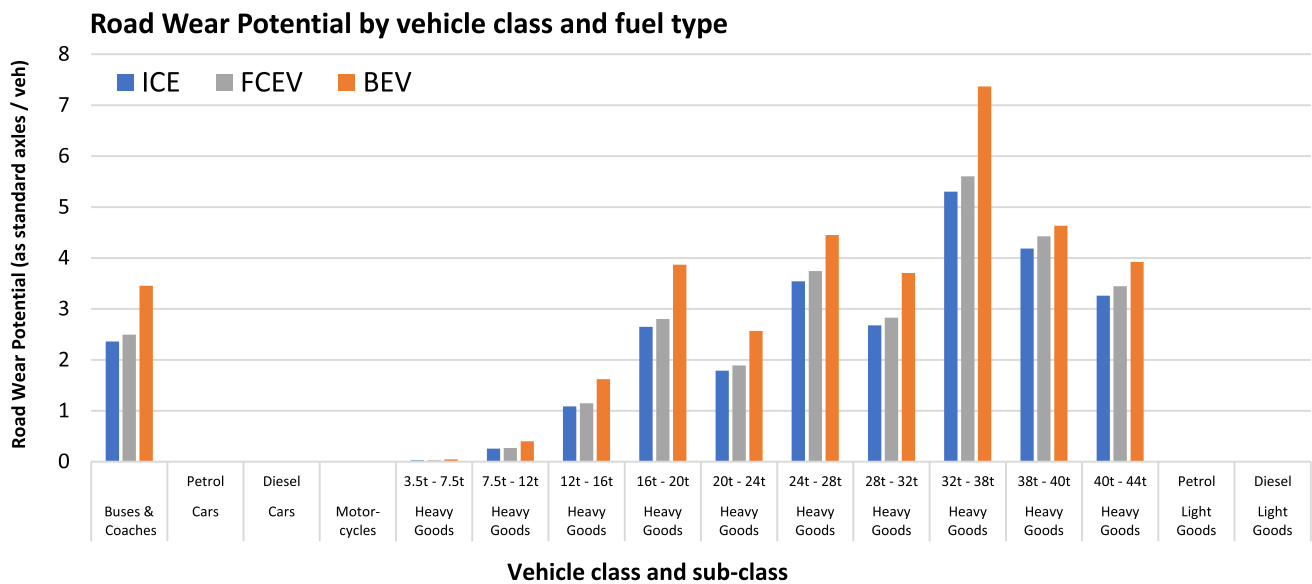
Fig. 1 Road Wear Potential (RWP) per vehicle, sorted by vehicle sub-class, comparing ICE, BEV and HFCEV. RWP is the number of standard axles per axle, multiplied by the number of axles on the vehicle. Vehicles under 7.5t have negligible RWP in this context

in wear potential for a relatively small increase in vehicle weight in large vehicles, for the same reason. The mitigating effect of additional axles is also clear – the reduced number of effective standard axles per actual axle more than offsets the increased number of axles, hence the total RWP decreases for vehicles where the axle count increases. This happens at the 16-20t category, where the axle count increases to 3, at 28-32t where it increases to 4, at 38–40t which requires 5 axles, and 40–44t requiring 6 axles.

Road wear impact factor

Next, we develop this into the assessment of the Road Wear Impact Factor by Class and overall, for the four scenarios under consideration. Multiplying each vehicle's Road Wear Potential by the number of vehicles in the class and the average distance driven each year (UK Government Department of Transport 2019) produces the total Road Wear Impact Factor for each class. This produces Road Wear Impact Factors as shown in Fig. 2 below.

Clearly the overall RWIF is overwhelmingly due to the largest vehicles in use, even though they don't have the highest RWP. This reflects the greater use made of the largest vehicles—there are more 40–44t HGVs than any other category of HGV other than the smallest 3.5–7.5t vehicles, which has about 20% more; also a typical 44t vehicle covers well over twice the annual distance of a 7.5t one. Due to the much smaller RWP, vehicles below 12t have a negligible impact on national RWIF with any fuel type.

The impact of ZEV technology in larger vehicles can be clearly seen, with BEV having a substantially greater impact

than HFCEV. A table with a detailed breakdown of the calculations and results is presented in the Appendix.

Sensitivities

We considered the sensitivity of the results to different ways of estimating the input simplifications:

- Reference weight estimate.
- Varied load distribution, other than equal on each axle;
- Using HGV subcategories based on axle number rather than tax bracket.

Reference weight estimate

We initially assumed a reference weight at the midpoint between the top and bottom of each tax class. However, the reference weight, or typical effective weight, could be significantly different for HGVs, due to the potential for different loading and use patterns. We varied the originally estimated reference weight by scaling factors ranging from 0.5 to 1.07. Beyond 1.07, the ICE reference weight began to exceed the allowable weight in each category, particularly the heaviest, therefore a higher factor than this was clearly unrealistic.

We then used the same method to assess the overall RWIF for a range of scaling factors. We continued to use the principle that if the allowable weight for a particular axle configuration were exceeded, the weight would be held at the maximum allowable, and the distance travelled for vehicles in that sub-class would increase to provide the same gross annual carrying capacity. The result from this assessment is shown in Fig. 3:

Road Wear Impact Factor by vehicle class and sub-class, for four scenarios
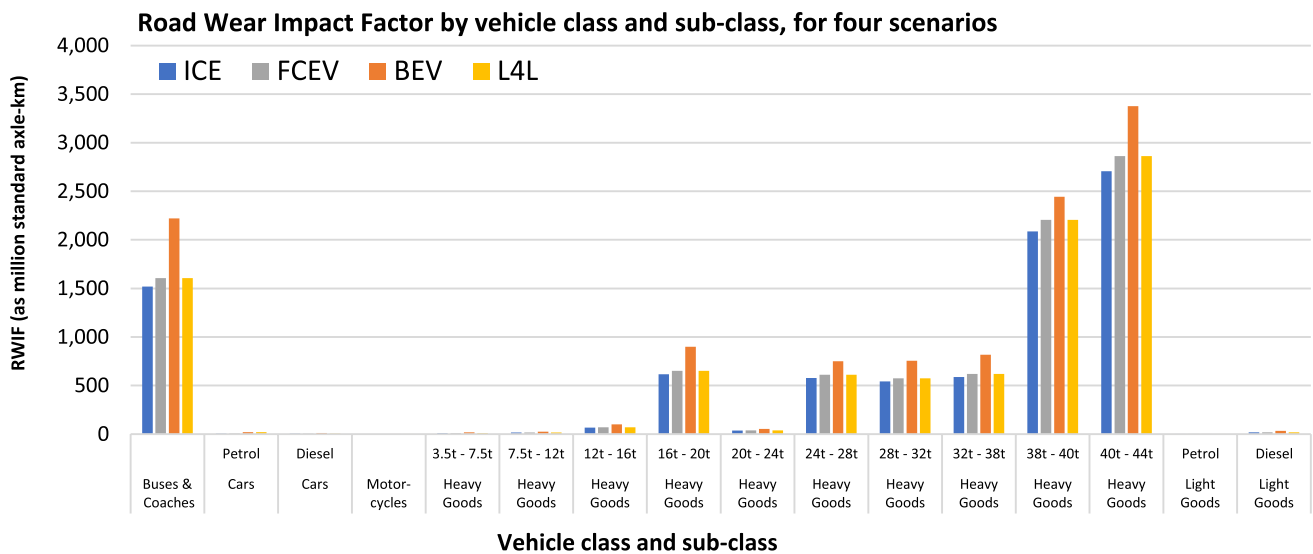
Fig. 2 Class / Sub-class Road Wear Impact Factor, comparing the present and future scenarios. Road Wear Impact Factor is the Road Wear Potential multiplied by the number of vehicles in each class or sub-class and by the average annual distance travelled. Vehicle classes with a typical vehicle weight below 12t have negligible RWIF on a national scale
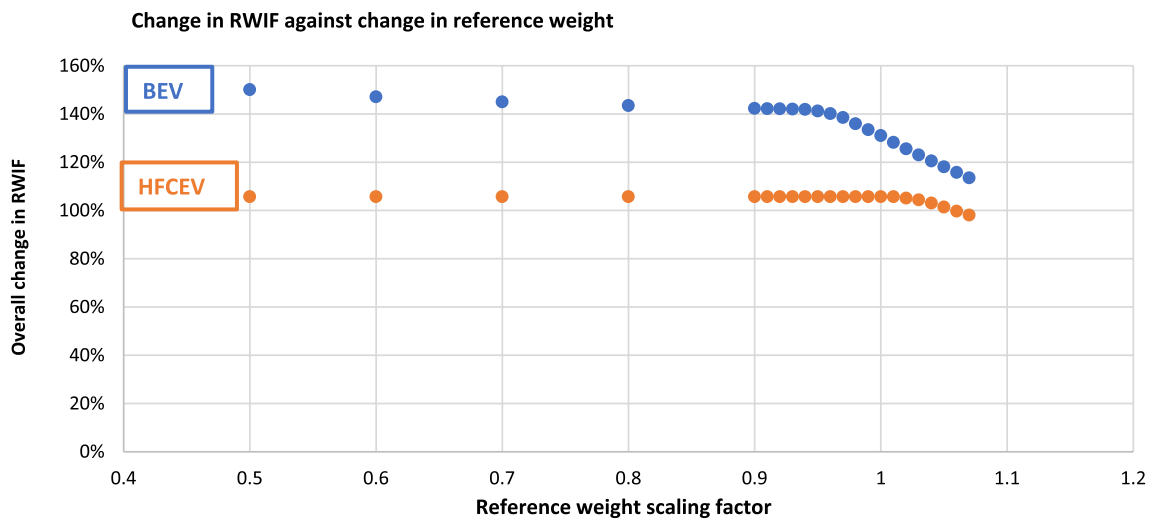
Fig. 3 Change in overall fleet RWIF as a consequence of change in modelled ICE reference weight. Where allowable vehicle weight is exceeded, modelled distance travelled per vehicle is increased

The final output, the change in RWIF with different fuels, is assessed as the ratio between the old and the new rather than a meaningful absolute value, so a change to both produces a similar result for most of the range. The change in RWIF decreases at higher scaling factors because increasing the distance travelled has a smaller impact than increasing vehicle weight due to the 4th power relationship, so this becomes significant at higher load scaling factors. On this basis, we describe the change in overall RWIF due to a fully BEV fleet as 20–40%, and for a fully HFCEV and Like for Like fleet as 6%.

Unequal loading

To assess the effect of unequal load distribution, we considered the effect of one axle carrying a percentage more than all the other axles, which were set as equal. An unevenly distributed load would result in a higher RWP than an evenly distributed one. However, when the same proportion of uneven-ness is applied to current and future cases, the relative increase in RWP and RWIF is unchanged. Ensuring that loads are more evenly distributed in ZEVs than at

Table 2 Comparison of overall RWIF for different types of HGV sub-class categorisation

	BEV (%)	HFCEV (%)	Like for Like (%)
% increase in overall RWIF (tax bracket-based sub-classes)	31.0	5.7	5.9
% increase in overall RWIF (axle number-based sub-classes)	30.6	5.7	5.9

present would be a way of mitigating the increased RWP, but that analysis is beyond the scope of this paper.

Different HGV subclasses

Data is available for HGV numbers and usage based on weight-related tax bracket or on number of axles, which is also related to maximum weight. Using tax brackets gives a finer division of data; using the axle number gives a better match to the effects between sub-classes and permitted vehicle weights. Our main approach has been to use the former. Here, we re-run the analysis on the basis of axle numbers, for comparison.

However, again because the treatment is the same for ICE and ZEV, the effect on the overall result is minimal. Results are presented in Table 2.

We consider this effect to be insignificant.

Conclusion and discussion

We introduced the hypothesis "There will be significant and quantifiable additional costs of road maintenance due to the increased weight of ZEVs over ICE vehicles. This will be markedly greater for BEVs than for HFCEVs."

We find that this partially correct—in the case of the largest vehicles, that is buses and heavy good vehicles, the hypothesis is shown to be true. However, in the case of smaller vehicles such as cars, light goods vehicles and motorcycles, it is unlikely that there will be a significant difference.

A complete conversion of the existing vehicle fleet to BEV would be likely to increase annual road wear in Scotland by around 20–40%, with a modelled base case value of 31.0%. Conversely, the same conversion to HFCEV would increase road wear by around 6% (Fig. 4). The combined, or "Like for Like" future fleet, where existing diesel vehicles are replaced by HFCEV and existing petrol vehicles are replaced by BEV, would also lead to increased road wear of around 6%.

We can see from Fig. 2 above that in each scenario, the Road Wear Impact Factor is dominated by the relatively small number of HGVs, 37,000 vehicles out of a total vehicle fleet of approximately 3 million, which contribute around 87% of the Road Wear Impact Factor. The 14,000 buses and coaches are also significant, contributing around 12%. The Road Wear Impact Factors due to cars, light goods vehicles and motorcycles are insignificant, contributing in total less than 1% of the Road Wear Impact Factor in all scenarios. This will not be news to highways engineers, but needs to be understood in the energy sector. HGVs and Buses & Coaches would be HFCEVs in both the all-HFCEV and the Like for Like scenarios; as those are the vehicles overwhelmingly responsible for road wear, this leads to the Road Wear Impact Factors being effectively identical for both of these scenarios.

This effect could possibly be mitigated in the future by the introduction of lighter-weight battery technology. This is, however, speculative—while such batteries are being researched, they are not yet commercially available (Ye and Li 2021). It might also be possible to re-engineer the basic vehicle to be lighter by using lighter materials or construction methods, although these would be equally applicable to

Fig. 4 Overall Road Wear Impact Factors, grouped by class. Subclass values have been combined to produce the overall class values

Aggregated Road Wear Impact Factor by vehicle class, four scenarios
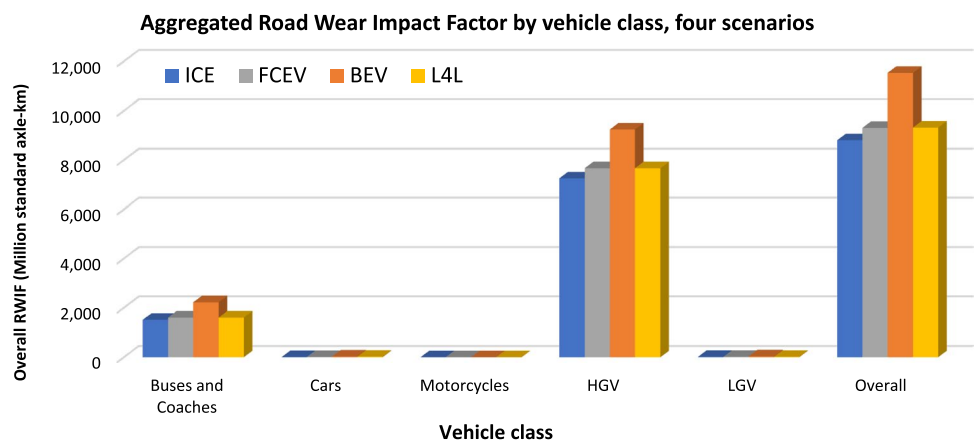
Table 3 Required annual expenditure on road maintenance in Scotland, with expected additional costs due to the conversion to ZEVs. Amounts converted from 2016 to 2021 values, inflation factor 1.108

	Required to maintain condition	Transition to BEV		Transition to HFCEV	
		Additional required expenditure (BEV)	Overall total required expenditure (BEV)	Additional required expenditure (HFCEV and Like for like)	Overall total required expenditure (HFCEV and Like for like)
Local Authorities	£324,000,000	£100,000,000	£424,000,000	£19,000,000	£341,000,000
Scottish Government	£206,000,000	£64,000,000	£270,000,000	£12,000,000	£218,000,000
Total	£530,000,000	£164,000,000	£694,000,000	£31,000,000	£561,000,000

other fuel types. Also, if "e-roads"—which charge vehicles as they drive—became ubiquitous, the need for large and heavy batteries might be reduced (Coban et al. 2022).

A further mitigating effect, requiring no new technology, would be to increase the required number of axles on large vehicles – due to the 4th power effect, the reduction in wear per axle would outweigh the extra wear due to the additional axles. This would, however, increase the vehicle manufacturing costs and fuel consumption (Johnsson 2004).

The all-BEV scenario represents an increase in road wear of about 31% from the present situation; all HFCEV and Like For Like both represent an increase of about 6%—that they are almost identical reflects the dominance of diesel in large vehicles at present.

It would also be important to design vehicles such that the additional weight of batteries is evenly distributed across all axles – this would prevent an imbalanced load creating significant extra wear. This could, however, force a change in operating practice for articulated HGVs, as some of the batteries might have to be installed in the trailer unit.

It should be noted that this study considers the impact on the road network as a whole, and takes account of the relative position of present and future requirements. It is likely that specific areas, especially where the existing road has deteriorated or is of lower initial quality, that the impact will be different and smaller vehicles might become significant. Future study, including more localised analysis, might be necessary to better understand local effects. Future study would also be useful to better understand the benefit of the mitigating factors outlined above.

In Scotland, responsibility for road maintenance is shared between the Scottish Government for trunk (primary) roads, and local authorities for the much greater network of all other roads from large A-class roads through to urban access; these bodies would bear the costs related to this additional road wear. The most recent Audit Scotland report into road maintenance expenditure refers to 2015 (Audit Scotland 2016), showing the required road maintenance expenditure to maintain the existing condition. This is set out in Table 3, converted to 2021 values (Bank of England 2022), along with the additional expenditure required to provide for ZEVs in the future:

This shows the additional road maintenance expenditure in Scotland required to maintain existing condition would need to increase by around £164 M per year if all large vehicles transitioned to battery electricity. Conversely, if all large vehicles transition to hydrogen fuel cells, then an additional £31 M would be required.

It has been reported that current levels of road maintenance are inadequate at present to sustain existing road quality (Williams 2019, Audit Scotland 2016). If this is still the case, the greater demands made of the roads in the future that we outline here can be expected to lead to an even faster deterioration (Addis and Whitmarsh 1981). However, we do not assess that impact in this paper.

These additional costs, and the consequence of the additional emissions, should be included when planning the support of different fuel types on a national fleet. The fuel choice of cars, light goods vehicles and motorcycles will make little difference to road wear. However, with more HFCEV buses & coaches and heavy goods vehicles, the overall road maintenance cost will be substantially lower than with those vehicles as BEVs; it will require only a relatively small increase over the current ICE vehicle situation.

Appendix

See Tables 4 and 5.

Table 4 Calculation of the Road Wear Impact Factor for the current scenario of an Internal Combustion Engine-based national vehicle fleet. Where 'Calculated' is shown at Data Source or Method, Roman numerals in the formula refer to the preceding columns as numbered in the heading row. * Max weight set at 19,000 kg and 27,000 kg, the maximum allowable for ZEV HGVs with 2 axles and 3 axles, respectively

I	II	III	IV	V	VI		Internal Combustion Engine vehicles						
							VII	VIII	IX	X	XI	XII	XIII
Veh. class	Subclass (fuel type or weight related tax bracket)	Number registered in Scotland	Chassis type (ICE)	Weight range			Ref. weight (ICE)	Nr. of axles per vehicle	Ref. weight / axle	Average annual km, per vehicle	Standard 80kN axles per axle (ICE)	RWP	RWIF
Data source or method:	(Scottish Government 2020b)	(Scottish Government 2020b)	(UK Government 2010)	(Scottish Government 2020b)			Calculated (VI—V)/2	(UK Government 2010)	Calculated VII/VIII	(UK Government Department of Transport 2019)	Calculated (VII/80)^4	Calculated XI x VIII	Calculated XII x X x III
		nr		%	from kg	to kg	kg	nr	kN	km	nr	Std. axles / vehicle	million std. axle – km / year
Buses & Coaches		14,154	Two axle rigid	14,000		24,800	17,000	2	83	45,471	1.180	2.361	1,519
Cars	Petrol	1,544,505		1,000		2,600	1,800	2	9	14,571	0.0001	0.0003	7
Cars	Diesel	973,215		1,000		2,600	1,800	2	9	14,571	0.0001	0.0003	4
Motor-cycles		71,666					200	2	1	4,490	neg	neg	<0.1
HGV	3.5t—7.5t	7,986	Two axle rigid	3,500		7,500	5,500	2	27	49,967	0.013	0.026	10
HGV	7.5t—12t	1,275	Two axle rigid	7,500		12,000	9,750	2	48	49,967	0.128	0.255	16
HGV	12t—16t	1,238	Two axle rigid	12,000		16,000	14,000	2	69	49,967	0.543	1.086	67
HGV	16t—20t	4,656	Two axle rigid	16,000		19,000*	17,500	2	86	49,967	1.325	2.651	617
HGV	20t—24t	678	Three axle rigid	19,000		24,000	21,500	3	70	30,420	0.596	1.789	37
HGV	24t—28t	5,367	Three axle rigid	24,000		27,000*	25,500	3	83	30,420	1.180	3.541	578

Table 4 (continued)

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
				Weight range		Internal Combustion Engine vehicles						
Veh. class	Subclass (fuel type or weight related tax bracket)	Number registered in Scotland	Chassis type (ICE)			Ref. weight (ICE)	Nr. of axles per vehicle	Ref. weight / axle	Average annual km, per vehicle	Standard 80kN axles per axle (ICE)	RWP	RWIF
Data source or method:	(Scottish Government 2020b)	(Scottish Government 2020b)	(UK Government 2010)	(Scottish Government 2020b)		Calculated (VI—V)/2	(UK Government 2010)	Calculated VII/VIII	(UK Government Department of Transport 2019)	Calculated (VII/80)^4	Calculated XI x VIII	Calculated XII x X x III
		nr		%		kg	nr	kN	km	nr	Std. axles / vehicle	million std. axle – km / year
				from kg	to kg							
HGV	28t—32t	4,446	Four axle rigid	27,000	32,000	29,500	4	72	45,693	0.669	2.676	544
HGV	32t—38t	637	Four axle articulated	32,000	38,000	35,000	4	86	173,886	1.325	5.302	587
HGV	38t—40t	3,958	Five axle artic	38,000	40,000	39,000	5	77	125,999	0.837	4.185	2,087
HGV	40t—44t	6,596	Six axle artic	40,000	44,000	42,000	6	69	125,999	0.543	3.257	2,707
LGV	Petrol	9,842		2,500	3,500	3000	2	15	26,262	0.001	0.002	1
LGV	Diesel	296,495		2,500	3,500	3000	2	15	26,262	0.001	0.002	18
Total million Standard axle -km per year, as Road Wear Impact Factor												
All HGVs		36,837					7,250					6,520
All Cars		2,524,000					11					11
All LGVs		308,000					18					18

Table 5 Calculation of the Road Wear Impact Factor for the all BEV and all HFCEV scenarios. Where 'Calculated' (or 'calc') is shown at Data Source or Method, the formula is given, with Roman numerals in the formula refer to the preceding columns as numbered in the heading row

I	II		Battery Electric drivetrain weight formula — BEV weight = 1.0744×ICE weight + 430.17						Fuel cell drive train weight formula — HFCEV weight = 1.014×ICE weight						
		XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXIV
Vehicle class	Sub-class	Reference weight	Nr. of axles per vehicle	Ref. weight / axle	Average annual km, per vehicle	Standard 80kN axles per axle	RWP	RWIF	Reference weight	Nr. of axles per vehicle	Ref. weight / axle	Average annual km, per vehicle	Standard 80kN axles per axle	RWP	RWIF
Data source / method:	(Scottish Government 2020b)	From formula above	(UK Government 2010)	Calc: XIII/XIV	(UK Government Department of Transport 2019)	Calc. (XV/80)^4	Calc. XVII x XIV	Calc. XVIII x XVI x III	From formula above	(UK Government 2010)	Calc: XX/XIX	(UK Government Department of Transport 2019)	Calc: (XXII/80)^4	Calc. XXIV x XXI	Calc. XXV x XXIII x III
		kg	nr	kN	km	nr	Std. axles / vehicle	million std. axle – km / year	kg	nr	kN	km	nr	Std. axles / vehicle	million std. axle – km / year
Buses & Coaches		18,695	2	92	45,471	1.726	3.45	2,222	17,238	2	85	45,471	1.248	2.496	1606
Cars	Petrol	2364	2	12	14,571	0.0004	0.0009	20	1825	2	9	14,571	0.0002	0.0003	7
Cars	Diesel	2364	2	12	14,571	0.0004	0.0009	13	1825	2	9	14,571	0.0002	0.0003	4
Motor-cycles		645	2	3	4,490	neg	neg	<0.1	203	2	1	4,490	neg	neg	<0.1
HGV	3.5t—7.5t	6339	2	31	49,967	0.023	0.046	18	5577	2	27	49,967	0.014	0.027	11
HGV	7.5t—12t	10,906	2	53	49,967	0.200	0.400	25	9887	2	48	49,967	0.135	0.270	17
HGV	12t—16t	15,472	2	76	49,967	0.810	1.620	100	14,196	2	70	49,967	0.574	1.148	71
HGV	16t—20t*	19,232	2	94	49,967	1.933	3.867	900	17,745	2	87	49,967	1.401	2.802	652
HGV	20t—24t	23,530	3	77	30,420	0.856	2.567	53	21,801	3	71	30,420	0.631	1.892	39
HGV	24t—28t*	27,000	3	88	31,352	1.483	4.450	749	25,857	3	85	30,420	1.248	3.743	611
HGV	28t—32t	32,000	4	78	45,871	0.926	3.705	756	29,913	4	73	45,693	0.707	2.829	575
HGV	32t—38t	38,000	4	93	174,042	1.842	7.367	817	35,490	4	87	173,886	1.401	5.605	621
HGV	38t—40t	40,000	5	78	133,344	0.926	4.631	2,444	39,546	5	78	125,999	0.885	4.424	2206
HGV	40t—44t	44,000	6	72	130,452	0.654	3.923	3,376	42,588	6	70	125,999	0.574	3.444	2862
LGV	Petrol	3500	2	17	27,413	0.002	0.004	1	3042	2	15	26,262	0.001	0.002	1
LGV	Diesel	3500	2	17	27,413	0.002	0.004	34	3042	2	15	26,262	0.001	0.002	19

Table 5 (continued)

		Battery drivetrain weight formula							Fuel cell drive train weight formula						
		BEV weight = 1.0744×ICE weight + 430.17							HFCEV weight = 1.014×ICE weight						
	Battery Electric and Fuel Cell Electric Vehicles														
I	II	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXIV
Vehicle class	Sub-class	Reference weight	Nr. of axles per vehicle	Ref. weight / axle	Average annual km, per vehicle	Standard 80kN axles per axle	RWP	RWIF	Reference weight	Nr. of axles per vehicle	Ref. weight / axle	Average annual km, per vehicle	Standard 80kN axles per axle	RWP	RWIF
Data source / method:	(Scottish Government 2020b)	From formula above	(UK Government 2010)	Calc: XIII/XIV	(UK Government Department of Transport 2019)	Calc: (XV/80)^4	Calc: XVII x XIV	Calc: XVIII x XVI x III	From formula above	(UK Government 2010)	Calc: XX/XIX	(UK Government Department of Transport 2019)	Calc: (XXII/80)^4	Calc: XXIV x XXI	Calc: XXV x XXIII x III
		kg	nr	kN	km	nr	Std. axles / vehicle	million std. axle – km / year	kg	nr	kN	km	nr	Std. axles / vehicle	million std. axle – km / year
								Total 11,528 million Standard axle -km per year, as Road Wear Impact Factor							Total 9302 million Standard axle -km per year, as Road Wear Impact Factor
All HGVs								9,238							7665
All Cars								32							12
All LGVs								36							19

Data availability The datasets generated during and/or analysed during the current study are available in the GitHub repository, https://github.com/J-M-Low/Battery-Battering.git.

Declarations

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