The Non-Exhaust Particulate Emissions Impact of EURO VI to Battery Electric Bus Fleet Transitions

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First Bus

Clean Air Programme · UKRI Natural Environment Research Council · Met Office

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Situation (pre-project)

There was a real need for better evidence on Electric Bus Non-Exhaust Emissions (NEEs) alongside the EURO VI to EV Bus Fleet transition

There was little public evidence on electric vehicles NEES or regenerative braking, and even toolkit factors for conventional internal combustion engine vehicles were very crude

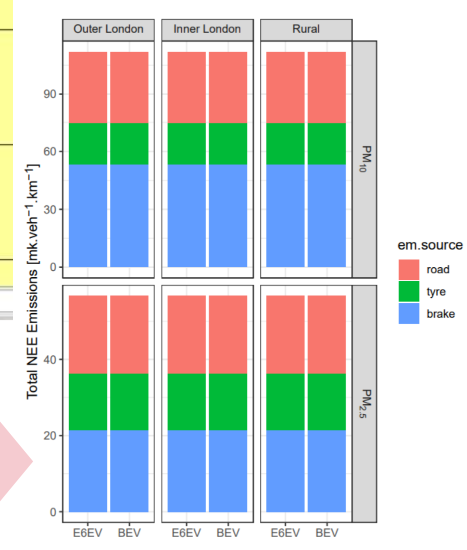
Example: NAEI

					Fleet activity data			Emission factors					Emissions calculation		
16								Exhaust Emission Factors (g/km)		Non-Exhaust PM2.5 emission factors (g/km)			Exhaust Emissions (tonnes)		Non-Exhaust emissions (tonnes)
17	Vehicle segment	Fuel	Euro standard	Technology	Number of buses	Average bus mileage (km)	Total bus mileage (km)	NOx	PM2.5	Tyre wear	Brake wear	Road Abrasion	NOx	PM2.5	PM2.5
18	Urban Buses Midi <=15 t	Diesel	Pre-Euro I		0	40,000	-	10.392	0.788	0.0148	0.0214	0.0205	0.0000	0.0000	0.0000
19	Urban Buses Midi <=15 t	Diesel	Euro I		0	40,000	-	7.758	0.267	0.0148	0.0214	0.0205	0.0000	0.0000	0.0000
20	Urban Buses Midi <=15 t	Diesel	Euro II		0	40,000	-	8.467	0.129	0.0148	0.0214	0.0205	0.0000	0.0000	0.0000
21	Urban Buses Midi <=15 t	Diesel	Euro III		2	40,000	80,000	7.576	0.136	0.0148	0.0214	0.0205	0.6061	0.0109	0.0045
22	Urban Buses Midi <=15 t	Diesel	Euro IV		15	40,000	600,000	4.623	0.036	0.0148	0.0214	0.0205	2.7741	0.0215	0.0341
23	Urban Buses Midi <=15 t	Diesel	Euro V	EGR	15	40,000	600,000	5.879	0.044	0.0148	0.0214	0.0205	3.5272	0.0265	0.0341
24	Urban Buses Midi <=15 t	Diesel	Euro V	SCR	15	40,000	600,000	3.902	0.038	0.0148	0.0214	0.0205	2.3410	0.0226	0.0341
25	Urban Buses Midi <=15 t	Diesel	Euro VI		15	40,000	600,000	0.407	0.004	0.0148	0.0214	0.0205	0.2440	0.0026	0.0341
26	Urban Buses Standard 15 - 18 t	Diesel	Pre-Euro I		0	40,000	-	16.766	0.703	0.0148	0.0214	0.0205	0.0000	0.0000	0.0000
27	Urban Buses Standard 15 - 18 t	Diesel	Euro I		0	40,000	-	10.327	0.375	0.0148	0.0214	0.0205	0.0000	0.0000	0.0000
28	Urban Buses Standard 15 - 18 t	Diesel	Euro II		0	40,000	-	11.220	0.179	0.0148	0.0214	0.0205	0.0000	0.0000	0.0000
29	Urban Buses Standard 15 - 18 t	Diesel	Euro III		0	40,000	-	9.847	0.181	0.0148	0.0214	0.0205	0.0000	0.0000	0.0000
30	Urban Buses Standard 15 - 18 t	Diesel	Euro IV		12	40,000	480,000	6.168	0.050	0.0148	0.0214	0.0205	2.9604	0.0238	0.0273
31	Urban Buses Standard 15 - 18 t	Diesel	Euro V	EGR	12	40,000	480,000	7.277	0.058	0.0148	0.0214	0.0205	3.4931	0.0277	0.0273
32	Urban Buses Standard 15 - 18 t	Diesel	Euro V	SCR	12	40,000	480,000	5.151	0.054	0.0148	0.0214	0.0205			
33	Urban Buses Standard 15 - 18 t	Diesel	Euro VI		12	40,000	480,000	0.476	0.006	0.0148	0.0214	0.0205			
34	Urban Buses Articulated >18 t	Diesel	Pre-Euro I		0	40,000	-	21.251	0.874	0.0148	0.0214	0.0205			
35	Urban Buses Articulated >18 t	Diesel	Euro I		0	40,000	-	13.120	0.467	0.0148	0.0214	0.0205			
36	Urban Buses Articulated >18 t	Diesel	Euro II		0	40,000	-	13.911	0.240	0.0148	0.0214	0.0205			
37	Urban Buses Articulated >18 t	Diesel	Euro III		0	40,000	-	12.237	0.223	0.0148	0.0214	0.0205			
38	Urban Buses Articulated >18 t	Diesel	Euro IV		12	40,000	480,000	8.050	0.062	0.0148	0.0214	0.0205			
39	Urban Buses Articulated >18 t	Diesel	Euro V	EGR	12	40,000	480,000	6.938	0.070	0.0148	0.0214	0.0205			
40	Urban Buses Articulated >18 t	Diesel	Euro V	SCR	12	40,000	480,000	6.407	0.064	0.0148	0.0214	0.0205			
41	Urban Buses Articulated >18 t	Diesel	Euro VI		12	40,000	480,000	0.425	0.006	0.0148	0.0214	0.0205			
42	Coaches Standard <=18 t	Diesel	Pre-Euro I		1	40,000	40,000	14.194	0.584	0.0148	0.0214	0.0205			
43	Coaches Standard <=18 t	Diesel	Euro I		2	40,000	80,000	11.173	0.470	0.0148	0.0214	0.0205			
44	Coaches Standard <=18 t	Diesel	Euro II		3	40,000	120,000	12.866	0.210	0.0148	0.0214	0.0205			
45	Coaches Standard <=18 t	Diesel	Euro III		4	40,000	160,000	11.737	0.270	0.0148	0.0214	0.0205			
46	Coaches Standard <=18 t	Diesel	Euro IV		4	40,000	160,000	7.459	0.062	0.0148	0.0214	0.0205			
47	Coaches Standard <=18 t	Diesel	Euro V	EGR	1	40,000	40,000	11.420	0.078	0.0148	0.0214	0.0205			
48	Coaches Standard <=18 t	Diesel	Euro V	SCR	3	40,000	120,000	7.059	0.076	0.0148	0.0214	0.0205			
49	Coaches Standard <=18 t	Diesel	Euro VI		4	40,000	160,000	0.936	0.009	0.0148	0.0214	0.0205			
50	Coaches Articulated >18 t	Diesel	Pre-Euro I		1	40,000	40,000	17.658	0.685	0.0148	0.0214	0.0205			
51	Coaches Articulated >18 t	Diesel	Euro I		2	40,000	80,000	13.666	0.535	0.0148	0.0214	0.0205			

... Exhaust NOx | Exhaust PM | Non-Exhaust PM | Worked example Guidance | **Worked example**

FACTORS SAME REGARDLESS OF BUS SEGMENT

So, extrapolating to FIRSTBUS's incoming Battery Electric Vehicle (BEV) buses



Scoping (review and meta analysis)

Initial focus (during lockdown) was on available published evidence, and what could be done in the short-term to fill information-gaps

We focused on

NEE (brake, tyre, road)
Resuspended PM
Regenerative Braking
Exhaust Emissions

Beddows & Harrison (2021)
US EPA (2011)
Hamada & Orphan (2022)
EMEP/EEA Guidebook (2019)

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Beddows, D.C. & Harrison, R.M. PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. Atmospheric Environment, 2021, 244, p.117886. https://doi.org/10.1016/j.atmosenv.2020.117886.

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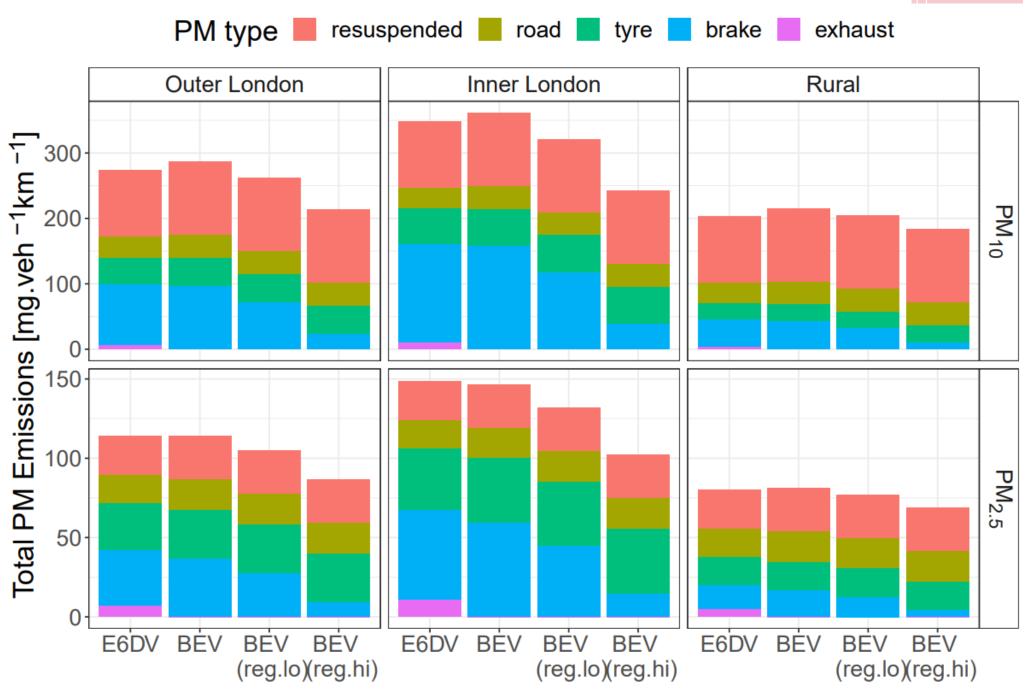
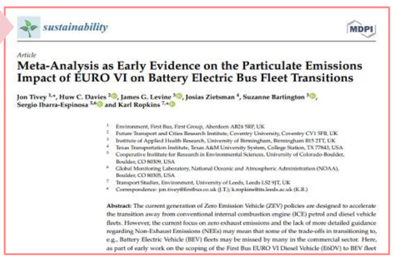
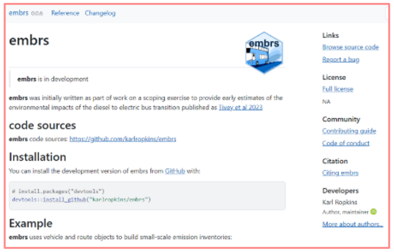


Outputs:



PAPER:
https://doi.org/10.3390/su15021522

Tivey, J., Davies, H.C., Levine, J.G., Zietsman, J., Bartington, S., Ibarra-Espinosa, S. and Ropkins, K., Meta-Analysis as Early Evidence on the Particulate Emissions Impact of EURO VI on Battery Electric Bus Fleet Transitions. *Sustainability*, *15*(2), p.1522. 2023.



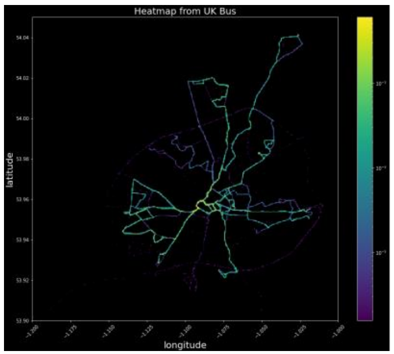
SOFTWARE:
https://github.com/karlropkins/embrs

R software package, freely distributed under public license

ALSO thank you ZEMO for UKBC Profile update

Bus Tests (real-world activity data gathering)

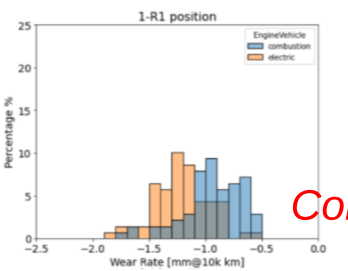
FIRSTBUS, in collaboration with BRIDGESTONE, ALEXANDER DENNIS (ADL) and JURATEK, instrumented 5 Diesel EURO VI and 5 Battery Electrical Buses to collect activity data from routes in and around York.



Axis	Position	EngineVehicle	count	mean	min	max
Drive	2-L1	combustion	60.0	-1.27	-2.01	-0.49
Drive	2-L1	electric	42.0	-1.41	-2.03	-0.82
Drive	2-L2	combustion	51.0	-1.31	-2.01	-0.67
Drive	2-L2	electric	57.0	-1.35	-2.03	-0.58
Drive	2-R1	combustion	76.0	-1.23	-2.03	-0.49
Drive	2-R1	electric	39.0	-1.29	-2.00	-0.64
Drive	2-R2	combustion	71.0	-1.19	-2.03	-0.55
Drive	2-R2	electric	38.0	-1.17	-1.92	-0.68
Steer	1-L1	combustion	50.0	-0.89	-1.43	-0.50
Steer	1-L1	electric	73.0	-1.10	-2.01	-0.59
Steer	1-R1	combustion	69.0	-0.94	-1.72	-0.50
Steer	1-R1	electric	70.0	-1.21	-1.90	-0.59

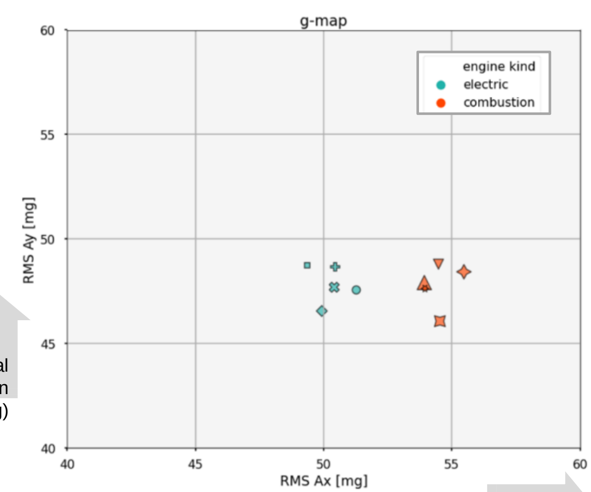
Wear rates consistently higher for BEV compared to EURO VI Diesel…

… and this associates with differences in the acceleration and braking behaviour of different types of buses…



Compare:

… on a wheel-by-wheel basis because individual vehicle analysis shows wear rates



lateral acceleration (turning)

longitudinal acceleration (brake/accelerations)

NB: This example is Tyre Wear versus Acceleration/Braking; similar for Tyre Pressures shows 50% and 35% penalties for over- and under-inflation, respectively.

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The **Clean Air Programme** is jointly delivered by the Natural Environment Research Council (**NERC**) and the **Met Office**, with contributions from the Economic and Social Research Council (**ESRC**), Engineering and Physical Sciences Research Council (**EPSRC**), **Innovate UK**, Medical Research Council (**MRC**), National Physical Laboratory (**NPL**), Science & Technology Facilities Council (**STFC**), Department for Environment, Food and Rural Affairs (**Defra**), Department for Health and Social Care (**DHSC**), Department for Transport (**DfT**), Scottish Government and Welsh Government.

TRANSITION is one of the Networks set up within UK Clean Air Network Programme. led by the **University of Birmingham** in collaboration with nine universities and over 20 cross-sector partners, the network seeks to deliver air quality and health benefits associated with the UK transition to a low-emission transport economy. The academic investigators and policy, public, commercial and not-for-profit sector partners will undertake joint research, to co-define indoor and outdoor air quality challenges and co-deliver innovative, evidence-based solutions.

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FIRSTBUS Test Fleet

Make	Model	Age	Mileage	Fuel/Battery types	Engine Type	Power Output	Emissions standard/status	Other on-board systems	Exhaust Filter	Regen-Braking
Volvo	B9TL	01/09/2008		ULS Diesel	ICE Diesel	260PS / 194KW	Euro VI	SCRT-Adblue	EATS - emission control	N/A
Volvo	B9TL	27/02/2009		ULS Diesel	ICE Diesel	260PS / 194KW	Euro VI	SCRT-Adblue	EATS - emission control	N/A
Volvo	B9TL	27/02/2009		ULS Diesel	ICE Diesel	260PS / 194KW	Euro VI	SCRT-Adblue	EATS - emission control	N/A
Volvo	B9TL	17/03/2009		ULS Diesel	ICE Diesel	260PS / 194KW	Euro VI	SCRT-Adblue	EATS - emission control	N/A
Volvo	B9TL	01/04/2009		ULS Diesel	ICE Diesel	260PS / 194KW	Euro VI	SCRT-Adblue	EATS - emission control	N/A
Optare	Metrodecker M1110EV	01/11/2020		Lithium Ion Battery	Electric Motor	300KW	ZEV	-	N/A	Yes
Optare	Metrodecker M1110EV	01/11/2020		Lithium Ion Battery	Electric Motor	300KW	ZEV	-	N/A	Yes
Optare	Metrodecker M1110EV	01/12/2020		Lithium Ion Battery	Electric Motor	300KW	ZEV	-	N/A	Yes
Optare	Metrodecker M1110EV	01/12/2020		Lithium Ion Battery	Electric Motor	300KW	ZEV	-	N/A	Yes
Optare	Metrodecker M1110EV	01/12/2020		Lithium Ion Battery	Electric Motor	300KW	ZEV	-	N/A	Yes

Existing Fleet Logging:

- Conventional (travel services) telemetry;
- Tyre and brake wear logged by visual inspection as part of routine maintenance

For the 10 Test Vehicles:

- Improved telemetry and additional tyre and brake wear measurement;
- Bridgestone (tyre manufacturer/supplier) proprietary Webfleet ‘Wear Dongle’ telemetry and tyres fitted with the Bridgestone Tyre Pressure Monitoring System;
- Data analysis by Bridgestone’s Digital Garage and Technical Centre (Europe)

embrs software

Objective: to make a simple-to-use vehicle emission modelling syntax for the models and methods used in the First Bus NEEs Study

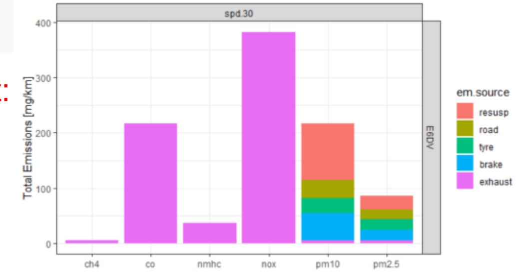
embrs is written in R, freely distributed by public license and uses vehicle and route objects to build emission models in the classic form:

$$\sum emission(object) * activity(object)$$

R code:

```r
library(embrs)
# a EURO VI ICE diesel bus weighing 15925 kg
bus.1 <- bus_ice(name="E6DV", veh.wt=15925, euro.class="vi", eng.fuel="diesel")
# a 30 km/hr route
route.30 <- route_veh_spd(30)
# multiple them
mod <- bus.1 * route.30
# plot that
plot(mod)
```

output:

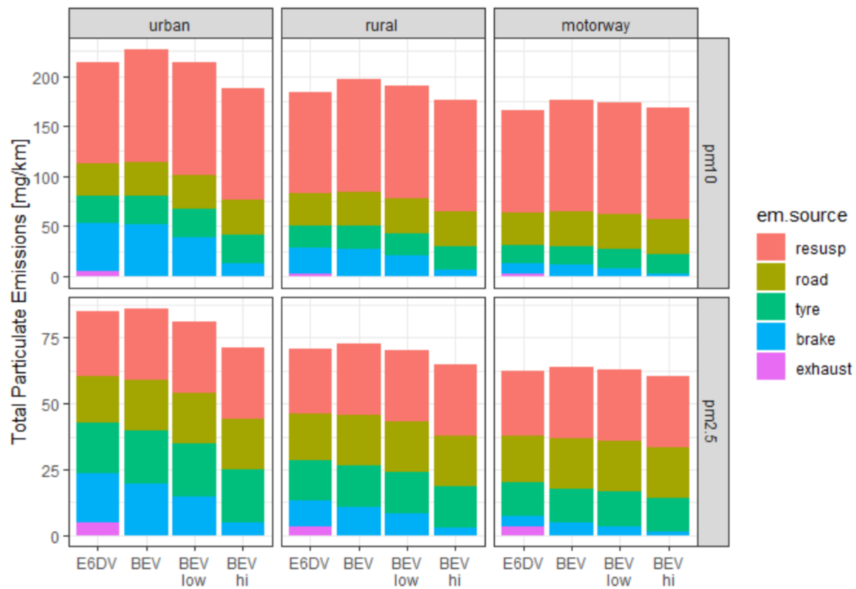


R code:

```r
# EURO VI diesel versus Battery Electric BUS comparison from Tivey et al (2023)

# a EURO VI ICE diesel bus weighing 15925 kg
bus.1 <- bus_ice(name="E6DV", veh.wt=15925, euro.class="VI", eng.fuel="diesel")
# a battery electric bus weighing 17725 kg (and conventional brakes)
bus.2 <- bus_bev(name="BEV", veh.wt=17725)
# like bus.2 but with regenerative brakes operating at 25% efficiency
bus.3 <- bus_bev(name="BEV\nlow", veh.wt=17725, brk.regen = 0.25)
# like bus.3 but 75% efficiency
bus.4 <- bus_bev(name="BEV\nhi", veh.wt=17725, brk.regen = 0.75)
# a small fleet
fleet <- bus.1 + bus.2 + bus.3 + bus.4
# some routes
routes <- route_naei_urban() + route_naei_rural() + route_naei_motorway()
# an inventory
inventory <- fleet * routes
# just plotting PM contributions by vehicle (bus.1 to 4)
plot(inventory, plot.type="by.vehicle", em.type="just.pm")
```

output:



embrs

https://github.com/karlropkins/embrs