Strategies for improving the emission performance of hybrid electric vehicles

S. Bagheri[1], Y. Huang[1], P. D. Walker[2], J. L. Zhou[1], N. C. Surawski[1,*]

[1] Centre for Green Technology, School of Civil and Environmental Engineering, University of Technology Sydney, P. O. Box 123, Broadway, NSW, 2007, Australia

[2] School of Mechanical and Mechatronic Engineering, University of Technology Sydney, P. O. Box 123, Broadway, NSW, 2007, Australia

* Corresponding author:

N. C. Surawski; email address: Nicholas.Surawski@uts.edu.au

Abstract: Low emission vehicle technologies need widespread adoption in the transport sector to overcome its significant decarbonisation challenges. Hybrid Electric Vehicles (HEVs) represent an intermediate technology between pure electric vehicles and internal combustion engines that have proven capability in reducing petroleum consumption. HEV customers often cite improved fuel economy as a major benefit from adopting this technology; however, outstanding questions remain regarding their respective emission levels. Through an extensive literature study, we show that several issues remain with HEV emissions performance which stem from frequent high-power cold starts, engine calibration issues and inefficient operating conditions for catalytic converters. HEVs have more NO_x, HC, CO and particle number emissions compared to conventional vehicles by up to 21.0, 5.8, 9.0 and 23.3 times, respectively. Improved engine control algorithms, after-treatment design and thermal design of three-way catalysts emerge as research priorities for improving the emissions performance of HEVs.

Introduction

The transportation sector is the fourth largest contributor to global Greenhouse Gas (GHG) emissions (International Energy Agency, 2020). It accounts for 25% of worldwide GHG emissions (International Energy Agency, 2020), and is responsible for 28% of global energy consumption (IPCC, 2015), with approximately 40% of transport energy use being associated with urban transportation. Under a business-as-usual (or no mitigation) scenario (IPCC, 2014), annual GHG emissions from the transportation sector is expected to double by 2050 (compared to 5.6 $GtCO_2$-equivalents in 2010) and triple by 2100 due to increases in travel demand and vehicle kilometres travelled. Overall, decarbonisation in the transportation sector is proving to be very difficult with significant technological advances being required to meet the objectives of the Paris Climate Agreement. In terms of non-GHGs, transportation is a significant contributor to the deterioration of ambient air quality that has impacts on human health due to a number of criteria and unregulated emissions (Anenberg et al., 2017; Huang et al., 2020). According to the World Health Organization (World Health Organization, 2016), 4.2 million deaths per year are attributed to ambient air pollution with the relevant health endpoints mainly involving ischaemic heart disease, stroke and lung cancer.

The introduction of Low Emission Vehicles (LEVs) into the fleet is a key strategy in resolving problematic aspects associated with the transportation sector, including impacts on air pollution, climate change, and energy security issues. Key LEV technologies include battery electric vehicles, hydrogen fuel cell vehicles and advanced biofuel and internal combustion engine (ICE) technologies (Oshiro and Masui, 2015). This article focuses on Hybrid Electric Vehicles (HEVs) that represent an intermediate technology between pure electric vehicles and advanced ICEs (Huang et al., 2019). HEVs achieve reductions in petroleum consumption via the electric motor providing power assist (Oshiro and Masui, 2015) which reduces the need for the ICE to operate; especially at partial loads (Al-Alawi et al., 2013) where the electric motor can be considered the principal mover. Given limited petroleum reserves and predictions of future fuel price rises, HEV market adoption is estimated to increase to 8% of all new vehicle sales by 2040 (Al-Alawi et al., 2013). However, if incentives are applied to HEVs, such as vehicle sales tax exemption or subsidising incremental costs, their market adoption may increase up to 24% by 2040 (Al-Alawi et al., 2013). While HEVs provide improved fuel economy, key questions remain regarding whether their emissions performance is improved as well, which we aim to answer in this article through a desktop-based literature survey.

While HEVs are able to achieve significant fuel consumption savings, their emissions profile is not always improved (Huang et al., 2019). This is partially due to the issue of "cold start", a condition in which the ICE has not reached its normal operating temperature. Lack of a proper warm up results in reduced thermal efficiency (Huang et al., 2019) leading to higher fuel consumption and increased tailpipe emissions. In a HEV, since the electric motor provides power assist, the ICE operates less frequently but also intermittently based on the overall power demand of the vehicle. When additional power is demanded, the ICE must restart and since it has been off for some period of time, a cold start event (quite often under high power conditions) occurs. For conventional vehicles (CVs), cold start events occur only once at the beginning of the trip. In contrast, HEVs often encounter several events of the ICE turning on and off within a single trip as part of its powertrain energy management strategy (Varella et al., 2016), which is responsible for fuel consumption reduction by substituting it with the power from the electric motor when necessary. These multiple IC engine restarts are called high-power cold starts. A high-power cold start is a state in which the vehicle is already in motion when the ICE starts or re-starts. These repeated cold starts result in aftertreatment systems, in particular the three-way catalytic converter (TWC) (which is the main exhaust after-treatment system for spark ignition engines), operating below its light-off temperature (i.e. the minimum temperature required to initiate catalysis). Not achieving the TWC light-off temperature leads to increased emissions of carbon monoxide (CO), hydrocarbons (HCs) and nitrogen oxides (NO_x). In addition, engine calibration issues leading to fuel mixture enrichment, poor thermal efficiency and inhomogeneous air/fuel mixtures upon engine restarts are also implicated in increased HEV emissions, which in turn has an impact on particle number concentration.

Methods

An extensive literature search was conducted using the SAE Mobilus, Elsevier, and Web of Science databases. Only studies that included a direct comparison between HEV and CV emissions performance and pointed out to HEVs' emissions penalty due to high power cold starts were considered. The inclusion criteria for this study meant that the HEV/CV pair reported in the relevant article shared many common design features, such as the sharing the same vehicle make and model; with the only point of difference being that the HEV was hybridised and the CV was not. Data from graphs were digitised using the Web Plot Digitizer data extractor available at https://apps.automeris.io/wpd/ except for the data for Huang et. al. (2019) which was available within our research group. The thirteen studies that met the inclusion criteria for our study are summarised in Supplementary Table 1.

Results

The results from our literature review of all relevant studies on HEV emissions compared to CVs are presented in Figure 1 and Supplementary Table 1. An illustrative summary of relevant studies on the high-power cold start issue is depicted in Figure 1 whereby the average increase in emissions from HEVs versus comparable CVs are calculated. The large standard deviation between emission values (e.g. CO and Particle Number (PN) values) is principally due to the different number of engine restart events in the cycles over which the measurements were obtained.

The results from Figure 1 show a highly skewed emission difference between HEVs and CVs. Results from chassis dynamometer and Real Driving Emissions (RDE) tests were analysed separately since the difference in testing conditions significantly affected the results. Based on chassis dynamometer studies, the HEV emissions were found to be increased by up to 2100%, 24%, 5783% and 23300% for NO_x, CO, HCs and PN. Meanwhile, NO_x emissions were reduced by 39% in one study. The median emissions increase for NO_x, CO, HCs and PN are respectively equal to 104%, 22%, 641%, and 1786%. For the RDE testing results, HEV emission increases range up to 592%, 900%, 916%, and 3285% for NO_x, CO, HCs and PN; while reduced emissions of NO_x, CO, and HCs by to 97%, 97% and 100%, can be achieved with HEVs compared to CVs. The median emissions differences from RDE tests are -5%, 13%, -39% and 495% for NO_x, CO, HCs, and PN.

Furthermore, in order to examine the effects of vehicle-related parameters (such as model year, vehicle class and engine type) on the high-power cold start emissions penalty, separate boxplots are shown in Figure S2 (Supplementary Information) based on these parameters.

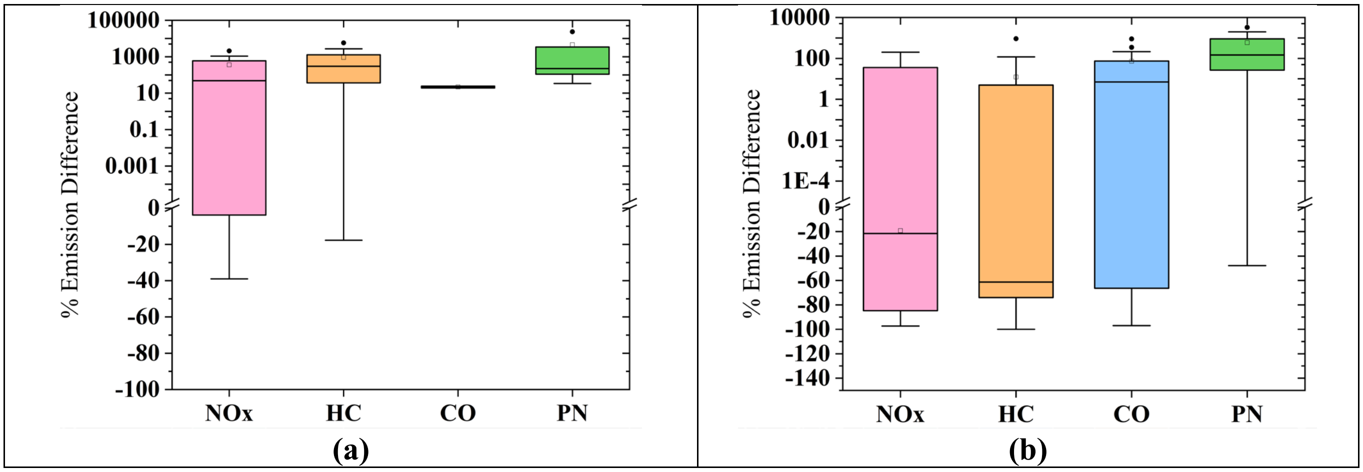


Figure 1. Percentage difference in emissions (i.e. % Difference = 100 × (Emissions$_{HEV}$ - Emissions$_{CV}$)/Emissions$_{CV}$) between HEVs and CVs. NO_x, HC and CO emissions are expressed in units of mass/distance and PN emissions in units of number/distance. (a) Results from chassis dynamometer testing. (b) Results from RDE tests. Positive values indicate HEVs increase emissions compared to CVs, while negative values show that HEVs reduce emissions compared to CVs. Note the logarithmic scale on the ordinate. Solid circles (●) indicate the maximum and minimum emissions difference while open squares (□) represent mean values. The upper whisker is based off the 75th percentile of the data plus one standard deviation and the lower whisker is the 25th percentile of the data minus one standard deviation.

At present, common HEV energy management systems decide when to start the IC engine based on vehicle speed, acceleration and the battery state of charge (SOC; usually to be maintained approximately between 45%-70%), without considering its effect on emissions (Yang et al., 2019). Over rural and urban routes, the power management strategy is usually set so that the vehicles main power source is the electric motor to minimise fuel consumption; therefore, the IC engine is frequently turned on and off which causes more emissions. However, in the case of highway routes, it is neither economic nor possible to employ the same strategy. Thus, the main power source over highway routes with high speed is often the IC engine which leads to less emissions due to less frequent restarting events from the engine. Thus, tailpipe emissions from hybridised and conventional vehicles are expected to be quite similar over highway driving styles; however, over urban routes hybridised vehicles emit more pollutants due to more high-power cold start events.

Discussion

Since the first study performed by Ng et al. (2001), attention has been drawn to high-power cold start performance and emissions events (that are quite common) with HEVs. In a high-power cold start, immediate power from the engine is required to assist the electric drivetrain while neither the engine is at its optimal operating condition (Pham and Jeftic, 2018) nor the TWC is at its light-off temperature (Carlson et al., 2007). Several studies have reported elevated regulated emission levels as well as PN emissions from HEVs compared to CVs (Cao et al., 2018; Costagliola et al., 2015; Duarte et al., 2014; Huang et al., 2019; Ng et al., 2001; Pham and Jeftic, 2018; Russell et al., 2015; Varella et al., 2016; Wei and Porter, 2011; Yang et al., 2019). In addition, there are also studies that claim that HEVs' emission rates are comparable to those of CVs (Christenson et al., 2007; Huang et al., 2019; Kontses et al., 2020). Given the mix of results, this implies that powertrain hybridisation does not always reduce tailpipe emissions.

Battery SOC is considered as a key parameter affecting fuel consumption and tailpipe emissions under low-power driving modes (i.e. urban driving). Fuel consumption, CO and NOx emissions increase by up to 57%, 27% and 56%, respectively, for a battery SOC of below 50%. On the other hand, for battery SOC of more than 70%, fuel consumption, CO, and NOx emission drop by 40%, 34% and 61% below average values (Duarte et al., 2014).

Although full or partial hybridisation of vehicles is carried out in order to improve fuel economy, research shows that energy management strategies in HEVs, which include minimisation of fuel consumption, result in poor emission behaviour due to frequent engine cold starts (or high-power cold starts) and restarting events which increase emissions (Ng et al., 2001; Yang et al., 2019) . These frequent ICE re-starts have the potential to make HEVs less competitive and less likely to achieve widespread market penetration due to making them more dependent on sophisticated emission control systems (Ng et al., 2001). Excess tailpipe emissions resulting from high-power cold starts is attributed to the high initial torque requirement of a moving vehicle when the ICE restarts under unfavourable conditions (i.e. ICEs are designed to provide significant torque at higher rather than lower engine speeds). Based on our literature review, the following recommended alterations to the design and operation of HEVs that are required to mitigate their cold start emission issues are presented in Table 1 and discussed in the next three sub-sections.

Table 1. Summary of HEV emission control options under three categories.

Control Option	Control Strategy	Author	Effect
Engine/After Treatment System Warm-up	Electrically Heated Catalyst	Laurell (2019) et al.	40%-50% HC and NO_x Emission Reduction
	Engine Pre-Warming	Smith (2010) et al.	Significant CO, HC, and NO_x Emissions Drop
Engine Calibration Adjustment	Motored Start	Chambon (2013) et al.	12%-38% HC Emission Reduction
	Stratified Cranking		34%-60% HC Emission Reduction
	Elevated Engine Load		Increased NO_x Emission Faster Catalyst Warm-up
	Elevated Engine Speed		Decreased NO_x Emission Faster Catalyst Warm-up
	Additional Spark Retard		Slight NO_x Emission Increase Faster Catalyst Warm-up
Filter Installation	Use of Sorbent Materials and GPFs	Gao (2012) et al.	44%-68% HC Emission Reduction 26%-48% NO_x Emission Reduction
		Yamamoto (2000) et al.	50%-70% HC Emission Reduction

Thermal management control options

In spite of the high efficiency with which a TWC converts exhaust gas emissions to complete combustion products in a fully warmed-up state (Laurell et al., 2019), multiple cold start events deteriorate their optimal performance due to cooling down below light-off temperatures. During their investigation of two HEVs, Thomas et. al. (2019) found that it takes the TWC 400-500 seconds to light-off following any restart event, which is much longer than other spark ignition vehicles' warm-up durations (Thomas et al., 2019). Therefore, the HEV energy management strategy design and application should facilitate achieving the catalyst light off temperature more rapidly to minimise their cold start emission penalty, since low catalyst conversion efficiencies results in increased CO, HC and NO_x emissions. In achieving these outcomes, it is important to remember that any restart event is followed by fuel enrichment to achieve an improvement in combustion properties which leads to elevated levels of CO, HC and PN emissions (Thomas et al., 2019).

To minimise the warm-up period of exhaust after treatment systems, Laurell et al. (2019) employed an Electrical Heating Catalyst (EHC) using either pre-heating or insulation methods. The EHC design mainly composed of a heating disc held by a supporting matrix through several supporting points. The whole array was installed at the catalyst inlet with the disc (acting as a heating coil) heated using electricity provided by the alternator. Thermal energy was then transferred to the supporting matrix which enabled the catalyst to meet high thermal requirements even under adverse conditions. According to their results, use of an EHC results in a 40%-50% reduction in HC and NO_x emissions based on the heating strategy (Laurell et al., 2019).

In addition, Smith et al. (2010) evaluated the effect of a specific supervisory control method on improving the emission characteristics of a plug-in HEV, which included an engine and aftertreatment system pre-warming and warming strategy. The strategy was started by a time-based pre-warming procedure which was activated with an engine start. The pre-warming procedure was designed to trigger at a specifically low battery SOC that was still higher than the lower SOC limit e.g. 40%. In addition, while the vehicle was still running in charge depleting mode, where the motor and battery are utilised as the primary driving source the ICE was operated under low load conditions for a defined period (e.g. 120 seconds) to start warming up. The engine pre-warming phase (similar to a period of idle operation) was followed by a main energy-based warming, whereby the amount of energy required for a satisfactory engine warm-up is the basis for calculating a scaling factor which limits the available power for the ICE until it is fully warmed up. After such warming up procedures, the vehicle is expected to operate as a normal HEV, whereby the ICE is relied upon as the primary power source (i.e. charge sustaining mode) and the excess power is stored in the battery. The charge depleting mode is activated during low power demand, idling and deceleration events where the ICE is turned off and the battery may be charged through regenerative braking. Smith et al. (Smith et al., 2010) further showed that regardless of the power source share in the vehicle power requirements, the proposed emission mitigation control method results in up to 23%, 95%, and 96% reduction in CO, HC and NO_x from HEVs.

As mentioned previously, hybridised vehicles' baseline energy management strategies mainly aim to minimise fuel consumption which result in multiple high-power cold starts (Smith et al., 2010) and elevated emission levels. Thermal management control options are capable of reducing emissions from HEVs while negatively affecting fuel economy due to more fuel consumption during the engine warming period as well as suppressing engine restart events before reaching light-off temperature (Laurell et al., 2019).

Engine calibration control options

A number of procedures have been attempted to speed up the catalyst warm-up time including increasing the engine idling speed and load, providing additional retardation of the spark timing, as well as stratified cranking that involves high pressure late compression stroke injection during engine restarts. According to the results obtained by Chambon et al. (2013), this injection mode causes a reduction in the HC emissions for both motored and conventional starts by 60% and 34% respectively (Chambon et al., 2013). Alternatively, results regarding the effect of engine load and speed indicate HC emissions are independent from either of these two parameters, but NO_x emissions are affected by both elevated engine load (i.e. NO_x increases with load) and speed (i.e. NO_x decreases with rpm). Therefore, an optimised combination of elevated engine load and speed leads to faster catalyst warm-up times while leaving NO_x and HC emissions unchanged. For example, operating at 1700 rpm and 20% elevated load results in a 22% faster catalyst warm-up time as well as 27% reductions in HC and unchanged NO_x emissions. Furthermore, this arrangement of elevated engine load and speed results in a 9% improvement in fuel economy due to increased engine efficiency at certain loads and speeds (Chambon et al., 2013).

With additional spark timing retardation, a faster catalyst warm-up time was achieved with a small increase in NO_x emissions. However, HC emissions showed higher values at greater engine idle speeds when the spark timing retardation was increased beyond six degrees of crank angle. Generally, the idle speed and load should be optimised so that the emission reduction due to accelerated catalyst warm-up times outstrips the emission increase due to alterations in an engine's operating characteristics. In addition, Chambon et al. (2013) focused on adjusting the engine calibration for a hybrid powertrain application emphasising the optimisation of cold start control strategies. They coupled the ICE to an electric motor that was capable of driving to a specific idling speed without firing it. This procedure, known as a motored start, resulted in minimising (or even completely removing) the transient phase when the engine is cold, which leads to HC emission reduction between 12-38% in comparison with those from conventional starts.

After-treatment design control options

Gao et. al. (2012) performed a computational study that evaluated the use of adsorbing materials as temporary filters for cold-start tailpipe emissions until the TWC reaches its light-off temperature. These filters must be capable of trapping and storing emissions as well as converting emissions before being released from the filter, while also not influencing fuel economy or engine performance. The filters should also tolerate high temperatures and flow velocities in the exhaust (Yamamoto et al., 2000). The major advantage of using sorbent materials is that they do not interfere with the engine performance and do not affect fuel consumption or battery power (Gao et al., 2012) since they inherently operate in a passive mode. According to their results, sorbent filters can reduce 68% and 44% of the tailpipe HC emissions for the tested plug-in HEV and HEV respectively. Alternatively, NO_x emissions were found to decrese by 26–32% and 28–48% for the plug-in HEV and HEV, respectively, as a result of employing sorbent filters. Insights from an experimental study undertaken by Yamamoto et al. observed a reduction of 60% in HC emissions in the presence of an in-line HC adsorbing system (Yamamoto et al., 2000).

Conclusion

This study has identified a range of issues with HEV emission performance based on a desktop-based literature review. The inclusion criteria for our study identified 12 articles that performed a direct cross-comparison between conventional ICE and HEV emissions performance while also investigating the issue of a high-power cold start. Our analysis shows that cooling of the TWC during engine-off periods, as well as fuel mixture enrichment, reduction in thermal efficiency and inhomogeneous air/fuel mixtures upon engine restart are responsible for adverse emissions behavior in HEVs. Maximum emission increases for HEVs compared to conventional ICEs are quite significant, spanning a range of a 5.8-fold increase for HCs and 23.3-fold increase of PN. We also outlined a range of strategies for improving HEV emissions behavior which fall under the categories of thermal management, engine calibration and after-treatment redesign control options. Actioning of these control options by automotive manufacturers and researchers alike will assist with the future uptake of low emitting and fuel efficient HEVs that play a role in decarbonisation of the transport sector and improved air quality outcomes.

Author contributions

Sahar Bagheri: Methodology, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, **Yuhan Huang:** Writing – Review & Editing, Funding acquisition, **Paul Walker:** Writing – Review & Editing, **John Zhou:** Writing – Review & Editing, Supervision, **Nic Surawski:** Conceptualization, Writing – Review & Editing, Supervision, Funding acquisition, Project Administration.

Data availability

Data is available from the corresponding author (N. C. S. Nicholas.Surawski@uts.edu.au) upon request.

Acknowledgements

N. C. S. and Y. H. acknowledge funding support through the Blue Sky Research grants scheme from the Faculty of Engineering and Information Technology at the University of Technology Sydney.

References

Al-Alawi, B. M. & Bradley, T. H. Review of hybrid, plug-in hybrid, and electric vehicle market modeling studies. *Renew. Sust. Energ. Rev*. **21**, 190-203 (2013).

Anenberg, S. C. et al. Impacts and mitigation of excess diesel-related NO x emissions in 11 major vehicle markets. *Nature* **545**, 467-471 (2017).

Cao, T. et al. Characterization of the emissions impacts of hybrid excavators with a portable emissions measurement system (PEMS)-based methodology. *Sci. Total Enivron*. **635**, 112-119 (2018).

Carlson, R. W., Duoba, M. J., Bohn, T. P. & Vyas, A. D. Testing and analysis of three plug-in hybrid electric vehicles. *SAE Technical Paper* 2007-01-0283 (2007).

Chambon, P., Deter, D., Irick, D. & Smith, D. PHEV cold start emissions management. *SAE International Journal of Alternative Powertrains* **2**, 252-260 (2013).

Christenson, M., Loiselle, A., Karman, D. & Graham, L. A. The effect of driving conditions and ambient temperature on light duty gasoline-electric hybrid vehicles (2): Fuel consumption and gaseous pollutant emission rates. *SAE Technical Paper* 2007-01-2137 (2007).

Costagliola, M. A., Prati, M. V., Mariani, A., Unich, A. & Morrone, B. Gaseous and particulate exhaust emissions of hybrid and conventional cars over legislative and real driving cycles. *Energy and Power Engineering* **7**, 181-192 (2015).

Duarte, G. O., Varella, R. A., Gonçalves, G. A. & Farias, T. L. Effect of battery state of charge on fuel use and pollutant emissions of a full hybrid electric light duty vehicle. *J. Power Sources* **246**, 377-386 (2014).

Gao, Z. et al. Cold-start emissions control in hybrid vehicles equipped with a passive adsorber for hydrocarbons and nitrogen oxides. *P. I. Mech. Eng. D-J. Aut.* **226**, 1396-1407 (2012).

Hannan, M. A., Azidin, F. A. & Mohamed, A. Hybrid electric vehicles and their challenges: A review. *Renew. Sust. Energ. Rev*. **29**, 135-150 (2014).

Huang, Y. et al. Fuel consumption and emissions performance under real driving: Comparison between hybrid and conventional vehicles. *Sci. Total Enivron*. **659**, 275-282 (2019).

Huang, Y. et al. Re-evaluating effectiveness of vehicle emission control programmes targeting high-emitters. *Nat. Sustain*. **3**, 1-4 (2020).

IPCC. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (2014).

IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, pp 1-151 (2014).

International Energy Agency. CO_2 Emissions from Fuel Combustion: Overview. https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview (2020).

Kontses, A., Triantafyllopoulos, G., Ntziachristos, L. & Samaras, Z. Particle number (PN) emissions from gasoline, diesel, LPG, CNG and hybrid-electric light-duty vehicles under real-world driving conditions. *Atmos. Environ.* **222**, Article Number 117126 (2020).

Laurell, M., Pace, L., Ekström, F. & Konieczny, K. Strive for zero emissions impact from hybrids. *SAE Technical Paper* 2019-24-0146 (2019).

Ng, H. K., Anderson, J. A., Duoba, M. J. & Larsen, R. P. Engine start characteristics of two hybrid electric vehicles (HEVs)—Honda insight and Toyota Prius. *SAE Technical Paper* 2001-01-2492 (2001).

Oshiro, K. & Masui, T. Diffusion of low emission vehicles and their impact on CO_2 emission reduction in Japan. *Energ. Policy* **81**, 215-225 (2015).

Pham, A. & Jeftic, M. Characterization of gaseous emissions from blended plug-in hybrid electric vehicles during high-power cold-starts. *SAE Technical Paper* 2018-01-0428 (2018).

Russell, R. L. et al. Emissions, fuel economy, and performance of a class 8 conventional and hybrid truck. *SAE Technical Paper* 2015-01-1083 (2015).

Smith, D. E., Lohse-Busch, H. & Irick, D. K. A preliminary investigation into the mitigation of plug-in hybrid electric vehicle tailpipe emissions through supervisory control methods. *SAE International Journal of Engines* **3**, 996-1011 (2010).

Thomas, D., Li, H., Ropkins, K., Wang, X. & Ge, Y. Investigating the engine behavior of a hybrid vehicle and its impact on regulated emissions during on-road testing. *SAE Technical Paper* 2019-01-2199 (2019).

Varella, R. A., Gonçalves, G., Duarte, G. & Farias, T. Cold-running NOx emissions comparison between conventional and hybrid powertrain configurations using real world driving data. *SAE Technical Paper* 2016-01-1010 (2016).

Wei, Q. & Porter, S. Evaluation of solid particle emissions from hybrid and conventional gasoline vehicles. *SAE International Journal of Engines* **4**, 610-618 (2011).

Whitehead, J., Washington, P. S. & Franklin, P. J. The impact of different incentive policies on hybrid electric vehicle demand and price: An international comparison. *World Electric Vehicle Journal* **10**, 1-19 (2019).

World Health Organization. Ambient air pollution: A global assessment of exposure and burden of disease. Geneva, Switzerland, pp 1-131 (2016).

Yamamoto, S., Matsushita, K., Etoh, S. & Takaya, M. In-line hydrocarbon (HC) adsorber system for reducing cold-start emissions. *SAE Technical Paper* 2000-01-0892 (2000).

Yang, Z. et al. Real driving particle number (PN) emissions from China-6 compliant PFI and GDI hybrid electrical vehicles. *Atmos. Environ.* **199**, 70-79 (2019).

Supplementary Information

HEV powertrain architectures

HEVs obtain partial or full hybridisation of their powertrain by coupling an electric motor and battery to the ICE. Based on their mechanical configuration, HEV powertrains can be classified as either series, parallel, or series/parallel topologies (Figure S 1). In the case of a series HEV, vehicle driving power is provided by the electric motor only and power from the ICE is used to charge the battery. By contrast, in a parallel HEV, both the electric motor and ICE are responsible for delivering vehicle driving power. In a series/parallel HEV, the configuration may function as either a series or parallel HEV allowing the electric motor and ICE to perform simultaneously or independently using a planetary gear set (Hannan et al., 2014; Pham and Jeftic, 2018; Whitehead et al., 2019).

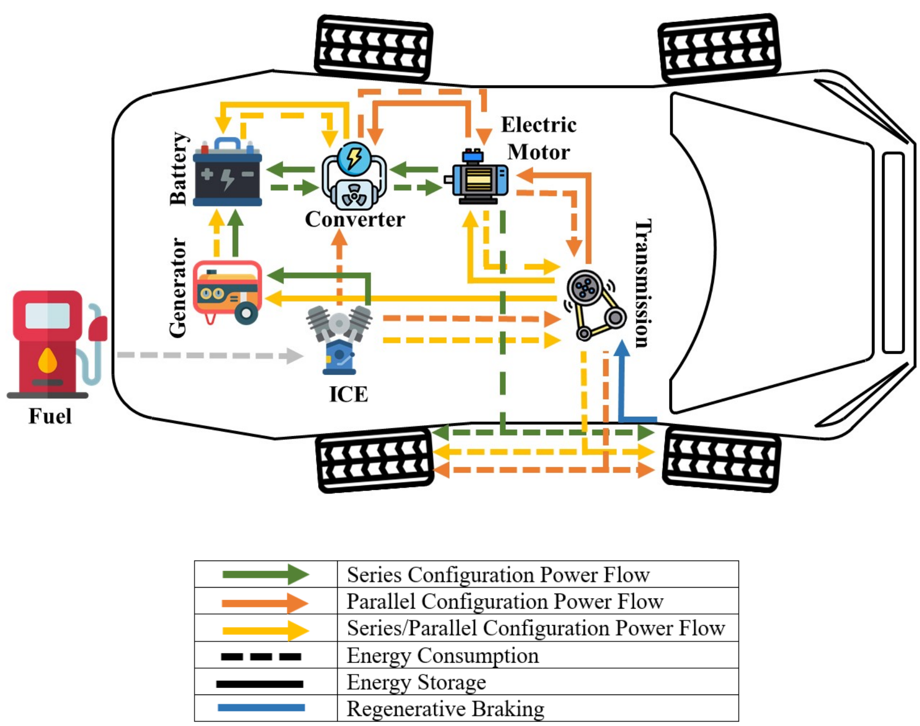
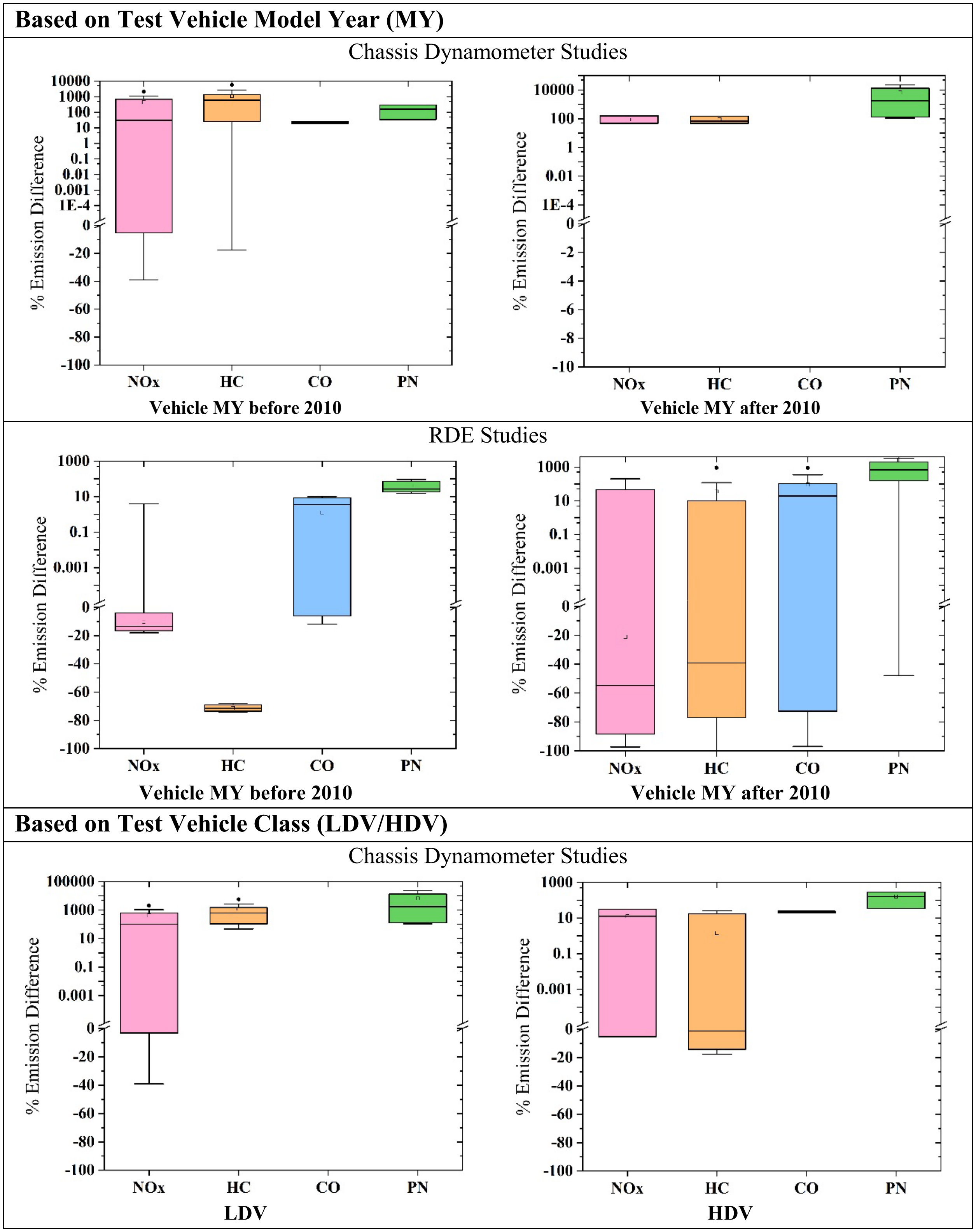


Figure S1. Hybrid Electric Vehicle Configurations. Solid Lines and Dashed Lines Show Energy Storage and Energy Consumption, Respectively.

Specified Boxplots based on Vehicle Properties



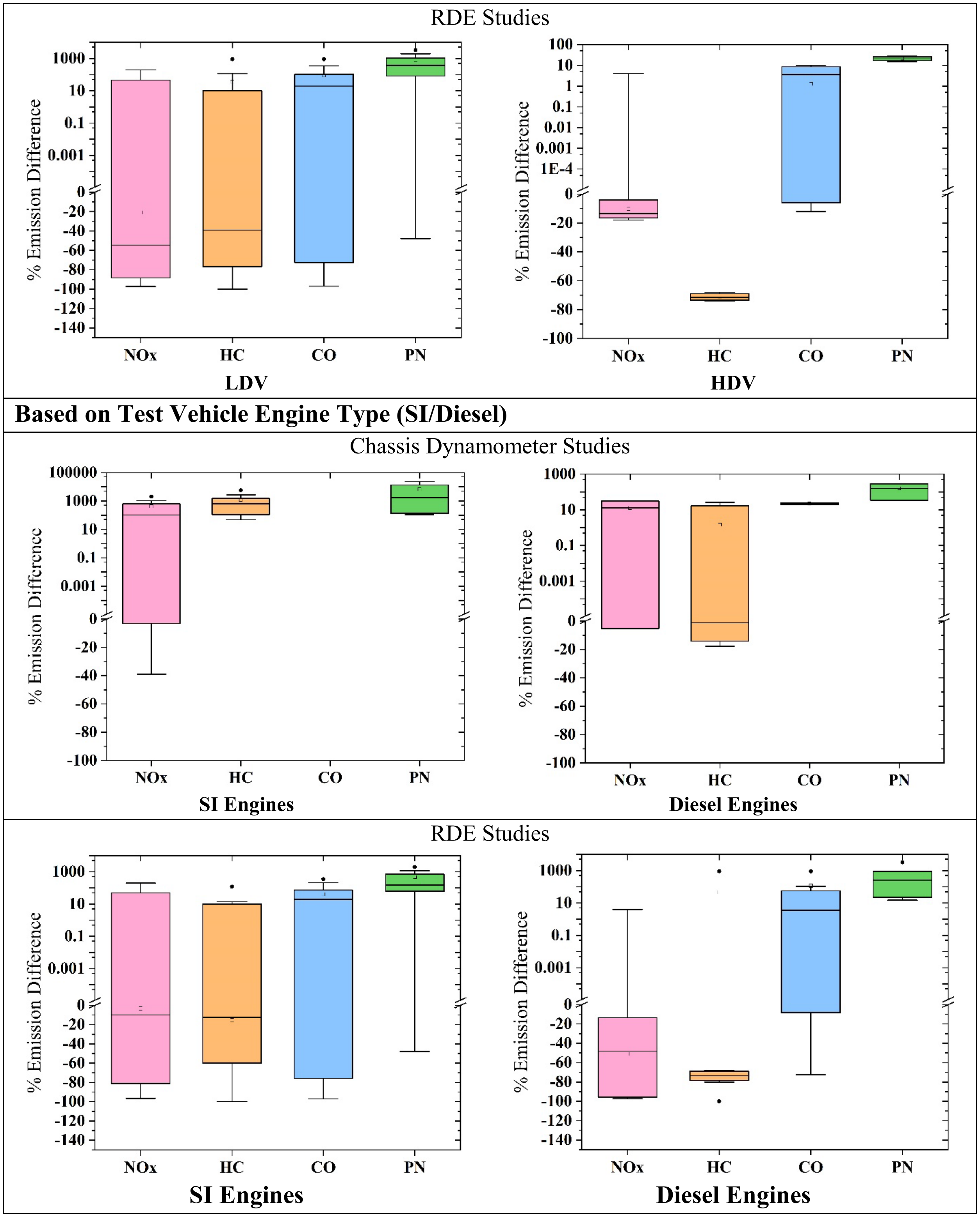


Figure S2. Percentage difference in emissions between HEVs and CVs based on vehicle properties. In this figure, HDV stands for High Duty Vehicle, LDV Stands for Light Duty Vehicle and SI stands for Spark Ignition.

Database of results showing increased HEV emissions relative to CVs

Table S1. Summary of results that compared HEVs with CVs and found an emissions increase. UDDS and HWFET refer to, respectively, Urban Dynamometer Driving Schedule and Highway Fuel Economy Transient Cycle**.** Note that in the 13th study from Ng et al. (2001), we only used qualitative insights from this paper since data could not be extracted from the transient cycles presented in this paper.

Author	Hybridised Powertrain	Vehicles Class	Test Vehicles' Engine Type	Tailpipe Emissions	Average HEVs' % Increase	Measurement Method	Test Cycle	Driving Mode	Engine Aftertreatment Technology	Hybrid Configuration	Test Vehicle Model Year	Initial Battery SOC	HEVs Excess Emissions Reason
Carlson et al. (2007)	PHEV	Light Duty	SI	NO_x	80%-95%	Chassis Dynamometer	UDDS	Urban	TWC	-	2004	Full	Reduced TWC Conversion Efficiency
				HC	87%-98%		HWFET						
Pham et al. (2018)	PHEV	Light Duty	SI	NO_x	80%	Chassis Dynamometer	Designed Cycle	Urban	TWC	-	2013	90%-100%	Reduced TWC Conversion Efficiency
				NMOG	75%								
Varella et al. (2016)	HEV - PHEV	Light Duty	SI	NO_x	60%-80%	PEMS	Real World Driving Cycle	Urban Extra-Urban Highway	TWC	Series Parallel Series/Parallel	-	-	Reduced TWC Conversion Efficiency
			Diesel						OC DPF				
Huang et al. (2019)	HEV	Light Duty	SI	CO	38%-79%	PEMS	Real World Driving Cycle	Urban Rural Highway	TWC	-	2015 2016	-	The Aim is to Run the IC Engine as Efficiently as Possible
													Reduced TWC Conversion Efficiency
													More Power Demand from the Engine to Suffice both Vehicle Power Demand and Battery Stored Energy
	HEV		SI	NO_x	73%	PEMS		Urban	TWC	Series/Parallel	2011		

Duarte et al. (2014)		Light Duty		CO	63%		Real World Driving Cycle	Extra-Urban Highway					Reduced TWC Conversion Efficiency
Costagliola et al. (2015)	HEV	Light Duty	SI Diesel	CO HC PN	51% 90% 34%-94%	PEMS	UDC Artemis Urban	Urban	TWC DPF	Parallel	-	-	Reduced TWC Conversion Efficiency Fuel Enrichment During Engine Restarts
Russel et al. (2015)	HEV	Heavy Duty	Diesel	CO $PM_{2.5}$	96%-97% 25%-74%	Chassis Dynamometer	Designed Cycle	Urban	SCR DPF	Parallel	2010	-	-
Cao et al. (2018)	HEV	Heavy Duty	Diesel	CO $PM_{2.5}$	7%-10% 26%-27%	PEMS	Designed Cycle	-	DPF	-	2006-2011	-	Reduced TWC Conversion Efficiency
Wei et al. (2011)	HEV	Light Duty	SI	PN	97%-99%	Chassis Dynamometer	FTP HWFET	Urban Highway	TWC	-	2011	-	Insufficient Air Supply Low Temperature in the Combustion Chamber Inhomogeneous Air-Fuel Mixture
Robinson et al. (2011)	HEV	Light Duty	SI	PN	27%-81%	PEMS	Real World Driving Cycle	Urban	TWC	-	2010	60%-70%	Fuel Enrichment During Engine Restarts
Yang et al. (2019)	HEV	Light Duty	GDI PFI	PN	67%-92%	PEMS	Real World Driving Cycle	Urban Rural Highway	TWC	-	2017 2018	50%-60%	-
Conger et al. (2015)	HEV	Light Duty	SI	PN	71%	PEMS	Real World Driving Cycle	Urban Rural Highway	TWC	-	2010	-	-

Oxidation Catalytic Converter (OC)
Diesel Particulate Filter (DPF)
Selective Catalytic Reduction (SCR)
Among all Chassis Dynamometer studies, three studies considered measurement of NOx, three studies considered HC, one study considered CO and one study considered PN. Among all the RDE studies, five studies measured NOx, three studies measured HC, four studies measured CO, and five studies measured PN.