EMISSIONS AND NOISE MITIGATION THROUGH USE OF ELECTRIC MOTORCYCLES

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ABSTRACT

Gasoline-powered motorcycles contribute disproportionately to traffic noise and emissions, so motorcycle electrification merits investigation. Recent advances in battery efficiency allow electric motorcycles (EMCs) to join electric cars and bicycles as a viable consumer option. This work quantifies noise and emissions using both simulations and experimental data, examines the factors that make EMCs big offenders, and uses popular EMC specifications to estimate the costs and benefits of electrification. Motorcycles produce more CO, CH_4, NOx, HC, and particulate matter than passenger vehicles per vehicle mile traveled. Due to limited regulation of motorcycles and weak enforcement, motorcycle sound exceeds that of most other vehicles, with roughly double the perceived noise of automobiles at speeds over 30 mph and surpassing even medium trucks and buses at speeds over 50 mph, at which point motorcycles exceed the 80 dBA U.S. standard limit. Electrification can resolve such issues, though range limitations and high prices are presently a barrier to widespread adoption. In order to realize these environmental benefits, it is important that electrification occur with a corresponding shift away from coal as an energy source. Stricter emissions' regulations and stronger enforcement of existing prohibitions on certain forms of customization could also reduce the outlier status of gasoline-powered motorcycles.

Key words: Motorcycles, Electric Motorcycles, Motorcycle Emissions, Motorcycle Sound Emissions, Electrification

INTRODUCTION

Motorcycles often serve both recreational and transportation purposes. In crowded cities, where parking is scarce, their small size is an asset. In South and Southeast Asia, motorcycles regularly dominate city streets (Poushter 2015). Their small size does not reduce their noise or emissions much, however. The 2-stroke and 4-stroke emissions of motorcycles harm human health while their noise is both a nuisance and a health issue.

The burgeoning market of electric motorcycles, fueled by the changing landscape in technology, provides an opportunity to mitigate such impacts. Regardless of traditional or electric motorcycle usage, safety remains a concern. The number of years a motorcyclist has been riding is inversely correlated with crash risk, as is helmet use (Fagnant and Kockelman 2015). Still, the 2015 U.S. fatality rate of 54.58 deaths per 100,000 registered motorcycles was 6 times the rate for passenger cars. Assuming an average automobile occupancy of two people, motorcyclists die at 58 times the rate of passenger-car occupants per person-mile travelled (NHTSA 2015). As of 2015, there are 8,600,936 registered motorcycles in the United States, having traveled a combined total of 19,606 million miles (NHTSA 2015).

The scope of this paper is limited to motorcycle noise and emissions. The potential for electrification to reduce negative impacts has been explored by Simpson (2006), Ehsani et al. (2018), Tuttle (2012), and others, but the bulk of research has been on passenger cars and trucks. Considerations of electric two-wheeled vehicles are dominated by e-bikes (Cherry et al. 2018, Weinert et al. 2007, Dill 2012). In contrast, this paper analyzes experimental and simulation data to identify motorcycles' sound and emissions impacts and the potential for mitigation through electrification.

MOTORCYCLE NOISE

A demand for high-speed transportation typically comes with increased noise pollution (Murphy et. al. 2014). However, motorcycles are the exception to this rule. As seen in Figure 1, their sound surpasses that of most other vehicles at speeds above 50 mph (FHWA 1998).

Motorcycle noise and emissions are increased by aggressive driving and regular revving, even when idling. New and recently-repaired engines are thought to require a "breaking-in" period, and during this period the rider may rev the engine to vary engine speed (CM 2012). There is also a widespread belief among riders that "loud pipes save lives" by drawing attention, though this belief is contradicted by studies that have found louder motorcycles are more likely to be involved in collisions (Torrey et al 2006). Cultural factors and aesthetic preferences may also contribute to a rider's preference for louder motorcycles (Torrey et al 2006).

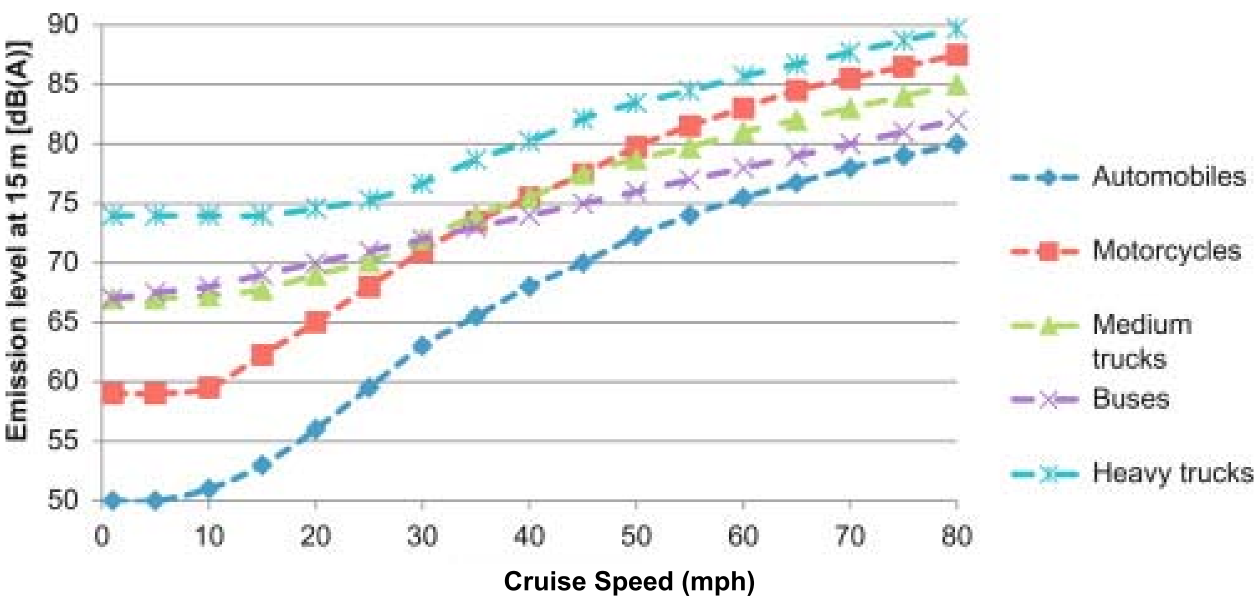

FIGURE 1 Weighted noise emissions by vehicle type vs. cruise speed *(Source: FHWA 1998)*

NOISE EMISSIONS BY VEHICLE TYPE

To further illustrate how motorcycle noise disproportionately contributes to overall traffic noise, the following data was collected from the FHWA's Traffic Noise Model 2.5 (TNM 2.5). The data are based on averages from a sample of 1,000 of each type of vehicle.

Methodology

For the purposes of gathering simplified information to compare motorcycle noise emissions to other vehicle types, data from the TNM 2.5 Lookup Tables for hard ground were used. With this information, accurate comparisons across different vehicles can be formed. Receiver distance was expected to have a large impact on the LAeq output from the vehicles. Both a short-range receiver distance and long-range receiver distance were plotted.

TNM Noise Results

The data indicate motorcycles surpass selected vehicle types at higher speeds at both short and long ranges. Note that motorcycles approach 80 dB, the U.S. standard limit, at speeds of just 50 mph. Motorcycles have a much smaller carrying capacity, in terms of passengers and goods, yet account for more traffic noise than automobiles, medium and heavy trucks, and buses. As LAeq is measured on a logarithmic scale, rather than linear, small differences in dBA values can create substantial differences in perceived intensity. As motorcycle engine size varies, one can presume that motorcycles with larger engines greatly exceed these predicted averages. This is problematic because noise exceeding 85 dBA is hazardous (Chepesiuk 2005). Prolonged exposure to such noise levels can be more damaging.

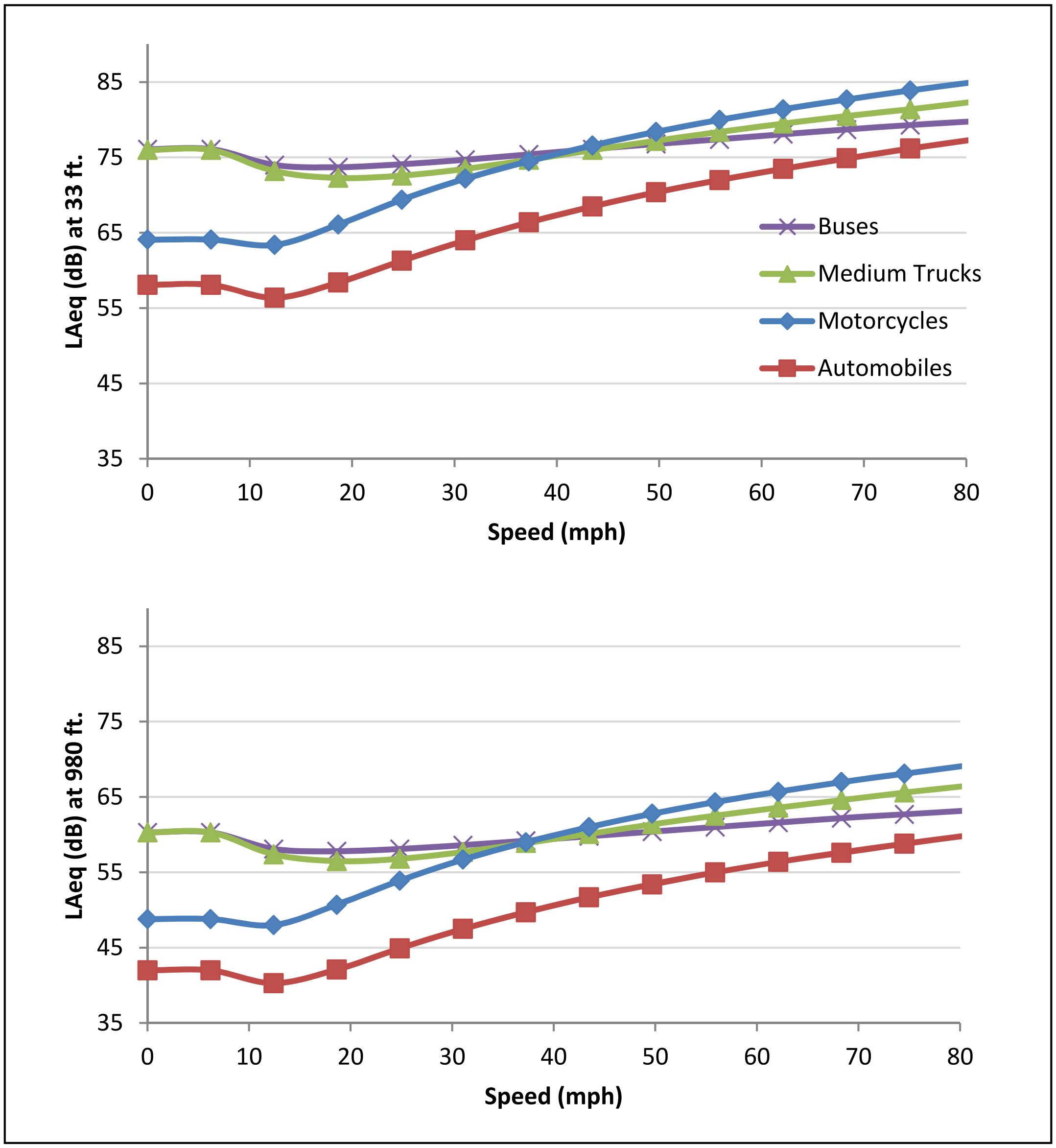

FIGURE 2 Vehicle sound levels vs. speed *(data from FHWA-TNM)*

Perceived loudness from specific LAeq exposure varies widely from person to person. Due to this variability, quantifying specific perceived volume would not be useful for application. However, it is generally understood that a difference of 10 dB translates to a sound that is perceived as twice as loud (Murphy et al 2014), so motorcycles traveling at higher speeds may be perceived as nearly twice as loud as automobiles at the same speed.

VARIABLES AFFECTING NOISE: EXPERIMENTAL DATA

To illuminate factors influencing gasoline-powered motorcycle sound levels, data studied here were sampled from motorcycles operating in Austin, Texas.

Method

Roadside measurements of passing motorcycles (n = 40) were made using a sound pressure level meter. Variables noted include meter distance from the source, speed (estimated by speed limit), observed acceleration, and a number of rider and motorcycle attributes. Explanatory variables were transformed into binary sets and a value of 0.5 was assigned to unknown data points. Four OLS iterations were performed for the sample. Variables with large p-values were extracted from the data set, one at a time, following each iteration. The order in which these variables were discarded was as follows: Male? (p = 0.515), U.S. Manufacturer? (p = 0.558), and Moped vs. Motorcycle (p = 0.221).

Experimental Noise Data

Gender of the driver, vehicle manufacturer, and type (scooter versus motorcycle) were found to be poor predictors of motorcycle sound level. As expected, sudden accelerations and distance from the device were strong predictors of maximum dB recorded. Ambient sound (p = 4.91E-7) was the most statistically significant for the sound level. Interestingly, motorcycles that were just starting were quieter than those operating on the road during sampling. The motorcycles of riders without helmets were somewhat louder than those ridden by helmeted riders. Results suggest riding style and context may be greater factors in noise emissions than the characteristics of the motorcycle.

TABLE 1 Factors Affecting Motorcycle dB, Regression Results

Variable	Coefficients	t-stat	P-value
Ambient Noise Level	1.449	9.4	0.000
Distance from Sound Meter (m)	0.4466	1.8	0.081
Motorcycle Recently Started?	-9.613	-3.8	0.001
Motorcycle Accelerating?	4.822	2.3	0.028
Rider Wearing Helmet?	-1.704	-1.5	0.139
Number of observations	40		
Adjusted R-squared	0.712		

Further research in a quieter environment, with a larger sample or weighting for model popularity, could expand these results. Similar experiments in other regions and countries could provide insight into the effectiveness of different models of regulation and enforcement.

MOTORCYCLE SOUND LAWS

The U.S. Environmental Protection Agency (EPA) has set a standard upper limit on motorcycle sound levels, at 80 dB measured at 50 feet, with constant engine speed at 50% RPM, but U.S. states differ in specific additional limits, restrictions on tampering with acoustical equipment, and enforcement (USCFR 1998). A motorcycle may be perfectly legal in one state yet in violation of the law if it crosses into another state.

U.S. state-mandated sound limits range from no restrictions at all to limitations dependent on speed, engine size, or year of manufacture (AAA 2018). Cut-off years vary among the states that have different limits for motorcycles of different ages. California has a tiered system, with incrementally lower maximum legal levels for motorcycles manufactured between 1969 to 1985.

Florida, in contrast, has different standards for those motorcycles built before and after 1979 (AAA 2018).

Forty-six U.S. states, including Texas, have muffler laws that require the factory-installed muffler prevent “excessive or unusual noise” and forbid acoustical modifications such as muffler cutouts and bypasses (Texas State Law Sec. 547.604, Holtsclaw 2017). Still, aftermarket pipes are easily obtained, and customizations are challenging for law enforcement to identify (Fagnant et al. 2013). Oregon, New York, and Montana specify maximum decibel levels at specific distances (AAA 2018); the equipment to obtain accurate readings can be costly, however, and is rarely available when enforcing regulations (Fagnant et al. 2013).

Japan, the European Union, and Singapore

Regulations can also vary dramatically between and within other countries. Japan sets different sound limits based on engine size and depending on whether the motorcycle is cruising, accelerating, or stationary, with those limits ranging from 65 dBA to 94 dBA (JMA 2012). Permissible sound levels in the European Union (EU) also vary by motorcycle type, from 74 dBA to 80 dBA (Eur-Lex 2018). The EU also carefully details procedures for measuring sound levels (Eur-Lex 2018). Singapore sets the maximum decibel level at 94 dBA and references both European and Japanese standards for noise emissions (EPMA 2008).

TAILPIPE EMISSIONS

Emissions from conventional motorcycles have both detrimental environmental and health effects. As technology has improved, motorcycles have not seen the same progress in reducing emissions as other vehicles. Motorcycles emit less CO2, NOx, SO2 and PM10 per person-mile traveled than most cars, but more VOC and CO if there is no catalytic converter present (Fagnant et al. 2013). Motorcycles with smaller engines have better mileage and produce fewer emissions, but motorcycles with larger engines perform worse than most other vehicles of all types (Fagnant et al. 2013).

Motorcyclists have been found to be at a greater risk for respiratory illness and decreased mucociliary clearance (MCC, Brant et al. 2014). This can be linked to a rider’s exposure to the emissions from both their vehicle and surrounding vehicles. In Brant’s study, commercial motorcyclists were found to be exposed to a median level of 75 mg/m^3 of NO2 during the 14-day monitoring period. 92% of the subjects reported airway symptoms, and 32% reported slower nasal MCC. For contrast, 19% of healthy individuals have slowed MCC (Brant et al. 2014).

U.S. Emissions Over Time, 1990-2030

To see how motorcycle emissions have changed over time and how those changes compare with emissions from passenger vehicles, U.S. emissions data were evaluated using U.S. EPA software, MOVES2014a. This Motor Vehicle Emission Simulator (MOVES) generates emissions and energy consumption for different vehicle types using emissions data gathered between the 1990s and 2000s.

The following data were created through a MOVES simulation for gasoline-powered motorcycles in 1990, 2000, 2010, 2020, and 2030. The simulation estimated the combined starting and running emissions from motorcycles for the entire U.S. The total distance travelled was also estimated, enabling the calculation of the total average U.S. emissions per mile for the presented species. The percentage of the initial rate for each species is depicted in Figure 3.

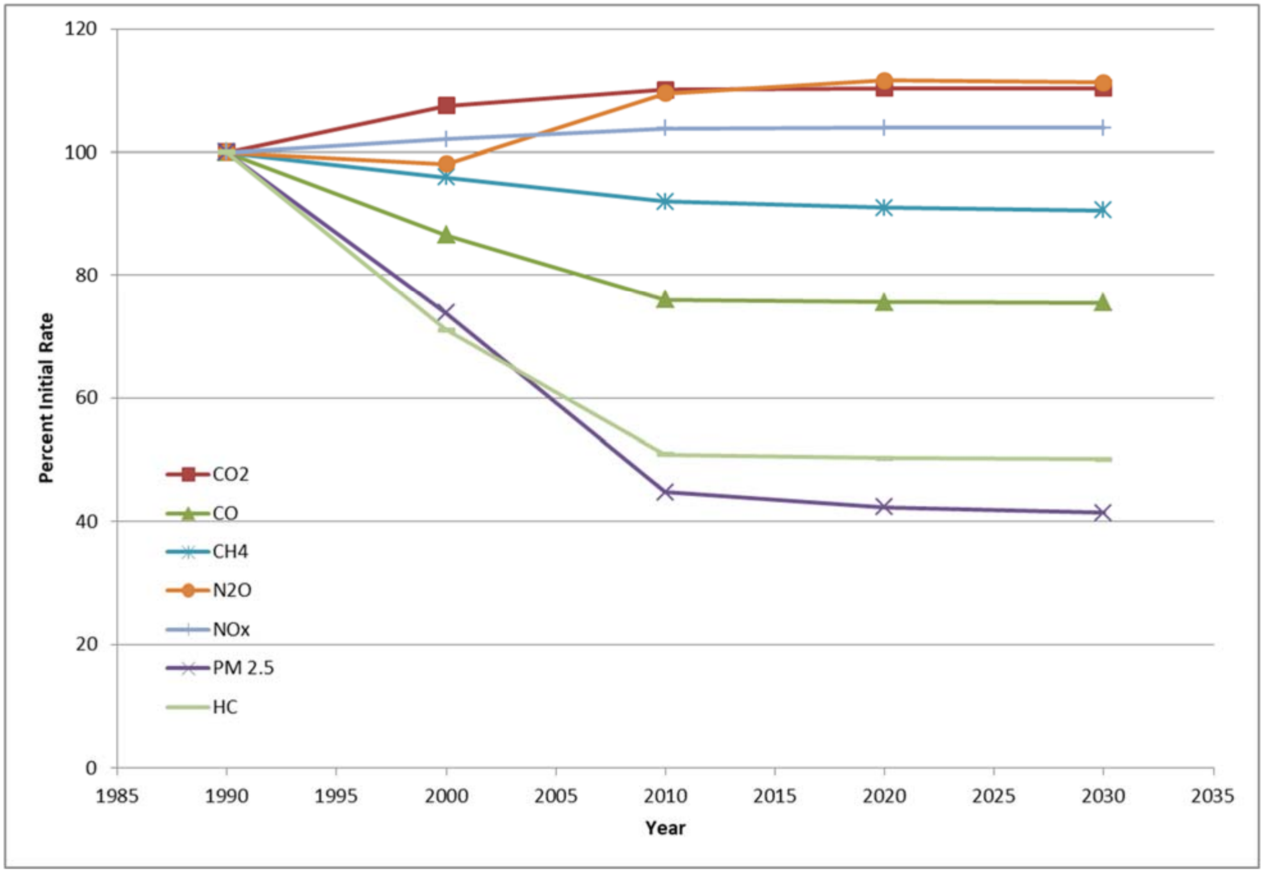

FIGURE 3: Average U.S. emission rate changes for motorcycles over time *(output from MOVES)*

As emission control and catalytic technologies advance, one expects harmful emissions of all types to decrease. Since some emission species have not decreased, the existing emissions policy or enforcement of motorcycle laws may be inadequate. The sharp increase in nitrogen oxides is of particular concern; N2O increases tropospheric ozone and contributes to smog and acid rain (Portmann, et al. 2012, Carlin 1995).

For comparison, the same emission species for duplicate years were calculated for all passenger vehicles (PVs) across the United States. An identical procedure was used for Figure 4 to make parallels clear. A comparison of the estimated total average emission rates is represented numerically in Table 2.

TABLE 2 Average U.S. Emission Rates for MCs and PVs in 2010 *(output from MOVES)*

Vehicle	CO2 (g/mi)	CO (g/mi)	CH4 (g/mi)	N2O (g/mi)	NOx (g/mi)	PM 10 (g/mi)	PM 2.5 (g/mi)	Sulfate PM 2.5 (g/mi)	HC (g/mi)
Motorcycle	365.46	33.00	0.057	0.008	1.193	0.028	0.025	0.003	2.236
Passenger Car	392.78	6.456	0.017	0.026	0.026	0.014	0.013	2.85E-4	0.561

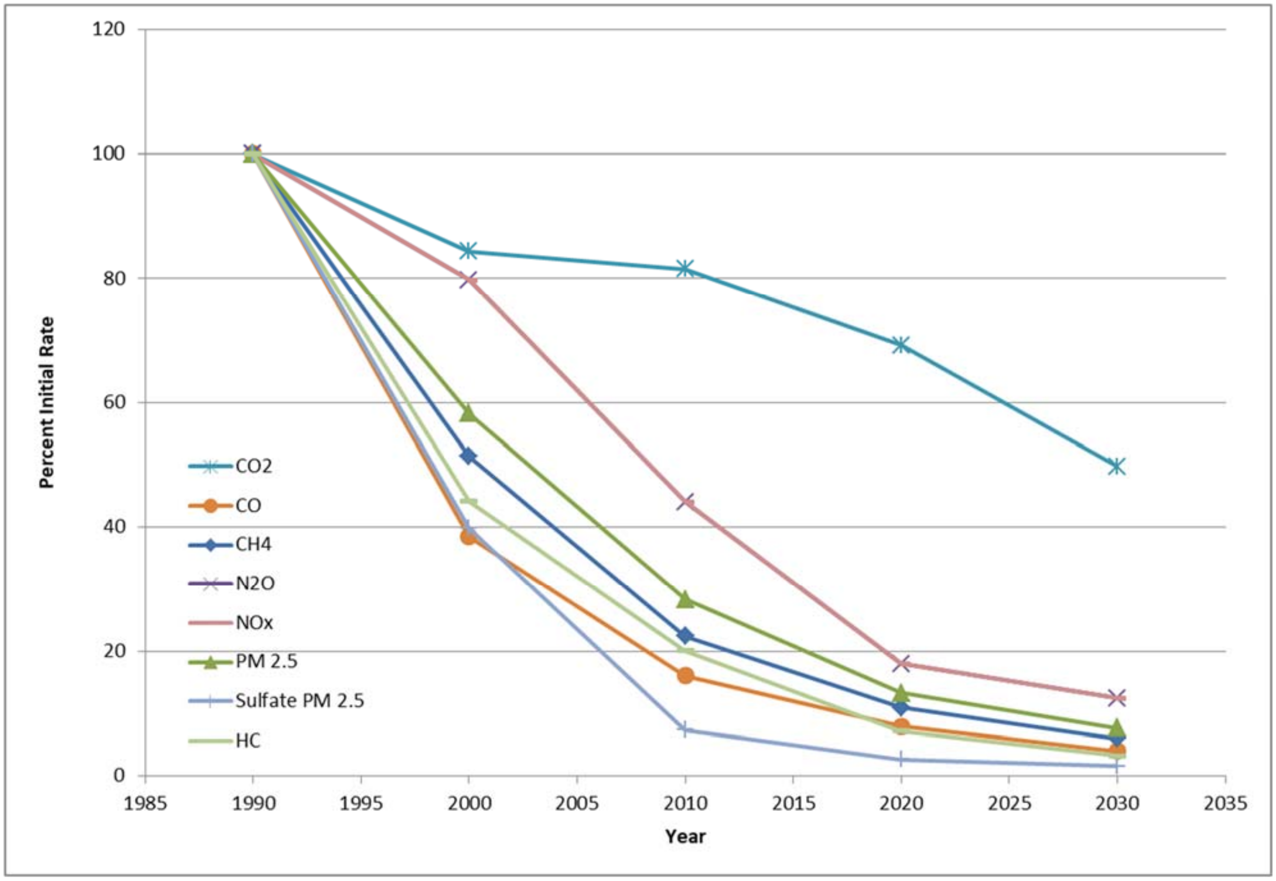

FIGURE 4 Average U.S. emission rate changes for passenger vehicles over time *(output from MOVES)*

While motorcycle emission species are inconsistent in their change over time, passenger vehicle emissions have significantly decreased in all areas, suggesting a technological or regulatory gap. In fact, passenger vehicles outperform motorcycles in emissions of most species like nitrogen oxides and carbon monoxide as of 2010. According to MOVES prediction estimates, passenger vehicles will outperform motorcycles in nearly all emission species in the coming decades. This will further exaggerate the emission costs per person-mile between PVs and MCs. Electrification is one route to mitigation. Regulations, examined below, could also play a role.

U.S. Emissions Regulations and Enforcement

In 2003, the U.S. EPA updated federal regulations on motorcycle emissions, which had remained largely unchanged since they were first introduced in the late 1970s (RiderzLaw 2016). Under the new regulations, motorcycles are still allowed higher emissions than light-duty vehicles (LDVs). MC engines tested at 18,600 miles are permitted to emit up to 1.29 gm/mi of HC and NOx, while most LDVs are limited to no more than 0.018 gm/mi of HCHO and 0.2 gm/mi of NOx. MCs are allowed up to 19.3 gm/mi of CO, while LDVs are allowed 4.2 gm/mi. The EPA does not set any requirements for particulate matter (PM) emissions on MCs (EPA 2009). Internationally, standards vary; European emission standards are generally stricter than US EPA standards (Federal Register 2004).

Enforcement of emissions standards, or lack thereof, also presents an issue. In Texas, a handful of cities require emission testing on some vehicles, but motorcycles are completely exempt (Texas DPS 2017). Even agencies with a reputation for strict enforcement, like the California Air Resources Board, provide exemptions for motorcycles (CDMV 2018).

ELECTRIC MOTORCYCLES

Many traditional manufacturers plan to release electric models in the coming years (Fleming 2015, Nadar 2018, Welsh 2016). EMCs are drastically more energy efficient than conventional motorcycles. For instance, the 2017 Zero S Motorcycle has a manufacturer-estimated equivalent fuel economy of 475 mi/gal in the city and 240 mi/gal on highways, using the US EPA's formulas (Zero Motorcycles 2017). These fuel economies are over 10 times the average 21.5 mi/gal of light-duty vehicles in the US (Sivak 2014) and over four times the 53 mi/gal average of a U.S. sample of 229 motorcycles (Fagnant et al. 2013).

EMC manufacturers also note the need for no routine drivetrain maintenance (Zero 2018), but consumers may be concerned about EMC batteries taking too long to charge and being too expensive or too heavy (Kunschik 2017). Cherry et al.'s (2013) stated-choice study in Vietnam found that consumers responded to economic incentives, with sales tax having a greater effect on vehicle choice than purchase price. The same study found improvements in range, speed, and acceleration made EMCs more appealing. Guerra's (2016) research in Solo, Indonesia found strong market potential for EMCs, especially as battery technologies improve and climate change concerns lead to increased demand for alternatives to petroleum.

The results of a study of mode choice transitions in Kunming, China, where motorcycles are severely restricted due to safety and congestion concerns, imply that former car users were less likely to switch back to cars over time, possibly because e-bikes provided an appealing alternative (Cherry, et al. 2018). In cities without such restrictions, EMCs may provide a similar role, though the researchers warn against applying their findings too generally (Cherry, et al. 2018). Motorcycle use varies widely between countries. For instance, in contrast to the relatively low motorcycle mode share in the U.S., 85% of Indonesian households and 87% of households in Thailand have at least one working motorcycle or scooter, with comparable percentages in other Southeast Asian countries (Poushter 2015).

A study in Thailand showed that further improvements to the electricity mix consumed and the recycling of batteries used in EVs could better allow for sustainable implementation of electric bikes and motorcycles. Lead-acid batteries were found to be less expensive than lithium-ion batteries but require more frequent replacement (Kerdlap and Gheewala 2016). To reduce metal depletion and toxicity, batteries must be recycled (Kerdlap and Gheewala 2016). The recycling of lead-acid batteries can prevent 98% of impacts from toxicity. EMCs can be a sustainable transport option so long as cleaner electric grid energy production and battery recycling are implemented (Kerdlap and Gheewala 2016).

BENEFIT-COST ANALYSIS

To evaluate the potential costs and benefits of electrification, a sampling of EMCs available today was compared with five popular gasoline-powered motorcycles on features and capabilities.

The following tables contain relevant manufacturer-estimated features of popular gasoline motorcycles and selected EMCs. As EMCs are relatively new, popularity rankings are not available as of this writing, so EMC models were selected from major manufacturers that provided the necessary information for comparison.

TABLE 3 Details of 5 Popular Gasoline Motorcycles

Year	Make	Model	Engine Size (cc)	Fuel Capacity (gallons)	Fuel Economy (mpg)	Range (miles)	Weight (lbs)	MSRP Price ($)
2017	Suzuki	VanVan 200	199 cc	1.7 gal	85 mpg	145 mi	282 lbs.	$4,600
2017	Honda	Rebel 500	471	3.0	67	200	408	6,000
2017	Yamaha	SCR950	942	3.4	51	173	547	8,700
2017	Triumph	Street Cup	900	3.2	76	243	440 (dry)	10,500
2017	Harley-Davidson	Road Glide	1753	6.0	45	270	853	21,300

Note: Rankings and specifications found at http://www.popularmechanics.com/, https://powersports.honda.com/, http://www.yamahamotorsports.com/, http://www.suzukicycles.com/, http://www.triumphmotorcycles.com/, and http://www.harley-davidson.com/.

TABLE 4 Specifications for 5 Electric Motorcycles Available in the US

Year	Make	Model	Max Battery Capacity (kWh)	Highway Range (miles)	Charging Time* (hr)	Top Speed (mph)	Weight (lbs)	MSRP ($)
2017	Zero	S ZF6.5	6.5 kWh	59 mi	4.7 hr. (standard*)	91 mph	313 lbs.	$11,000
2015	Alta	Redshift SM	5.8	50	4 (Level 2), 6 (Level 1)	80	283	15,500
2017	Zero	SR ZF13.0	13.0	98	8.9 (standard*)	102	414	16,000
2015	Energica	Ego	11.7	93	3.5 (level 2), 0.5 (DC fast charge)	150	569	34,000
2016	Lightning	LS-218	12, 15, 20	100	2 (level 2), 0.5 (DC fast charge)	218	495	38,900

*Charging times vary by power rate. Standard charging times for both 120V and 240V outlets.

Note: Rankings and specifications found at http://charged.io/best-electric-motorcycles/, http://www.zeromotorcycles.com/, http://www.altamotors.co/, http://lightningmotorcycle.com/, and http://www.energicamotorusa.com/.

Electrification would not compromise performance. The Lightning LS-218, for example, won a 2012 race in record speed, beating competing production motorcycles (Lightning Motorcycles 2017). Most of the popular EMCs available are intended for sports and performance purposes, which helps account for their higher MSRP. Of the sampled vehicle makes and models, the EMCs had a 55.7% higher average MSRP, though Zero offers more affordable EMCs for common use. Weight difference, although a common complaint associated with electrification, is comparable between electric and gasoline motorcycles.

Range and charging time are important factors when considering electrification. Although most EVs can be charged through standard home charging, level 2 and level 3 chargers significantly reduce charging time. Many manufacturers do not list standard charging time, presumably because the information might discourage purchases. Most manufacturers offer additional accessories that significantly decrease charging time. This makes charging times difficult to quantify, as it can vary even between motorcycles of the same make and model, depending on consumer choices.

Although EMCs cost less to charge than gasoline motorcycles cost to fuel, battery capacity limits the travel range. EMCs have a shorter range per full charge than gasoline motorcycles on a full tank in all the cases listed. The EMCs sampled averaged 61.2% less range at highway speeds. As estimated city ranges are higher than highway estimates, range limitations would be less of an issue in dense, urban environments where trip distance is typically shorter.

External Environmental Costs

While transportation only made up 0.2% of the U.S electrical grid in 2013 (EIA 2014), that number will likely grow as EVs become more popular. For electric motorcycles, emissions are present not at the tailpipe but at the power plants that provide the battery's charge. As such, outputs are highly dependent on the method used to produce electricity.

Emissions costs can also vary depending on where pollutants are emitted; output at tailpipe-level in a city has more ramifications for human health, for instance, than output from a remote power plant, so "exporting" emissions through electrification could have benefits even when emissions rates are similar to those of gasoline-powered vehicles (Reiter and Kockelman 2017). Motorcycle fuel consumption is approximately 30% greater in cities than in the countryside, so emissions from combustion may be even more centered in urban areas, and thusly more damaging, than these data suggest (Chen et al. 2003).

The average energy consumption of the 5 EMC models featured in Table 4 was calculated to be 0.1270 kWh/mi. Using 2014 output rates for the United States electric grid as reported in the Emissions & Generation Resource Integration Database (eGRID), the per-mile emissions of five species which EMCs indirectly produce were estimated and contrasted with MOVES output of gasoline-powered motorcycles' emissions (Table 5). These data do not fully capture the impacts of extreme outliers; a California Air Resources Board (2006) survey found that nearly 38% of motorcycle owners admitted to replacing exhaust systems and, as noted above, many of those replacements were likely made to increase power or change the motorcycle's sound.

The average per-mile output estimates for EMCs are less than most passenger cars and conventional motorcycles for CO2, NOx, and other species not featured due to negligible output. However, in our results EMCs produce more emissions with greater environmental costs, such as sulfur oxides and methane. This is likely because some electric sub-grids in the U.S. rely heavily on coal (Nichols et al. 2015). A direct comparison here between EMCs and gasoline-powered motorcycles outputs could be misleading, however; as noted above, emissions due to EMCs occur at power plants generally situated to reduce the impacts of their output. Areas with higher use of renewables than the U.S. average would also yield better emission rates for EMCs. For the optimal benefits of electrification to manifest, the transition must be accompanied by changes in how energy is produced and distributed.

TABLE 5 2014 U.S. Grid Emissions and Annual Motorcycle Emissions

Emission Species	Electric Grid Output Rate (g/kWh)[b]	Electric Motorcycles				Gasoline-Powered Motorcycles			
		Output Rate (g/mi)	Total Annual Output[c] (g/year)	Costs per Mile ($2017/mi)	Yearly Cost* ($2017/year)	Output Rate[d] (g/mi)	Total Annual Output[c] (g/year)	Costs per Mile ($2017/mi)	Yearly Cost* ($2017/year)
CO2	518.46 g/kWh	65.84 g/mi	158,016	$0.0019	$4.57	365.46 g/mi	877,104 g/year	$0.0211	$50.75
CH4	50.94	6.46	15,504	$0.0050	$11.90	0.057	136.8	$0.0001	$0.21
N2O	7.35	0.93	2,232	$0.0126	$30.31	0.008	19.2	$0.0002	$0.52
NOx	0.4082	0.057	136.8	$0.0002	$0.57	1.193	2863.2	$0.010	$23.70
SO2	0.7257	0.098	235.2	$0.0023	$5.54	0.01103[e]	0.0005	$0.0005	$1.25
Total Costs				$0.0220	$52.89			$0.0318	$76.43

[a] data adapted from USDOT (2015) and Marten and Newbold (2012)
[b] From 2014 eGRID summary tables (EPA 2014)
[c] based on 2,400 mi/year, from 2011-2016 average mileage of registered U.S. motorcycles (FHWA 2017)
[d] MOVES2014a simulation data
[e] From Chester and Horvath (2009)

This analysis also simplifies the intricacies of estimating costs, a thorough examination of which is beyond the scope of this paper. In Table 6, general emission valuations for the five species examined are presented in dollars per metric ton and are the monetized values recommended by the US Department of Transportation for CO2 and NOx (US DOT 2015). Values for CH4 and N2O are from Marten and Newbold (2012). The SO2 emissions rate is from Shindell (2015). Costs assume a 3% discount rate and have been converted to 2017 dollars using the U.S. Consumer Price Index. To approximate the lowered cost of emissions at power plants versus the tailpipe, the cost estimates for EMCs halve these values.

Noise Costs

Quantifying the costs of traffic noise is challenging. Studies that base costs on highway noise, as is common in the U.S., neglect the greater impact noise has on city streets (Litman 2009). Metrics that focus on impacts on residential values do not account for more general effects on quality of life, businesses, pedestrians, or wildlife (Litman 2009; Francis and Barber 2013).

This analysis uses an unweighted average cost of $0.13 per VMT for gasoline motorcycles, as estimated in Litman's (2009) review and adjusted using the CPI to 2017 dollars. With an average yearly VMT of approximately 2,400 miles for motorcycles (FHWA 2017) and assuming the noise produced by EMCs to be negligible, electrification could save annual noise costs of $312 per vehicle.

Total Per-Mile External Costs

The combined costs of the noise and emissions of conventional motorcycles were estimated as approximately $0.1618 per mile, versus $0.1520 for electric motorcycles. Emissions appear to comprise most of the costs of motorcycle use, but this neglects extreme offenders. Future work could quantify the disproportionate impact of those motorcycles that have been modified to bypass manufacturing standards restricting noise or emissions.

CONCLUSIONS

While regulations and technological advancements have steadily reduced noise and emissions for passenger vehicles, motorcycles have not followed suit. U.S. motorcycle emissions experience between a 60% decrease and a 10% increase, depending on gas species, over the five decades simulated in this work. For comparison, passenger cars are predicted to experience a 50% to 98.5% decrease, without accounting for higher passenger car occupancy.

Motorcycle sound can be perceived as nearly twice that of automobiles at high speeds. The psychological and health effects of increased urban noise can significantly impact dense urban populations. Motorcycles, despite having lower seating capacity than other vehicles, are one of the loudest contributors to traffic noise.

With little to no improvement in motorcycle gaseous emissions over the past few decades and noise levels exceeding that of most other vehicle types, change is warranted. The electrification of motorcycles has the potential to reduce most emissions species, with some caveats. Electric motorcycles and electric vehicles in general can help combat traffic noise. Per-VMT costs in noise and the five emissions species studied total approximately $0.161 for gasoline-powered motorcycles and $0.152 for EMCs.

Electrification does carry distinct barriers to its implementation. EMCs should be paired with a shift to less-polluting sources of energy, or EMC adoption could increase social costs. Recycling of the lithium-ion batteries is also important to protect from battery-associated toxicity exposure. The price of EMC models would need to decrease for widespread and popular implementation.

Further research could provide more insight into reducing the negative impacts of gasoline-powered motorcycles. Field testing of motorcycles in particular geographic locations could reveal problems faced in specific communities; for example, acoustical and exhaust modification may be more common in certain areas. Regional differences in energy sources, and how they may affect EMCs' environmental costs, could also be explored. Additional legislation to establish stricter manufacturing standards and reliably enforce current design and tampering laws is also important. Priorities should be targeting emissions for all motorcycles and reducing the impacts of motorcycles modified to be far louder or more polluting than the average.

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