EMISSIONS AND NOISE MITIGATION THROUGH USE OF ELECTRIC MOTORCYCLES

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ABSTRACT
Gasoline-powered motorcycles contribute disproportionately to noise and emissions, but the potential benefits of the electrification of motorcycles have not been thoroughly explored. In part, this is due to their relative newness; advances in battery efficiency have only recently allowed electric motorcycles (eMCs) to join electric cars and electric bicycles as a viable consumer option. This work investigates the current state of motorcycle noise and emissions using both simulations and experimental data, examines the factors that have led to motorcycles being outliers and offenders in these areas, and uses the specifications of major-manufacturer eMC offerings to estimate the costs and benefits of electrification. Motorcycle emissions have experienced anywhere from a 60-percent decrease to a 10-percent increase over a 50-year period, while U.S. passenger cars demonstrate a 50-percent to 98.5-percent decrease in all emissions species studied. Factors contributing to this discrepancy include limited regulations, which can be difficult to enforce and which vary regionally; changing engine technologies; and rider preferences. Motorcycle sound exceeds that of most other vehicles, with roughly double the perceived noise at high speeds. Electrification could serve to reduce noise and some emissions species, though range limitations and higher prices may prove a barrier to widespread adoption. For environmental benefits to manifest, it is critical that electrification occur with a corresponding shift in away from coal and natural gas 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 can serve both recreational and transportation purposes. In crowded cities, where parking is scarce, their small footprint is an asset. In South and Southeast Asia, motorcycles can dominate city streets (Poushter 2015). Motorcycles’ small size does not lower operating noise or emissions, however; their contribution to traffic noise is out of proportion with their carrying capacity, and their emissions can exceed that of larger vehicles. Emissions contribute to climate change and have consequences for human health. Noise from motorcycles, beyond being a nuisance, also poses a health risk.

The burgeoning market in electric motorcycles, fueled by changing technologies, provides an opportunity to mitigate some of the worst impacts of motorcycles. Some issues are shared between electric and gasoline-powered motorcycles. Safety is perhaps the foremost concern. In 2015, the U.S. fatality rate of 54.58 deaths per 100,000 registered motorcycles was 6 times the rate for passenger cars. Fatalities for motorcyclists occurred nearly 29 times more frequently than for occupants of passenger cars per vehicle-mile travelled (NHTSA 2015). This may contribute to why in the United States (US) they made up only 3% of total registered vehicles as of 2012 and were responsible for just 0.7% of vehicle-miles travelled (FHWA 2017).

The scope of this paper, however, is limited to noise and emissions. The potential for electric vehicles 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 or fleet operations. Considerations of electric two-wheeled vehicles are dominated by e-bikes (Cherry et al. 2018, Weinert et al. 2007, Dill 2012). Focuses specifically on motorcycles, this paper analyses experimental and simulation data to address sound and emissions impacts and the potential for mitigation through electrification.

The paper first looks at gasoline-powered motorcycles, examining sound levels and emissions independently. The authors then turn to eMCs, offering a cost-benefit analysis based on selected make/models.

MOTORCYCLE NOISE

Generally, the demand for high speed transportation comes at the cost of increased noise pollution (Murphy et. al. 2014). Still, motorcycles are outliers. As seen in Figure 1, the sound level of motorcycles typically surpasses that of other vehicles above 50 mph (FHWA 1998).

Conditions unique to motorcycles may contribute to high sound levels. Motorcycle noise emissions are increased by aggressive driving and revving of the engine. Riders may rev the engine for mechanical or safety reasons. 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). To avoid stalling in situations where they may need to accelerate to avoid a crash, it is common for riders to downshift and rev their engine when approaching a stop or slowing down (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 preference for louder motorcycles (Torrey et al 2006).
HOISE EMISSIONS BY VEHICLE TYPE

To further illuminate how motorcycle noise disproportionately contributes to overall traffic noise, we collected the following data 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, we used the data from the TNM 2.5 Lookup Tables for hard ground. With this information, we can form accurate comparisons across different vehicles. We expected receiver distance 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.

**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 noise emissions. 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 larger-engine motorcycles 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.
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 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).

**Results**

We found gender, manufacturer, and type (scooter versus motorcycle) to be poor predictors of motorcycle sound level. Somewhat unexpectedly, sudden accelerations and distance from the device were strong predictors of maximum dB recorded. Ambient sound (P = 4.91E-7) was the greatest explanatory variable 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 (4th Iteration OLS)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>t-stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Noise Level</td>
<td>1.449239</td>
<td>9.446408</td>
<td>4.91E-11</td>
</tr>
<tr>
<td>Distance from Sound Meter (m)</td>
<td>0.446556</td>
<td>1.799456</td>
<td>0.080827</td>
</tr>
<tr>
<td>Motorcycle Recently Started?</td>
<td>-9.61283</td>
<td>-3.76912</td>
<td>0.000624</td>
</tr>
<tr>
<td>Motorcycle Accelerating?</td>
<td>4.82159</td>
<td>2.287058</td>
<td>0.02854</td>
</tr>
<tr>
<td>Rider Wearing Helmet?</td>
<td>-1.70416</td>
<td>-1.5159</td>
<td>0.138787</td>
</tr>
</tbody>
</table>

Number of observations 40  
Adjusted R-squared 0.711699

Further research in a quieter environment, with a larger sample or weighted for model popularity, could expand on 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**

**In the United States**

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 additional limits, restrictions on tampering with acoustical equipment, and enforcement (USCFR 1998). A motorcycle perfectly legal in one state may be 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 simply 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).

In 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).

GASEOUS EMISSIONS

Emissions from conventional motorcycles have both environmental and health effects. Despite this, motorcycles have not seen the same progress in lowering emissions as other vehicles as technology has improved. 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).

Comparison of Total U.S. Emissions, 1990-2030

To see how motorcycle emissions have changed over time and how those changes compare with emission 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 for the entire U.S. from motorcycles. 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 would expect harmful emissions of all types to decrease. That some emission species have not suggests that 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.

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)

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

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.
**Emissions Regulations and Enforcement in the US**

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). The new regulations allow MCs to have 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, but most LDVs are limited to no more than .018 gm/mi of HCHO and .2 gm/mi of NOx. MCs are allowed up to 19.3 gm/mi of CO, while LDVs are allowed 4.2 gm/mi of CO. 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 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 strict enforcement, like the California Air Resources Board, provide exemptions for motorcycles (CDMV 2018).

**ELECTRIC MOTORCYCLES**

Electrification is one means of addressing the issues with gasoline-powered motorcycles. Many traditional motorcycle companies pledging to release electric models in the coming years (Fleming 2015, Nadar 2018, Welsh 2016).

EMCs are more energy efficient and may have less impact on the environment. The differences can be dramatic. 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 non-sales-weighted average of 53 mi/gal of a sample of 229 motorcycles (Fagnant et al. 2013).

Consumers may also value fewer maintenance issues and lower costs. Manufacturers tout the need for no routine drivetrain maintenance (Zero 2018). That said, consumers may be concerned about eMC batteries being too expensive, too heavy, and taking too long to charge (Kunschik 2017). A stated-choice study in Vietnam found that consumers responded to economic incentives, with sales tax having a greater effect on vehicle choice than even purchase price (Cherry 2013). 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 more 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 & 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).

COST-BENEFIT ANALYSIS

To evaluate the potential costs and benefits of electrification, we compared a sampling of eMCs available today 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: Selected Specifications for 5 Popular Gasoline Motorcycles

<table>
<thead>
<tr>
<th>Year</th>
<th>Make</th>
<th>Model</th>
<th>Engine Size (cc)</th>
<th>Fuel Capacity (gallons)</th>
<th>Fuel Economy (mpg)</th>
<th>Range (miles)</th>
<th>Weight (lbs)</th>
<th>MSRP Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>Suzuki</td>
<td>VanVan 200</td>
<td>199</td>
<td>1.7</td>
<td>85</td>
<td>145</td>
<td>282.2</td>
<td>4,600</td>
</tr>
<tr>
<td>2017</td>
<td>Honda</td>
<td>Rebel 500</td>
<td>471</td>
<td>3.0</td>
<td>67</td>
<td>200</td>
<td>408</td>
<td>6,000</td>
</tr>
<tr>
<td>2017</td>
<td>Yamaha</td>
<td>SCR950</td>
<td>942</td>
<td>3.4</td>
<td>51</td>
<td>173</td>
<td>547</td>
<td>8,700</td>
</tr>
<tr>
<td>2017</td>
<td>Triumph</td>
<td>Street Cup</td>
<td>900</td>
<td>3.2</td>
<td>76</td>
<td>243</td>
<td>440 (dry)</td>
<td>10,500</td>
</tr>
<tr>
<td>2017</td>
<td>Harley-Davidson</td>
<td>Road Glide</td>
<td>1753</td>
<td>6.0</td>
<td>45</td>
<td>270</td>
<td>853</td>
<td>21,300</td>
</tr>
</tbody>
</table>


Table 4: Selected Specifications for 5 Electric Motorcycles Available in the US

<table>
<thead>
<tr>
<th>Year</th>
<th>Make</th>
<th>Model</th>
<th>Max Battery Capacity (kWh)</th>
<th>Highways Range (miles)</th>
<th>Charging Time* (hr)</th>
<th>Top Speed (mph)</th>
<th>Weight (lbs)</th>
<th>MSRP ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>Zero</td>
<td>S ZF6.5</td>
<td>6.5</td>
<td>59</td>
<td>4.7 (standard*)</td>
<td>91</td>
<td>313</td>
<td>11,000</td>
</tr>
<tr>
<td>2015</td>
<td>Alta</td>
<td>Redshift SM</td>
<td>5.8</td>
<td>50</td>
<td>4 (Level 2), 6 (Level 1)</td>
<td>80</td>
<td>283</td>
<td>15,500</td>
</tr>
<tr>
<td>2017</td>
<td>Zero</td>
<td>SR ZF13.0</td>
<td>13.0</td>
<td>98</td>
<td>8.9 (standard*)</td>
<td>102</td>
<td>414</td>
<td>16,000</td>
</tr>
</tbody>
</table>
Electrification would not compromise performance. The Lightning LS-218 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.

**Environmental External-Cost Estimates**

For electric motorcycles, emissions are present not at the exhaust pipe but at the power plants that provide the battery’s charge. As such, outputs are highly dependent on the method used to produce electricity. To provide insight into eMCs’ potential contributions to emissions, we calculated eMCs’ output per mile of significant pollutants generated through the U.S. electric grid and estimated the cost to society of those emissions both per-mile and annually. While transportation only made up 0.2% of the United States Electrical Grid (EGRID) in 2013 (EIA 2014), that number will likely grow as EVs become more popular.

To quantify the emissions produced by eMCs and compare with traditional motorcycles, we looked at average output rates for the US EGRID for a sample year, presented in Table 5 (EPA 2014). Based on these data, average rates of emissions output were calculated for the five eMC models featured previously in Table 4. We then contrasted those results with output rates for gasoline-powered motorcycles as determined by MOVES simulation, reported in Table 2 above.

Emission valuations, in dollars per metric ton, 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). Costs assume a 3% discount rate and have been converted to 2017 dollars using the U.S. Consumer Price Index.
Table 5: 2014 U.S. Grid Emissions and Calculated Electric and Gas Motorcycle Emissions

<table>
<thead>
<tr>
<th>Emission Species</th>
<th>Cost/ton* ($2017)</th>
<th>Grid Output Rate (g/kWh)</th>
<th>Electric</th>
<th>Gasoline-Powered</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>58</td>
<td>518.46</td>
<td>65.84</td>
<td>0.003810</td>
</tr>
<tr>
<td>CH4</td>
<td>1535</td>
<td>50.94</td>
<td>6.46</td>
<td>0.009917</td>
</tr>
<tr>
<td>N2O</td>
<td>27,159</td>
<td>7.35</td>
<td>0.93</td>
<td>0.02526</td>
</tr>
<tr>
<td>NOx</td>
<td>8,277</td>
<td>0.45</td>
<td>0.057</td>
<td>0.0004718</td>
</tr>
<tr>
<td>SO2</td>
<td>47,148</td>
<td>0.77</td>
<td>0.098</td>
<td>?</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td></td>
<td></td>
<td>?</td>
<td>$0.03946</td>
</tr>
</tbody>
</table>

Note: grid output rounded for clarity.
* data adapted from USDOT (2015) and Marten and Newbold (2012).
** based on 2,400 mi/year, from 2011-2016 average mileage of registered U.S. motorcycles (FHWA 2017)

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 of the emissions with greater environmental costs, such as sulfur oxides and methane. This is likely because some electric grids rely heavily on natural gas and coal (Nichols et al. 2015). Areas with higher use of renewables than the U.S. average would yield better emission rates for eMCs. For the benefits of electrification to manifest, the transition must be accompanied by changes in how energy is produced and distributed.

CONCLUSIONS

While regulations and technological advancements have steadily improved noise and emissions for passenger vehicles, motorcycles have not kept up. U.S. motorcycle emissions experience between a 60% decrease and a 10% increase, depending on gas species, over the five decades simulated. 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.

Electrification is not without issues. Implementation of 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, as, for example, acoustical and exhaust modification may be more common in certain areas. Regional differences in energy sources, and...
how they may affect eMC environmental costs, could also be explored. Additional legislation to establish stricter manufacturing standards or enforce current standards regarding modifications may be necessary.
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