EMISSIONS AND NOISE MITIGATION THROUGH USE OF ELECTRIC MOTORCYCLES

Michael Hernandez
The University of Texas at Austin
Department of Civil, Architectural, and Environmental Engineering
michael_hernandez@utexas.edu

Kara M. Kockelman
(Corresponding author)
Professor and William J. Murray Jr. Fellow
Department of Civil, Architectural, and Environmental Engineering
The University of Texas at Austin, 301 E Dean Keeton, ECJ Suite 6.9, Austin, TX 78712-1076
kkockelm@mail.utexas.edu
Phone: 512-471-0210

Under review for presentation at the 97th Annual Meeting of the Transportation Research Board and for publication in Transportation Research Record.

ABSTRACT
The consequences of gasoline-powered motorcycles are evaluated in terms of gaseous and sound emissions. The mitigation of such issues is explored through electrification of U.S. motorcycles. Geography plays a large role, with laws, enforcement, and power-grid efficiency varying across countries, states, and local jurisdictions. Time also plays a major role in this assessment, as power-grid emissions, motorcycle engine technologies, and regulations evolve over time. Electric motorcycles have only recently experienced significant improvements to battery-efficiency and availability from multiple manufacturers. This research illuminates how motorcycles are outliers and offenders in terms of noise and air pollution, relative to other motorized modes. U.S. motorcycles have shown little to no improvement in emissions across several decades, while passenger cars have made tremendous progress. 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. Motorcycle sound exceeds that of most other vehicles, with roughly double the perceived noise at high speeds. Use of electric motorcycles will notably reduce noise and emissions in most U.S. regions. However, range limitations are and about 50-percent higher pricing limit adoption, regulations, and cost reductions are needed.

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

INTRODUCTION
Motorcycles are a seemingly effective form of transportation. They are presumably efficient by the amount of space they consume. This can be beneficial in urban areas where parking is scarce (Cottrell 2010); however, motorcycle use made up only 3% of total registered vehicles in the United States in 2012 (FHWA 2017). Furthermore, they only made up 0.7% of vehicle-miles travelled in the United States. This relatively small number of riders has partially led to lack of legislation in the United States.

There are some clear disadvantages to motorcycle use- particularly in terms of safety. For example, the exposed seating of the driver increases the fatality rate of crashes. In 2015, the fatality rate, 54.58 per 100,000 registered vehicles, was 6 times the rate for passenger cars. Motorcyclists fatalities occurred nearly 29 times more frequently than occupants of passenger
cars per vehicle-mile travelled (NHTSA 2015). The disadvantages extend beyond safety. Emissions, both in terms of sound and gas, present a significant issue with motorcycles. Lack of legislation on bikes is largely responsible.

**Noise Emission**

Noise emission is an issue with most forms of transportation. Generally, the demand for high speed transportation comes at the sacrifice of increased noise pollution. (Murphy et al 2014). This has several impacts on society.

The EPA has set standards on noise emission at 80 dB, measured at 50 feet, with constant engine speed at 50% RPM (U.S. Code of Federal Regulations 1998). However, local regulation on noise standards varies widely. Many riders are able to bypass the standards with modifications and custom-made motorcycles. Modifications, such as illegally removing a muffler, can allow sound produced at the exhaust pipe to exceed 80 dB. For example, Texas law requires that a muffler in good working condition be used on all motor vehicles and forbids use of muffler cutouts or bypasses (Texas State Law Sec. 547.604). Noise emission is also increased by aggressive driving and revving of the engine. There are a few possible explanations as to why motorcyclists rev their engine. It may be a new engine- which requires a “break-in” period to increase the life of the engine. Similarly, it could be a recently repaired engine which also requires this break-in period. Another explanation could be for perceived safety purposes. Since most bikes do not have automatic transmission, it is common for riders to downshift and rev their engine when approaching a stop or slowing down. This technique is used to avoid stalling in a situation where they may need to accelerate to avoid a crash (Count Motorcycles LLC 2012). There may be more sinister reasons for engine revving among motorcyclists, as well.

As seen below, motorcycles typically surpass noise emission levels of medium trucks, automobiles, and buses at speeds above 50 mph.

![Figure 1: A-weighted noise emissions for separate vehicle categories under cruise conditions. Source: Federal Highway Administration (1998)](image)

Environmental noise can lead to a number of adverse health effects – including sleep disturbance, stress, hypertension, and other cardiovascular health problems. (Murphy et al 2014). A positive correlation was found between residential road traffic noise and hypertension. The odds ratio for hypertension was 1.9 and 3.8 in men for groups regularly exposed to 56-70 dB than non-exposed subjects (Davies and Kamp, 2012, Barregard et al. 2009).
Figure 2: Pyramid illustrating ailments of increasing severity linked to environmental noise. Source: (Babisch 2002)

Additionally, motorcyclists are at increased risk for hearing loss. Helmets are not able to provide the necessary protection for the exposed rider. Two possible solutions include ear muffs that block noise or ear plugs for the rider (McCombe 2003).

Motorcycle Gaseous Emissions

In 2003, the US Environmental Protection Agency updated regulations on motorcycle emissions. Motorcycle emission standards remained largely unchanged since the late 1970s when they were originally set (RiderzLaw 2016). There is also discrepancy between European Emission Standards and US EPA standards. European Emission Standards are generally stricter than US EPA Standards (EPA 2004).

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. Motorcycles with larger engines actually perform worse than most vehicles. (Fagnant et al. 2013). The US EPA allows the MCs to have higher emissions than it does LDVs. MC engines tested at 18,600 miles are permitted to emit up to 1.29 gpm of HC and NOx, but most LDVs are limited to no more than .018 gpm of HCHO and .2 gpm of NOx. MCs are allowed up to 19.3 gpm of CO, while LDVs are allowed 4.2 gpm of CO. The EPA also does not set any requirements for PM emissions on MCs. (U.S. Environmental Protection Agency (2009) Emissions Standards Reference Guide. Washington, D.C.).

Enforcement of emissions standards also presents an issue. In Texas, only El Paso, Travis, Williamson, Dallas, Houston/Galveston areas actually require emission testing on vehicles. Furthermore, motorcycles are completely exempt from emissions testing. (Texas Department of Public Safety). Even agencies that are notorious for enforcement of emissions standards and smog testing like the California Air Resources Board (CARB) provide exemptions for motorcycles (California Department of Motor Vehicles).

Additionally, motorcyclists have been found to be at a greater risk for respiratory illness and a decrease in mucociliary clearance (Brant et al. 2014). This can be linked the exposed nature of the motorcycle. The motorcyclist is exposed to the emissions their vehicle emits in addition to
emissions from surrounding vehicles. In this study, motorcyclists were exposed to median of 75 mg/m^3 of NO2 with significant association to impaired mucociliary clearance.

**Electric Motorcycles**

While gasoline-powered motorcycles present a number of issues, incorporation of electric motorcycles on a larger scale can potentially mitigate these issues. Many motorcycle companies have pledged to release electric models in the coming years. Harley-Davidson pledged to release its first electric bike within the next five years in June of 2016 (Lambert 2016).

There are many attractive qualities that electric bikes present to consumers—increased fuel economy and reduction of environmental impacts. The 2017 Zero S Motorcycle has a fuel economy at a manufacturer estimated 475/240 mpg (city/highway) equivalent using the EPA recommended formula (Zero Motorcycles 2017). Another quality that many consumers find to be ideal is the lowered cost and hassle of maintenance. In an interview with Audrey and Mark Sze-To of Electric Avenue: Scooters and Motorbikes in Austin, Texas, it was mentioned that the cost of maintaining a passenger vehicle in a dense, urban environment has become too costly—with parking mentioned as a contributing factor (Audrey and Mark Sze-To 2017). Electric bikes do not require any of the maintenance that a gasoline-powered motorcycle requires.

However, there have been some issues concerning the batteries of electric bikes. In an interview with Greg Kunschik from Urban Motorsports in Austin, Texas, he stated that there are concerns in that the batteries are too expensive, too heavy, and take too long to charge (Kunschik 2017). While battery technology has significantly improved within the last decade, further analysis can provide more insight on these issues.

Guerra’s (2016) research in Solo, Indonesia found market potential for electric bikes. As battery technology improves and gas prices rise, the potential to replace gas-powered bikes will increase. Of course, motorcycle and moped use dominates in Solo, Indonesia, while motorcycles are just 3% of registered vehicles in the United States (FHWA 2017).

A study in Thailand showed that more improvements to the electricity mix consumed and recycling of batteries used in EVs can better allow for sustainable implementation of electric bikes and motorcycles. Lead-acid batteries were shown to be a more affordable option for many where cost is a concern. The recycling of batteries can prevent 98% of impacts from toxicity. EMs can be a sustainable transport option so long as cleaner electric grid energy production and battery recycling are implemented (Kerdlap and Gheewala 2016).

**ANALYSIS**

**Cost-Benefit Analysis of Selected Motorcycles**

Transportation only made up 0.2% of the United States Electrical Grid in 2013 (U.S. Energy Information Administration, Annual Energy Outlook, 2014). However, there has been considerable growth in electric vehicles and one may see that number change.

There are many questions as to the differences of costs, specifications, and performance features between electric motorcycles and gasoline motorcycles. The following tables contain relevant manufacturer estimated features of popular gasoline and electric motorcycles.

**Table 1: Selected Specifications for 5 Popular Gasoline Motorcycles**
### Table 2: Selected Specifications for 5 Popular Electric Motorcycles

<table>
<thead>
<tr>
<th>Year</th>
<th>Make</th>
<th>Model</th>
<th>Max Battery Capacity (kWh)</th>
<th>Highway 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>
<tr>
<td>2015</td>
<td>Energica</td>
<td>Ego</td>
<td>11.7</td>
<td>93</td>
<td>3.5 (level 2), 0.5 (DC fast charge)</td>
<td>150</td>
<td>569</td>
<td>34,000</td>
</tr>
<tr>
<td>2016</td>
<td>Lightning</td>
<td>LS-218</td>
<td>12, 15, 20</td>
<td>100</td>
<td>2 (level 2), 0.5 (DC fast charge)</td>
<td>218</td>
<td>495</td>
<td>38,900</td>
</tr>
</tbody>
</table>

*Charging times do not appear in common unit. Standard charging time tend to hold for both 120V and 240V outlets.

performance. The Lightning LS-218 broke a record for highest average two-way speed of any producing bike in August 2012 (Lightning Motorcycles 2017). Weight, although a common complaint associated in electrification, seems to have an almost negligible difference between electric and gasoline motorcycles.

Charging time and range are important factors when considering the costs of electrification. Although most EVs can be charged through standard home charging, level 2 and level 3 chargers significantly reduce the charging time. Many manufacturers do not even list standard charging time because of less appealing duration. On the other hand, most of these companies offer charging accessories that significantly decrease charging time. Charging time is difficult to quantify in this regard – as it relies on the owner’s expenses and needs. Although electric motorcycles cost less to charge than gasoline motorcycles cost to fuel, the range can suffer. Electric motorcycles have a shorter range per full charge than a gasoline motorcycle on a full tank of fuel in all of the cases listed. The electric motorcycles sampled averaged 61.2% less range than gasoline motorcycles. However, the listed ranges reflect highway speeds. Estimated city ranges are higher than highway estimates. This would be less of an issue for implementation in dense, urban populations where there are shorter distances between destinations.

**MOVES Model Application**

U.S. emissions data was gathered using EPA software, MOVES2014a. This Motor Vehicle Emission Simulator (MOVES) uses emissions data gathered between the 1990s and 2000s to generate emissions and energy consumption for different vehicle types. The following data were created through a MOVES simulation for motorcycles for the years 1990, 2000, 2010, 2020, and 2030. The simulation estimated the combined starting and running emissions for the entire United States from gasoline motorcycles. The total distance travelled was estimated as well. Thus, the total average U.S. emissions per mile were calculated for several emission species. The percentage of the initial rate for each species is depicted into a condensed graph.
As seen in the emission simulation, some gas species outputs have decreased over time while others have increased. In particular, there is a significant increase in nitrogen oxides—known for causing adverse health effects, increasing tropospheric ozone, and a known cause of smog and acid rain. As emission control and catalytic technologies advance over time, one would expect emissions in all areas to decrease. However, perhaps a lack of emission policy or enforcement on motorcycles has led to this inconsistency among emission species.

For comparison, the same emission specie for duplicate years were calculated for all passenger vehicles across the United States. The same procedure was used for graphing and comparison purposes. The results for passenger vehicles are depicted below. A comparison of the estimated total average emission rates are represented numerically in Table 3.
Figure 4: Average U.S. Predicted Emission Rate Percent Change for Passenger Cars

Table 3: Average U.S. Estimated Emission Rate for MCs and PCs in the year 2010

<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>365.460</td>
<td>33.007</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>392.783</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>

One can clearly see that while motorcycle emission species are inconsistent in their change over time, passenger vehicle emissions have significantly decreased in all areas. In fact, passenger vehicles outperform motorcycles in emissions of most specie like oxides of nitrogen and carbon monoxide as of 2010. According to MOVES prediction estimates, passenger vehicles will outperform motorcycles in nearly all emission specie in the coming decades. This will further exaggerate the emission costs per person-mile between PVs and MCs.

EV Emissions through EGRID Data

The following table shows data for average outputs and rates for the Unites States Electric Grid for 2014 (EPA 2014). Along with this data, an averaged electric motorcycle per rate emission output was calculated among the five electric motorcycle models featured in Table 2.
Table 4: Electric Grid Emission Data, Rates, and Sample Average eMC Output

<table>
<thead>
<tr>
<th>Emission Species</th>
<th>Output (tons)</th>
<th>Rate (g/kWh)</th>
<th>Averaged Electric Motorcycle Rate Output (g/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric CO2</td>
<td>1166000</td>
<td>518.46</td>
<td>65.84</td>
</tr>
<tr>
<td>CH4</td>
<td>230000</td>
<td>50.94</td>
<td>6.46</td>
</tr>
<tr>
<td>N2O</td>
<td>33000</td>
<td>7.35</td>
<td>0.93</td>
</tr>
<tr>
<td>NOx</td>
<td>1000</td>
<td>0.45</td>
<td>0.057</td>
</tr>
<tr>
<td>SO2</td>
<td>1750</td>
<td>0.77</td>
<td>0.098</td>
</tr>
</tbody>
</table>

Note: output is rounded to nearest practical amount

The averaged per mile estimates are less than most passenger cars and gasoline motorcycle in areas such as CO2, NOx, and other areas not featured due to negligible output. However, there is some concern for species like sulfur oxides and methane. This is likely because some electric grids rely heavily on natural gas and coal for energy production (Nichols et al. 2015). Areas with higher use of renewables for energy production would yield better emission rates for EVs.

NOISE EMISSION DATA

The following data was collected from the FHWA’s Traffic Noise Model 2.5 (TNM 2.5). The data is based on averages from a sample of 1000 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 still form accurate comparisons across different vehicles. We expected receiver distance have a large impact on the LAeq output from the vehicles. Both a short range receiver distance and long range receiver distance were plotted. Vehicle types chosen for comparison were motorcycles, automobiles, medium trucks, and buses.
As seen through the data, motorcycles surpass the other vehicle types at higher speeds at both short ranges and long ranges. It is important to note that motorcycles approach 80 dB, the current manufacturing standard, at speeds of 50 mph. Motorcycles have a much smaller carrying capacity, in terms of passengers and goods, yet account for more noise emissions. It is important
to note that $L_{Aeq}$ is measured on a logarithmic scale, rather than linear. This can create a substantial difference in perceived intensity upon small differences in dBA values. Due to the variability in motorcycle engine sizes, one can presume that there exist larger engine motorcycles that 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 even more problematic.

Perceived loudness from specific $L_{Aeq}$ 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). This shows that motorcycles at higher speeds can be perceived as approaching twice as loud as automobiles at the same speed.

Motorcycle Sound Laws Between States

While there are US EPA manufacturing standards set at 80 dB for road use, laws between states concerning enforcement and tampering of acoustical equipment vary (U.S. Code of Federal Regulations 1998). This can make enforcement of motorcycle noise standards dependent on the state and local laws in which one lives. State laws typically either use wording that prohibit loud and excessive noise, require mufflers, have specific sound level requirements, or use some combination. 46 states have state muffler laws that require the factory installed muffler without modification to prevent excessive or unusual noise (Holtsclaw 2017). Michigan, Oregon, Pennsylvania, and Vermont do not have specific laws regarding mufflers. Michigan, Oregon, and Pennsylvania contain laws that require certain sound levels at specific distances. Such laws are difficult to enforce because evidence from sound meter data is not usually admissible in court and can create unnecessary costs. Vermont has not definitive legislation regarding motorcycle muffler laws. In general, noise violations are hard to enforce and require committed law enforcement officers (Holtsclaw 2017).

CONCLUSIONS

Motorcycles present a unique problem. Although they make up a small percentage of transportation, ownership rates are only increasing in dense, urban areas (Morris 2009). While regulations and improvements have steadily increased for passenger vehicles, change is occurring slowly for motorcycles. Perhaps motorcycle technology has not reached a point in making significant improvements to emissions.

The current state of motorcycles is troublesome. Emissions have experienced anywhere between a 60% decrease and a 10% increase in gas specie based on U.S data. With little to no improvement in gaseous emissions over the past few decades and noise levels exceeding that of most other vehicle types, some evolution is necessary. For comparison, passenger cars are predicted to experience a 50% to 98.5% decrease in all emissions over the five decades simulated. This disparity does not take into account that passenger cars have higher occupancy capabilities.

Electric motorcycles can offer lower emission rates in most areas. Notable exceptions include methane and sulfur oxide emissions in areas with dependence on coal and natural gas for energy production. Methane emissions averaged 6.4 g/mi per mile for the sampled electric motorcycles, which is higher than the 2010 averaged rate from the MOVES simulation. However, implementation of electric motorcycles would be best when paired with increased renewables in electric-grid energy production. Recycling of the lithium-ion batteries is also important for ensuring protection from battery-associated toxicity exposure. Costs of electric motorcycle
models would need to decrease for widespread and popular implementation. Of the vehicle makes and models investigated, the electric motorcycles had a 55.7% higher average MSRP. Noise is another pressing issue that needs to be addressed. The various psychological and health effects that increased urban noise can have significantly impacts dense urban populations. Motorcycles, offering less benefit to society in terms of capacity, are one of the loudest vehicular contributors to ambient traffic noise. Motorcycle sound can be perceived as nearly twice that of automobiles at high speeds. Electric motorcycles and electric vehicles in general can help combat this concern.

Further research into gasoline motorcycle impacts on society can provide more insight as to how to go about resolving the matter. Field testing of motorcycles in particular geographic locations could reveal problems faced in specific communities. Perhaps illegal acoustical and exhaust modification is more common in certain areas. More strict legislation might be necessary to impose stricter manufacturing standards or enforce current standards onto operators.

REFERENCES

California Department of Motor Vehicles. https://www.dmv.ca.gov/portal/dmv/detail/vr/smogfaq


Lambert, F. (2016). “Harley-Davidson will bring to market its first all-electric bike within 5 years”. Retrieved at https://electrek.co/2016/06/14/harley-davidson-electric-bike-within-5-years/


Texas Department of Public Transportation. https://www.dps.texas.gov/rsd/vi/consumerinfo/emissionTesting.htm
