WHO RIDES AND WHO PAYS: A COMPREHENSIVE ASSESSMENT OF THE COSTS AND BENEFITS OF MOTORCYCLING IN THE UNITED STATES

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ABSTRACT

This paper offers a comprehensive assessment of the benefits and costs of motorcycle use while exploring the characteristics, behaviors and attitudes of motorcycle riders. U.S. motorcyclists are at relatively high risk of crashing, per mile travelled, with rates 24 times higher than those of passenger car and light-duty truck drivers. However, motorcycles require just one quarter the parking space of a car, and can double network capacities (in terms of vehicles per hour), thereby reducing congestion.

While most motorcycles enjoy high fuel economy, their low seating capacities render them little or no better than most cars and some light-duty trucks (assuming average vehicle occupancies). They emit relatively fewer grams of CO2, NOx, SO2 and PM10 per person-mile traveled than most cars, but more VOC and CO, if a catalytic converter is not installed. Noise impacts are also a serious issue for many motorcycles, with an inconsistent patchwork of regulations applied across states and localities.

Results of a survey of current and former U.S. motorcyclists indicates almost use their motorcycles for recreational purposes and ride in groups, though about half also ride for more mandatory/less discretionary purposes and about 40% also ride solo. Less than a third has had formal motorcycle training, and helmet use appears lower among current riders who do not own a motorcycle. Engine size appears to be rising, and respondents showed strong support for policies that combat operating a vehicle under the influence (such as ignition interlock devices for offenders). Regression models illuminate key factors and marginal effects on motorcycle riding and ownership rates.

Key Words: Motorcycling, rider safety, motorcycle noise, emissions, fuel economy

BACKGROUND

Motorcycles are an attractive form of personal transportation for many people. They can serve as a secondary vehicle for recreational use, as well as a primary vehicle in congested regions, offering relative ease of parking and travel. Motorcycles differ from other motor vehicles in their costs and impacts, size, and traveler exposure. In a series of related sections, this paper quantifies the safety, fuel use, energy, emissions, space demands, and other differences inherent in motorcycle use, as compared to cars and trucks. Thanks to results of a new U.S. survey, the paper also describes who is more likely to own or have owned a motorcycle and which types of riders are more likely to ride more often, while exploring motorcyclist demographics, opinions, and behaviors. In this way, this paper tackles two questions: Who rides? And who pays? This work seeks a comprehensive examination of motorcycles as a unique mode by exploring the characteristics of different types of riders and conducting a comprehensive benefit-cost evaluation of motorcycle use across a wide range of metrics.

Motorcycle Safety

4,462 persons were killed in 4,187 fatal motorcycle crashes across the U.S. in 2010. Overall motorcyclist crash rates (per vehicle-mile traveled, or VMT) are more than twice those for passenger cars: 785 vs. 353 per hundred million miles travelled in 2008 (*1*). Their fatal crash rates are about 20 times higher: 27.67 vs. 1.31 per hundred million miles travelled in 2009 (*2*). Like pedestrians and bicyclists, motorcyclists are vulnerable users insofar as they are unprotected by the physical carriage of a vehicle. Unlike pedestrians and bicycles, motorcycles allow their riders to travel at high speeds, greatly increasing rider risk of serious injury, and death, in the event of a crash (*3*).

Many factors contribute to motorcycle (MC) safety issues. According to the U.S. Fatal Accident Record System (FARS) database (*4*), there were 1,972 single-vehicle *fatal* motorcycle crashes in 2010: 1,257 involved running off the road (ROR), and 504 were rollovers or overturns. Almost two-thirds (64%) of the fatal ROR crashes involved the motorcyclist running into or down an embankment or hitting a fixed object (such as a guardrail, barrier, curb, ditch, culvert, or sign).

Multi-vehicle collisions are also a significant safety issue. The average MC weighs just one-tenth that of many or most LDVs (e.g., the Suzuki GS500E weighs 424 lbs. [*5*], while the Toyota Camry and Ford F-150 pickup weigh in at 3240 lb. and 5000 lb. [unloaded]). Such weight imbalances translate to tremendous deceleration differences during a crash, putting riders at clear disadvantage.

In 2010 there were 2,215 fatal multi-vehicle crashes involving MCs, of which 52% were angle collisions, 15% were head-on, and 17% rear-end collisions, with the remainder comprising sideswipes and other crash types. 47 percent of multi-vehicle fatal MC crashes occurred at intersections (including 302 of the angle collisions), compared to 38% of fatal multi-vehicle collisions among all vehicle types in the U.S. This suggests that riders have higher risks at intersections, with car-driver awareness and visibility (of riders and their MCs) potentially crucial to improving motorcyclist safety. Additional safety concerns include alcohol (a factor in

32% of fatal motorcycle crashes, vs. 28% among all fatal crashes), speeding (a factor in 40% of fatal motorcycle crashes vs. 31% among all fatal crashes), horizontal curvature (57% of single-vehicle fatal crashes vs. 32%) and vertical curvature (39% of single-vehicle fatal crashes vs. 30%).

Helmet use is a key variable in crash outcomes, but only 66% of riders choose to wear law-compliant helmets (*6*). NHTSA (*7*) estimates that helmets reduce the probability of death (in the event of a crash) by 37% for motorcycle operators and by 41% for passengers, with likelihood of serious injury falling 13% that of minor injury by 8%. If all motorcyclists had been helmeted in 2008, 822 lives could have been saved with total economic savings over $1.3 billion (*7*). McKnight and McKnight's (*8*) study of 50 riders under varying helmet conditions concluded that helmet use has no negative impacts on riders' auditory or visual perceptions, and Fagnant and Kockelman (*9*) estimated that higher helmet usage is correlated with lower crash rates. Daniello et al. (*10*) cite several studies indicating that those who obtain MC training are more likely to wear a helmet and other protective gear.

Vehicle technologies have significant potential for reducing the number and severity of motorcycle crashes. Anti-lock braking systems (ABS) prevent tires from locking up and skidding, in reaction to unexpected hazards. Teoh (*11*) calculated that MC owners with ABS installed (21% of model-year 2003 through 2008 bikes) experienced 37% lower fatal MC crash counts (per registered vehicle year), which may be partly explained by more risk-averse riders investing in ABS-enabled MCs or exhibiting lower riding distances. Alternatively, such owners may travel more than others, and enjoy a greater-than-37% reduction in their death rates. More details are needed to disentangle such results. ABS can also be integrated with systems that electronically apply optimal braking to front and rear wheels (*12*), rather than relying on an operator's snap judgment to properly balance braking in critical situations. Hurt et al. (*13*) confirmed that riders often under-brake their front and over-brake their rear wheels which may cause loss of steering or total control. Additional emerging motorcycles safety enhancements include gyroscopic stability control, a feature that could reduce the probability of motorcycle run-off-road crashes, rollovers and overturns, comprising 30% of fatal motorcycle crashes in 2010 (*14*).

Space Consumption and Congestion

While safety impacts are a key MC concern, it is important to view each mode holistically. A second major difference between MCs and other vehicles is the amount of space they require. For example, motorcycle parking spaces measure approximately 4 ft x 8 ft, rather than 8.5 ft x 18 ft for cars and trucks (*15*). This 76% savings (not accounting for access and egress paths) allows for more efficient use of limited space, particularly densely developed areas. Litman (*16*) estimates total urban and CBD parking costs to lie between $1000 and $4400 per light-duty-vehicle space, per year in North America, depending on location and type of parking facility. With approximately four motorcycles per standard space, economic benefits of roughly $750 to $3300 may be realized for a motorist switching to a motorcycle who regularly parks downtown.

Research also shows how motorcycles impact traffic flows. Yperman (*17*) noted that during free-flow or near free-flow conditions, motorcycles in Europe and Asia behave like other vehicles, meriting a passenger car equivalency (PCE) value of 1. However, if and when traffic comes to a stop, he posits that MCs will be driven between travel lanes or on shoulders and may exhibit a PCE value of 0. Yperman estimated that a motorcycle's PCE ranges between 1 and 0.5 (motorcycles per passenger car) for moderately to more heavily congested traffic conditions (before motorcyclists may begin to drive between lanes, as allowed in Europe but generally not in the U.S.). He suggests a PCE value of 0.5 for most applications. Additionally, all state laws permit motorcycles to use high occupancy vehicle (HOV) lanes with just a single rider (*18*).

While these values can mean substantial travel savings for everyone, MCs' higher crash rates can counteract such benefits, by adding incident-related delays. The FHWA (*19*) estimates that 25% of U.S. congestion comes from is attributable to traffic incidents (including crashes, vehicle breakdowns, weather and other events), indicating that increased motorcycle use should lead to more incident-related traffic delay. Nevertheless, a holistic perspective of mitigation and contribution to traffic congestion points towards a net mobility benefit when switching towards greater motorcycle use.

Fuel Use, Energy, Emissions and Noise

Energy, emissions and noise also are important points of comparison, across modes, vehicle makes and models, routes, and riding/driving behaviors. Smaller motorcycles with less powerful engines typically achieve higher fuel economy and produce fewer emissions, while larger motorcycles and engine sizes can result in worse fuel economy and higher emissions than evident in many cars. Aggressive riding or driving will also consume more fuel and generate more emissions.

A sampling of 229 recent MC models returns fuel economies between 26.6 and 123 miles per gallon (mpg), with a simple (non-sales-weighted) average of 53 mpg (*5*). Chester and Horvath (*20*) estimated a 41 to 45 mpg average MC fuel economy, versus 33.7 and 25.1 mpg for new U.S. passenger cars and light trucks, respectively (and existing-fleet averages of 23.8 mpg and 17.4 mpg, respectively) (*21*). Of course, most such vehicles can hold 4 persons or more, though Santos et al. (*22*) estimate average U.S. vehicle occupancies of 1.67 persons per private vehicle trip. The new Zero S fully electric motorcycle greatly surpasses the most energy-efficient autos, with manufacturer-estimated fuel economy of 487/273 mpg (city/highway) equivalent for electric operation, using EPA (*23*) recommended methodology. This may be compared to the Toyota Prius C, which operates at 53/46 mpg, and the Chevrolet (hybrid-electric) Volt, stickered at 95/93 mpg equivalent for electric operation (*24*). The electric Zero S is also a very low-noise vehicle, but presumably no safer than other motorcycles.

Chester and Horvath (*20*) estimate that 2- and 4-cylinder motorcycles require 30% less energy (per person-mile traveled [PMT]) than pickup trucks and 15% less than sport-utility vehicles (SUVs), though they consume 17% more energy when compared to 4-door cars (sedans). Most energy savings are due to lower operating costs. Chester and Horvath assume higher MC manufacturing energy needs (per PMT) due to MCs' lower annual mileages and lifespans. If one assumes *equal* annual miles-traveled by all modes, lower energy consumption from MC parking, and equal energy usage for insurance, road construction, and lighting, MCs are estimated to use

4%, 31% and 42% less energy than cars, SUVs and pickups, respectively, over their lifetimes (pivoting off Chester and Horvath's [*20*] energy results).

Chester and Horvath (*20*) also computed and compared modal emissions based on 14 source categories, ranging from manufacture and operation to evaporative losses and various infrastructures. Table 1 illuminates differences in Chester's and Horvath's (*20*) *running* emissions, which are aggregate values reflecting results of multiple studies from the U.S., Asia, and Europe. Emissions are reported for MCs with and without emissions controls, like catalytic converters, secondary air injection, and electronic fuel injection. Such controls have been necessary for many new models to meet EPA standards that took effect in 2010.Though some newer models may satisfy EPA standards without catalytic converters (and reduce emissions by other means like more efficient fuel injection), manufactures such as Harley-Davidson have included catalysts on all newer models since 2010.

Several conclusions may be drawn from this evaluation. First, sports bikes perform worst among MCs, and 2-cylinder MCs generally perform better than 4-cylinder MCs. Emissions controls typically halve VOC, NOx and CO emissions, but have no impact on other emissions.When comparing 2- and 4-cylinder MCs to other vehicles, MCs produced lower running emissions (per PMT) for GHG (26% to 64% reductions), SO2 (27% to 64% reductions), NOx (30% to 98% reductions), and PM (21% to 65%). Their VOC emissions rates, however, are uniformly higher (173% to 2400% higher), as are CO rates when operating without a catalytic converter (73% to 341% higher).

Emissions regulations imposed on manufactures ultimately drive down U.S. emissions rates. Interestingly, the US EPA (*25*) allows MCs to have far higher emissions than it does LDVs (in part because of MCs' relatively low usage and the costs of testing so many small-sales vehicles). For example, MC engines tested at 18,600 miles of use can emit up to 1.29 grams per mile (gpm) of any combination of hydrocarbons (HC) and NOx, while the most polluting LDVs are restricted to no more than 0.018 gpm of hydrocarbons and hydrogen oxide (HCHO) and 0.2 gpm of NOx. MCs are capped at 19.3 gpm of CO, compared to LDVs' 4.2 gpm. Furthermore, the EPA regulates LDVs' non-methane organic gases (NMOGs) and PM emissions, but sets no such requirements for MCs. Motorcycles are also exempt from smog checks, though agencies like the California Air Resources Board (CARB) have previously proposed such legislation. Many imported MCs conform to Euro III exhaust standards, which are more stringent than EPA standards for most pollutants (*26*). European standards are also set to become more stringent (the Euro V standard) by 2015, with maximum CO emissions for MCs to be 5.1% and 12.4% of current EPA standards on HC and NOx, respectively. While motorcycles only comprise a small proportion of US travel (3% of registered vehicles and 0.7% of VMT in 2009 [*2*]), reducing MC emissions appears to be low-hanging fruit, if the US wishes to make continued gains towards improving air quality. Before pursuing such regulatory changes, however, implementation cost considerations should be examined in detail. Regulatory changes should also be enforceable, and enforced. CARB (*27*) noted that over one-third of on-road motorcycles had their OEM exhaust systems replaced by aftermarket pipes, which likely involved permanent removal of the catalytic converter, negating many required emissions improvements.

In addition to possible emissions impacts, removing exhaust pipes can impact MC noise. Though noise's external costs are difficult to quantify objectively, many sources, such as Eriksen (*28*), EEA (*29*), and Cotana et al. (*30*), cite MCs as having significantly greater noise costs than LDVs. For example, Delucchi and Hsu (*31*) estimate MC noise costs at 2 to 8 times those of LDVs, and Litman's review (*32*) characterizes noise costs as $0.132 per MC mile in urban areas, or 10 times greater than those of LDVs.

Motorcyclists can purchase a wide variety of aftermarket exhaust pipes to improve engine performance, add power by lowering weight, or simply customize their MC's engine sounds. Such pipes may not meet EPA noise standards of 80 dB (measured at 50 feet, with constant engine speed at 50% maximum RPM) (*33)* and they can be further modified by removing or changing baffles within the muffler. Such modifications are difficult to identify when enforcing regulations, especially since sound level meters are rarely used to enforce noise laws. For instance, Frisman (*34*) noted how in 2002 less than 4% of Connecticut's motorcycle-noise violators were cited for "exceeding decibel limits;" the remaining 96% were for cited for "causing unnecessary noise" (44%) or having "improper/defective mufflers" (52%).In-use requirements are left to U.S. states, which often set their own standards and testing procedures. Ten states regulate noise in the 80 to 88 dBA range, three have noise limits of 90 dBA or more, 15 states have no statewide MC noise regulation, and the remainder require a muffler and/or prohibit aftermarket exhaust systems altogether (*35*). However, since testing methodologies vary, based on measurement distance and engine RPMs, these limits are difficult to compare objectively. The American Motorcycle Association advocates a standard methodology using the Society of Automotive Engineers' SAE J2825 test, with passing noise limits up to 100 dBA for motorcycles with 3- and 4-cylinder engines (*35*). This test requires a decibel-meter, a tachometer, and other basic testing materials. Though these resources may not be available to some small local police agencies, the test provides a consistent and simple approach to standardized testing that is approved by most motorcycle riders, and provides a step more comprehensive noise regulations. The test was officially adopted in Maine (*36*) and New Hampshire (*37*) and is reportedly being used by a handful of cities across Canada (*38*).

Of course, having laws in place and enforcing them can mean two very different things. California's SB 435 was challenged for its required MC smog checks, so its focus changed to cracking down on loud exhaust pipes. After this version of SB 435 passed in 2010, state law enforcement officials were granted power to cite riders without EPA-certified stickers on 2013- and later-year models (*39*). Without consistent and easily enforceable noise regulations across the U.S., most violations may be treated case by case, since many noise complaints derive from quiet neighborhoods, where a single, known MC owner can create local issues and be uniquely identified.

MOTORCYCLIST ATTRIBUTES

To strengthen this review of MC's costs and benefits, a nation-wide crash-histories survey was developed by the authors and disseminated online by Survey Sampling International. 1257 American adults were randomly selected, 246 of whom were motorcyclists (current and past riders), enabling an assessment of differences in MC riders and non-riders. The survey purposely over-sampled MC riders, and MC registrations comprised one out of 18 reported household vehicles across the sampled population, compared to a U.S. rate of one in 30 vehicles (*1*). All 246 "riders" were then sorted according to riding frequency (riders who ride or previously rode almost every day [daily], about once a week [weekly], about once a month [monthly], or less than once a month [yearly]) and according to ownership status (current motorcycle owners [owners], current riders who are not current owners [current riders], and former motorcycle owners who no longer ride [former owners]).

Former riders were asked why they no longer own a motorcycle. Top responses included simply no longer needing a motorcycle (38 offered this as their primary reason, and 33 offered it as their second reason), safety concerns (30 and 41 respondents, for primary and secondary reasons, respectively), and cost or other financial issues (20 and 17, respectively). Among those noting safety issues, 6 persons remarked being personally involved in a MC crash, a number cited friends who had been hurt, someone noted, "too many nuts in cars on the road", and one sadly remarked, "too many friends died on bikes." Additional issues that respondents noted included (in order of importance) a lack of riding enjoyment, lack of cargo space, lack of adequate riding ability, lack of passenger space, aging-related issues, and moving across the country.

Table 2 details respondent characteristics, riding habits, perceptions and habits, with the "all motorcyclists" category representing results for the 222 who responded to all questions and the "non-motorcyclists" category representing those who have never owned a motorcycle or ridden one on a frequent basis. Weights were used to account for the (full) sample's over-representations of women (originally 65% of survey respondents) and motorcycle ownership. For more motorcyclist details (and behavioral predictions), see Fagnant and Kockelman (*9*). For more crash-related statistics (and behavioral predictions), based on the larger sample, please see Chen and Kockelman (*40*). For detailed text of questions asked, please see www.caee.utexas.edu/prof/kockelman/public_html/SURVEY_UScrashhistories_Spring2012.pdf.

Table 2 values offer several meaningful results. For example, riders are well represented in all riding-frequency categories, though a plurality were weekly riders. More motorcyclists are former owners than current owners or current riders, and males are heavily represented among all MC status categories and all riding frequencies. Motorcycling respondents reside in slightly larger households (both children and adults), with higher proportions that are married and full-time workers.

Respondent motorcyclists report an average of 15 years of riding experience and 3680 miles riding each year, with those who ride more often averaging greater annual mileage and have generally been riding longer. Trip lengths vary substantially between the groups, with average trip lengths increasing as riding frequency falls.

Only 8% of motorcycle riders use their motorcycle primarily for work, school and errands-related travel (i.e., non-discretionary travel), while the remainder is split between primarily recreational and leisure travel, and a roughly equal combination of non-discretionary- and recreation-related travel. Daily riders, however, are most likely to ride for functional purposes only, and only 10% likely to ride solely for recreational purposes. Most riders (62%) also generally ride in groups, with only 15% typically riding alone and the remainder stating that they often ride both alone and in groups.

Less than a third of respondents report having received formal MC training. Daily and yearly riders, along with former MC owners, report the lowest training rates, the latter of which suggests that motorcycle training rates may be *in*creasing among riders. 72% of respondents report always wearing a helmet, and only 6% never wearing one. Similarly, 93% of respondents state that they would wear a helmet if legally mandated, which is more than NHTSA's (*6*) 84% observation of total use (in states requiring helmets). Just-yearly riders report the highest helmet use rates (88% report "always"), while current riders appear the least likely to always wear a helmet (62%). Since 21% of these current riders report usually wearing a helmet, it is possible that they prefer to use a helmet, but rely on others to borrow or rent one when riding, and/or forgo a helmet on shorter or recreational trips, where they anticipate fewer hazards.

Respondents' MC engine sizes vary from under 100 cubic centimeters (cc) to 2200 cc, with an average engine size of roughly 760 cc. Ownership status suggests that engine sizes are rising, with current owners reporting much larger sizes (1073 cc engines, on average) when compared to former owners (592 cc average), with current riders falling between (855 cc), possibly because some are reporting a previously owned motorcycle engine size and others report on MCs recently borrowed or rented.

Motorcyclists report driving or riding about 0.5 mph faster than non-motorcyclists, on average (a result that is statistically significant at the 10% level). One sees a trend of riding or driving slower and valuing safety more as a respondent's riding frequency falls, with average speed over the posted limit down 24% and willingness-to-pay for safety up 156%, when comparing daily riders to yearly riders. Motorcyclists support impaired-driver policies, such as mandatory ignition interlocks for persons convicted of one and two or more DUI convictions, at (statistically) higher levels than non-motorcyclists. There was no statistically significant difference in their support of (or opposition to) other safety-related policies, including red light cameras, automatic speed enforcement, speed governors, or vehicle impoundment for DUI offenders.

Forecasting Motorcycle Rider Status

A multinomial logit (MNL) model (see, e.g., McFadden [*41*] and Greene [*42*]) was used to investigate which types of people are more likely to ride a MC. This model was chosen because it may be used as an effective tool where persons are making discrete choices, such as whether to own a motorcycle.

Four categories of individuals were assessed as previously discussed, including current MC owners, current riders, and former MC owners. Weights were applied based on gender and motorcycle ownership, as noted in the previous subsection. Stepwise elimination was conducted on potential explanatory variables using Biogeme software and a maximum likelihood estimation process until only variables statistically significant at a 5% level or better remained (so variables like Age, Years Licensed, Number of Children and Commercial Drivers Licensing were removed). Elasticities were also estimated for each covariate to determine practical significance by increasing variable values by 1% and observing resulting changes in motorcycle status likelihood. The resulting model and coefficient elastic impacts are shown in Table 3.

Model coefficients may be interpreted to understand which types of persons are more likely to own motorcycles, be current riders or former motorcycle owners. As expected, model results highlight how men are more likely than women to own and/or ride a MC at some point in their life, with male gender emerging as the single most influential parameter for current riders and former owners. Singles are estimated to be less likely than married persons to ride or have owned a motorcycle, everything else constant (including age and gender). This may be due to higher disposable incomes in two-earner households and/or joint ownerships (where a spouse claims to own the MC even though his/her partner may be the primary rider). In contrast, divorced individuals are more likely to be current MC owners (passenger and cargo needs would be lesser in their new family arrangement) and former owners (possibly because their spouse got the motorcycle in the divorce). For similar passenger and cargo reasons, as the number of adults in a household increases, the model results suggests less likely (current) ownership.

Those with higher levels of education were estimated to be less likely to be current or former motorcycle owners, while those with high household incomes (over $150,000 per year) were more likely to be current riders. The high income-current rider connection likely represents a greater ability of these individuals to afford renting or leasing a motorcycle. In contrast, unemployed individuals were less likely to be current riders, also possibly due to financial considerations. Retired persons appear less likely to be current riders, which may be linked to decreasing physical ability. However, retirement may have a net-neutral impact on ownership since retired individuals have more time for riding (and lower cargo and passenger needs) and may purchase a motorcycle when they previously rented one.

Finally, persons with more traffic violations on their records are estimated to be less likely to be current MC owners or riders, while those who at one point had licenses suspended are *more* likely to be a rider, ceteris paribus. Presumably, those who are more likely to engage in higher risk behaviors, such as MC riding, are (on average) more likely to engage in behaviors that may result in a license suspension or revocation. After controlling for that variable, costly violations in one's past may reduce disposable income previously available for leisure-oriented riding.

The crash-histories survey, described above, gives one a sense of "who rides" (and how often, for example). This paper now turns to the question of "who pays?", by pursuing a benefit-cost analysis.

A BENEFIT-COST ASSESMENT

To comprehensively view motorcycle travel from a holistic perspective, it is crucial to understand both who rides and what the personal and societal impacts are from this unique mode. In order to better understand these impacts, various MC designs and operator assumptions were evaluated against multiple LDVs. Comparisons reflect differences in crash frequencies and costs, congestion impacts, parking requirements, ownership costs, air pollution, and noise, under multiple driving environments. Comparisons allows for variations in rider behavior and experience (i.e., helmeted vs. non-helmeted, and novice, average, skilled) for four levels of roadway congestion. Benefit-cost ratios (B-C) summarize the relative utility of switching from a

PC or LDT to a motorcycle mile per mile, or as one's primary vehicle. All values are in 2012$ unless otherwise noted.

Vehicle makes and models can vary considerably, but top sellers tend to dominate many markets. This analysis considers the top-10 selling passenger cars and light-duty trucks for year 2010 (*43*) and 10 motorcycles, selected from the U.S.'s top-five selling brands (Harley-Davidson, Honda, Yamaha, Kawasaki, and Suzuki) (*44*). These "top 10" MCs offer an even mix of cruisers and sport bikes (with cruisers typically representing heavier motorcycles, where riders sit relatively upright, and sport bikes tend to be lighter, faster, and more maneuverable). Motorcycles are evaluated as a perfect substitute and thus primary mode of travel, so they are evaluated on the same VMT as LDVs (which average 11,000 miles of use per year in the U.S. [*1*]), which places them at a disadvantage, due to lower expected lifetimes (measured in total miles traveled before vehicle retirement/loss). Chester and Horvath (*20*) suggest that the average LDV covers 176,000 to 187,000 miles during its lifetime, while sport bikes and cruisers average only 60,000- to 75,000-miles, respectively. This distinction results in higher per-year ownership costs for motorcycles, versus LDVs, across the sample of 20 vehicles considered, despite motorcycles' 47% to 63% lower purchase prices (versus the average car and light-truck, respectively). Table 4 also considers maintenance, tires, and insurance costs to be ownership costs, based on AAA's (*45*) annual Driving Costs guide for cars and light trucks, and Chester and Horvath's (*20*) estimates for MCs.

LDVs' NOx, VOC, CO, and $PM_{2.5}$ running emissions were estimated with EPA's (*24*) Green Vehicle Guide air pollution scores and valued using guidance from NHTSA's (*46*) Corporate Average Fuel Economy (CAFE) analysis ($4,400 per ton of NO_x, $1,887 per ton VOC, $168,480 per ton $PM_{2.5}$ and Ozbay and Berechman's (*47*) valuation of CO (at $20 per ton). MC emissions assumptions are those used by Chester and Horvath (*20*) for two- and four-cylinder MCs with catalytic converters (since most manufacturers began employing catalysts or similar emissions-reducing technologies to meet current EPA standards by 2010 [*27*]). Emissions modeling software (EPA's MOVES and CARB's EMFAC) were also run, at the national and state (California) levels, to confirm these estimates. Though there was some variation across results, air quality costs are minimal relative to other costs in this comparison, so Chester and Horvath (*20*) aggregate rates are used, reflecting multiple sources and some real-world data.

Carbon dioxide (CO_2) impacts are calculated using average combined fuel economies, assuming 19.4 pounds of CO_2 are released per gallon of gasoline burned (*48*) at a cost of $50 per ton, based on guidance from Lemp and Kockelman (*49*), EPA (*50*), CRA (*51*), and Fisher et al. (*52*). Though this analysis considers only running (tailpipe) emissions, rather than life-cycle costs, MCs are estimated to be less costly to society in terms of *carbon* emissions, thanks to higher fuel economy. Higher fuel economy also translates to reduced operating costs, which are calculated assuming a summer 2012 U.S. gasoline price of $3.50 per gallon (*24*).

Comprehensive crash costs were estimated using USDOT guidance (*53*), with pure market impacts (excluding non-economic factors such as the value of life and pain and suffering) estimated by NSC (*54*). The largest non-market crash impacts were for fatalities, with comprehensive (market and non-market) fatal crash costs reaching $6.2 million, compared to just $1.45 million from market impacts. Crash rates were obtained from NHTSA (*1, 2*), with injury-severity distributions and property-damage-only crash rates estimated using NHTSA's 2010 GES database. At-fault allocations by injury severity were estimated from Kim and Boski's findings (*55*), based on 2774 multi-vehicle motorcycle crash records in Hawaii.

As discussed earlier, noise costs are based on Litman's (*32*) aggregate assessment of noise by vehicle class in urban areas, which considers estimates by Delucchi and Hsu (*31*), Maibach et al. (*56*), and others. Motorcycle parking-space savings are evaluated using annual surface-parking cost estimates for urban locations from Litman (*16*). Each parking space is assumed to hold either one LDV or four motorcycles, as discussed earlier (*15*).

Finally, congestion costs between vehicle types are compared under the assumption that light trucks, passenger cars, and MCs hold unique PCE values. Kockelman and Shabih (*57*) estimated through-traffic PCE for small SUVs and pickups at 1.07 and 1.14, respectively, by measuring mean headways and delays for vehicle types departing congested intersections. Motorcycle PCE values were assumed at 0.5, as suggested by Yperman (*17*) and Maibach et al. (*56*). Congestion costs for each vehicle type are estimated for three levels of freeway congestion (v/c ratios of 0.7, 0.9, and 1.1), using a variation of the Bureau of Public Roads (BPR) link-performance equation and methods found in Lemp and Kockelman (*49*):

$$CongestionCost = t_f \times \alpha \times \left[\left(\frac{Volume + PCE_i}{Capacity}\right)^{\beta} - \left(\frac{Volume}{Capacity}\right)^{\beta}\right] \times Volume \times VOTT \times p$$

where t_f is free-flow travel-time (over one mile distance), α and β are link-performance parameters (assumed to be 0.84 and 5.5, respectively [*58*]), p is the share of VMT users experience this congestion level (assumed to be 10%), with no congestion impacts or benefits (v/c values under 0.6) the rest of the time (i.e., 90 percent of a traveler's miles traveled), and $VOTT$ is value of travel time (assumed to be $10.87 per person-hour, based on half the 2011 mean U.S. wage rate [*60.*]).

Motorcycles are estimated to provide sizable travel-time savings, similar to variations in the PCE values. While some congestion reduction can be expected by MCs' more compact size, the actual PCE is a highly variable number, as Yperman (*17*) noted, shrinking as speeds decline, and possibly converging on zero in situations where MCs can "filter" in between lanes, such as in many high-density developing cities and perhaps places like California, where some riders pass stopped vehicles, along a lane stripe. PCE values are expected to increase (well beyond the 0.5 assumed here) when traffic speeds rise, since MCs are given more space by following vehicles (and have no reason to tailgate or regularly pass others under uncongested conditions).
Table 4 compares the above cost categories for passenger cars, light trucks, and four categories of motorcyclists, corresponding to relative rider skill, awareness of safety, and risk taking behavior. The first three categories – novice, average, and skilled – seek to represent the wide range of riders on the road, including those who defy average statistics by taking many precautions (e.g., wearing protective gear and taking training courses) or, conversely, neglecting such precautions and taking other risks (such as consuming alcohol before riding or driving recklessly). This range is represented by simply multiplying crash rates and thus costs by a factor of 0.5 for skilled riders and 1.5 for novice riders. While this range may extend further, to capture all types of riders, the +/- 50% scaling probably represents most riders. The fourth, "perfect

rider" category seeks to understand the relative crash costs imposed on motorcyclists by other drivers, by excluding single-vehicle crashes and multi-vehicle crashes where the rider is not at fault.

Benefit-cost ratios were computed based on the costs and benefits of using a motorcycle, relative to driving a PC or LDT. Since MC costs exceed MC benefits under all but one of the 32 scenarios (4 congestion levels across 8 vehicle/rider types) considered in Table 4 (due to high crash costs), an additional B/C ratio, excluding crash costs, is included for comparison. Finally, Table 4 reports the MC crash rate (relative to PCs or LDTs) that would be required to move the B/C ratio (including crashes) to equal 1. This metric indicates at which crash crate MCs become more costly to society as a whole (including their owners' costs) than their LDV counterparts. Crash costs (and B/C ratios which include crash costs) report values for both helmeted and non-helmeted riders, separated by a slash.

As Table 4 values suggest, motorcycles' various benefits appear to be severely negated by added crash costs, which, even for the skilled (and helmeted) riders (who can arguably reduce their accident risk by 50%), never return B/C ratios greater than 1. The sole exception to this distinction is helmeted riders in severe congestion, who never crash on their own and are never at fault in a multi-vehicle collision; but even under these very optimistic conditions, the B/C ratio is over one only when MCs are compared to LDTs. While motorcyclists may enjoy some reduced parking and operating costs, these do little to offset the fact that most current MC models are likely to provide fewer lifetime miles of travel than the average LDV (which shelters its interior from rain and other environmental factors, serves more travel purposes [such as multi-person trips], and is crashed less often). Though motorcycles do show greater benefit in highly congested situations, costs overshadow benefits when including crashes in all scenarios.

Depending on congestion conditions, MC crash costs must fall to a range of 0.8-2.2 or 1.8-3.6 times the crash costs of PCs and LDT, respectively, to become competitive with each vehicle type (i.e., provide a B/C ratio of 1.0, relative to the base LDV). With current MC crash costs 13 to 14.5 times greater than those of the average PC and LDT, MCs require substantial safety gains to improve competitiveness, with safety gains required not just to eliminate riders' own mistakes, but those of drivers as well. However, with greatly reduced crash rates and improvements in other areas (like emissions and noise), MCs may be able to reach (and surpass) benefits of LDVs. If emissions and noise costs were reduced to those of cars and LDTs, MCs' total costs (ignoring crash cost differences) should be substantially lower than those of passenger cars (and far below those of LDTs, which are already more costly due to their higher sales prices).

It should also be noted that MCs may never become reasonable substitutes for LDVs, due to their demands on rider balance, coordination, and stamina, while exposing riders to the elements, including poor climatic conditions. Mannering (*64*) refers to a 50- to 60-mile commute on a MC an "excruciating ordeal" for most people, especially in heavy traffic or during unpleasant weather.

CONCLUSIONS

This work conducts a comprehensive assessment of the benefits and costs of MC riding while exploring the characteristics, behaviors and attitudes of motorcycle riders, as well as factors that make individuals more likely to ride. Motorcyclists are at higher risk of crashing than passenger cars and light trucks, and the injury outcome is much more likely to be severe. At the same time, motorcycles have significant benefits for space savings, roadway capacity benefits and typically have superior fuel efficiency when compared to passenger cars and light trucks. Motorcycle life-cycle energy consumption is generally superior to SUVs and pickup trucks, though more consumptive than sedans. Motorcycle emissions profiles are also generally preferable for M gases, NOx, SO2 and particulate matter and less preferable for VOC and CO. Noise impacts are an issue with an inconsistent patchwork of regulation applied across states and localities.

The survey conducted in this investigation indicates most riders use their motorcycle for recreational purposes and ride in groups, though about half also use their motorcycle for functional purposes and about also 40% ride solo. Less than a third of the surveyed riding population received formal motorcycle training, though training rates appear to be increasing. Motorcycle helmet use appears lower among riders who currently ride but do not own their own motorcycle and motorcycle engine size appears to be increasing. Motorcycle rider respondents also showed strong support for policies that combat operating a vehicle under the influence.

In the motorcycle rider and ownership model, the most practically significant variables were male for all categories of motorcycle riders and the number of household vehicles for current motorcycle riders (both factors increasing likelihood), while the number of adults in a household was found to decrease the probability of current motorcycle ownership. The factors with the greatest impact on increasing riding frequency were riders who traveled for both functional and recreational purposes, and riders who had all their vehicles insured.

A benefit-cost analysis of switching from a PC or LDT to MC returned B-C ratios ranging from 0.07 to 0.59 when considering crash costs, and 0.91 to 3.22 when neglecting relative crash differences. While high MC crash rates do carry a high cost, even for the better/safer riders, lower vehicle lifespans and higher emissions and noise costs also limit MC values. The analyses also suggest that MC crash costs would have to fall to within 88% to 223% of PC rates and 181% to 369% of LDTs (rather than their present 1300% and 1450% levels [assuming 50% helmet use], respectively) to return B-C ratios of 1.0. While MCs' benefit-cost ratios doubled between uncongested (v/c = 0.5) and severely congested (v/c = 1.1) cases, they remained below 1 in all cases, unless the added crash losses of switching to an MC were ignored.

When examined as a whole, this work provides transportation analysts, policymakers and decision makers with key insights to the benefits, costs and overall implications of motorcycle use, while illuminating factors common to different types of motorcycle riders and common traits among those who ride more frequently. Motorcycles may provide many benefits to some riders, but their high external costs and increased crash risks dramatically limit their social value as a primary travel mode and limit their effectiveness in addressing continuing transport concerns: congestion, safety, and air quality.

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LIST OF TABLES AND FIGURES

Table 1: Running Emissions per Person-Mile Travelled

	GHG	VOC	SO2	NOx	CO	PM10
Motorcycle (2-cyl. no cat.)	150 g	5.0 g	8.6 mg	46 mg	29 g	27 mg
Motorcycle (2-cyl. cat.)	150 g	3.1 g	8.6 mg	23 mg	3.5 g	27 mg
Motorcycle (4-cyl. no cat.)	170 g	2.7 g	9.5 mg	370 mg	19 g	30 mg
Motorcycle (4-cyl. cat.)	170 g	1.2 g	9.5 mg	190 mg	9.5 g	30 mg
Motorcycle (sports bike)	270 g	4.4 g	15 mg	600 mg	30 g	48 mg
Gasoline sedan	230 g	0.20 g	13 mg	530 mg	6.9 g	68 mg
Gasoline SUV	270 g	0.23 g	15 mg	600 mg	6.8 g	61 mg
Gasoline pickup	420 g	0.44 g	24 mg	950 mg	11 g	72 mg

Table 2: Motorcycle Rider Characteristics

	Riding Frequency				Rider Status				
	Daily	Weekly	Monthly	Yearly	Owners	Current riders	Former owners	All MCs	Non-MCs
Daily riders	100%	0%	0%	0%	12%	9%	34%	22%	0%
Weekly riders	0%	100%	0%	0%	39%	38%	28%	33%	0%
Monthly riders	0%	0%	100%	0%	31%	36%	17%	26%	0%
Yearly riders	0%	0%	0%	100%	18%	17%	21%	19%	0%
Owners	12%	26%	26%	21%	100%	0%	0%	22%	0%
Current riders	12%	33%	40%	26%	0%	100%	0%	29%	0%
Former owners	76%	41%	33%	53%	0%	0%	100%	49%	0%
% Male	93%	79%	72%	67%	66%	82%	73%	79%	43%
Avg. income (Est.)	$61 k	$69 k	$72 k	$57 k	$63 k	$81 k	$58 k	$66 k	$60 k
Avg. # children in H.H.	0.23	0.81	1.39	0.59	0.54	1.38	0.54	0.79	0.54
Avg. # adults in H.H.	2.23	1.96	2.42	1.88	1.97	2.04	2.06	2.14	1.78
Avg. yrs. ed. post-H.S.	2.16	2.55	2.74	2.00	2.07	3.12	1.87	2.41	2.10
% Employed Full Time	41%	48%	53%	33%	40%	59%	33%	45%	31%
% Married	51%	63%	68%	70%	69%	60%	57%	63%	47%
Avg. # years riding	16.2	16.6	12.4	13.8	19.2	16.0	9.3	14.9	N/A
Avg. yearly miles	5497	3310	3045	1838	2972	3534	4039	3440	N/A
Avg. trip length (mi)	53	51	78	115	88	117	51	114	N/A
Work, errands, school	14%	1%	9%	10%	4%	6%	10%	8%	N/A
Recreation / leisure	10%	52%	54%	68%	45%	47%	47%	46%	N/A
Work & recreation	76%	47%	37%	22%	51%	47%	43%	46%	N/A
Ride alone	8%	21%	16%	19%	8%	22%	17%	16%	N/A
Ride in groups	61%	49%	68%	70%	65%	52%	65%	61%	N/A
Ride alone & in groups	31%	30%	16%	9%	27%	27%	18%	23%	N/A
Avg. # trainings	0.31	0.42	0.54	0.27	0.43	0.43	0.30	0.40	N/A
Formal training	24%	32%	40%	26%	29%	33%	25%	31%	N/A
Avg. years since training	6.7	5.7	5.2	2.3	4.5	5.1	4.7	5.1	N/A
Always wear helmet	67%	77%	67%	88%	84%	66%	75%	74%	N/A
Usually wear helmet	10%	8%	18%	7%	6%	19%	8%	11%	N/A
Sometimes wear helmet	14%	5%	5%	0%	4%	9%	6%	6%	N/A
Occas. wear helmet	2%	4%	2%	2%	2%	2%	4%	3%	N/A
Never wear helmet	6%	5%	9%	2%	4%	5%	7%	6%	N/A
Wear helmet if legally required	92%	96%	91%	95%	100%	88%	94%	94%	N/A
Avg. engine size (cc)	746	851	708	710	1058	863	631	801	N/A
Drive > spd. limit (mph)	3.55	3.49	2.75	2.70	3.65	2.37	2.91	3.17	2.60
Safety willingness to pay	$535	$894	$1,277	$1,370	$1,035	$899	$1,081	$1,017	$1,087
Ignition interlock support (1 DUI) [3]	4.33	4.15	3.67	4.00	3.95	3.81	3.82	4.04	3.57
Ignition interlock support (2+ DUI) [3]	4.61	4.56	4.37	4.26	4.45	4.24	4.18	4.46	3.99
#Observations (n_{obs})	49	73	57	43	58	68	120	222	1011

Table 3: Motorcycle-User Model Estimates (MNL Model)

Variable	Parameter Estimate				Elasticity Estimates			
	Not Rider	Owners	Current Rider	Former Owner	Not Rider	Owners	Current Rider	Former Owner
Owner (O) ASC	-	-5.16	-	-	-	-	-	-
Current Rider (CR) ASC	-	-	-3.92	-	-	-	-	-
Former Owner (FO) ASC	-	-	-	-3.03	-	-	-	-
Male Owner	-	1.02	-	-	-0.017	0.461	-0.046	-0.046
Male Current Rider	-	-	1.8	-	-0.090	-0.132	**1.225**	-0.160
Male Former Rider	-	-	-	1.45	-0.113	-0.165	-0.199	**0.920**
Single Owner	-	-1.98	-	-	0.004	-0.107	0.015	0.006
Single CR & FO	-	-	-0.772	-0.772	0.025	0.016	-0.118	-0.092
Divorced O & FR	-	0.687	-	0.687	-0.015	0.048	-0.014	0.088
# Adults in HH * Owner	-	-0.588	-	-	0.037	**-0.878**	0.069	0.069
Yrs. Education (Post HS) * Owner	-	-0.249	-	-	0.016	-0.386	0.036	0.027
Yrs. Education (Post HS) Former Owner	-	-	-	-0.18	0.042	0.049	0.065	-0.330
Income > $150k * CR	-	-	1.1	-	-0.008	-0.015	0.100	-0.009
Unemployed * CR	-	-	-1.07	-	0.004	0.004	-0.055	0.006
Retired * CR	-	-	-1.37	-	0.008	0.020	-0.126	0.019
# HH Vehicles * O	-	1.73	-	-	-0.131	**3.211**	-0.282	-0.262
# HH Vehicles * CR & FO	-	-	0.372	0.372	-0.104	-0.237	0.452	0.472
# Violations * O & CR	-	-0.226	-0.226	-	0.011	-0.071	-0.098	0.019
Susp. / Revoked Lic. * O & FO	-	0.86	-	0.86	-0.012	0.060	-0.060	0.094
Susp. / Revoked Lic. * CR	-	-	1.8	-	-0.024	-0.053	0.370	-0.060

Adj. ρ^2: 0.514 Log-Lik: -668.004 $n_{obs} = 1022$

Table 4: A Benefit-Cost Assessment of Switching to MC from PC or LDT

			Motorcycle Benefits				*Motorcycle Costs*				*B/C ratios of MC relative to PC or LDT*				*Maximum Crash Rate for B/C (b) to equal 1 Relative to LDV Mode*	
Congestion Level	*Vehicle / Rider Class*		*Congestion ($)*	*CO_2 ($)*	*Fuel ($)*	*Parking ($)*	*Air Quality ($)*	*Noise Costs ($)*	*Owner-ship Costs ($)*	*Crash Costs* ($)*	*(a) Without Crash Costs*		*(b) With Crash Costs**			
											PC	*LDT*	*PC*	*LDT*	*PC*	*LDT*
Minimal Congestion (v/c = 0.5)	Passenger Car		18	194	1,398	2,127	27	159	2,790	1,721	-	-	-	-	-	-
	Light Truck		20	298	2,149	2,127	28	159	3,388	1,541	-	-	-	-	-	-
	Motorcycle	Novice	9	115	832	532	193	1,612	3,632	29,377 / 41,696	0.91	1.67	0.07 / 0.05	0.10 / 0.07	88%	181%
		Average								19,585 / 27,798			0.11 / 0.08	0.16 / 0.11		
		Skilled								9,797 / 13,899			0.21 / 0.15	0.31 / 0.22		
		Perfect								4,626 / 6,566			0.42 / 0.31	0.63 / 0.45		
Moderate Congestion (v/c = 0.7)	Passenger Car		130	194	1,398	2,127	27	159	2,790	1,721	-	-	-	-	-	-
	Light Truck		146	298	2,149	2,127	28	159	3,388	1,541	-	-	-	-	-	-
	Motorcycle	Novice	65	115	832	532	193	1,612	3,632	29,377 / 41,696	0.94	1.71	0.08 / 0.05	0.11 / 0.08	91%	185%
		Average								19,585 / 27,798			0.11 / 0.08	0.16 / 0.11		
		Skilled								9,797 / 13,899			0.22 / 0.16	0.31 / 0.22		
		Perfect								4,626 / 6,566			0.43 / 0.31	0.64 / 0.46		
Heavy Congestion (v/c = 0.9)	Passenger Car		775	194	1,398	2,127	27	159	2,790	1,721	-	-	-	-	-	-
	Light Truck		870	298	2,149	2,127	28	159	3,388	1,541	-	-	-	-	-	-
	Motorcycle	Novice	387	115	832	532	193	1,612	3,632	29,377 / 41,696	1.07	1.92	0.09 / 0.06	0.12 / 0.09	110%	211%
		Average								19,585 / 27,798			0.13 / 0.09	0.18 / 0.13		
		Skilled								9,797 / 13,899			0.25 / 0.18	0.35 / 0.25		
		Perfect								4,626 / 6,566			0.49 / 0.36	0.73 / 0.52		
Severe Congestion (v/c = 1.1)	Passenger Car		4,670	194	1,398	2,127	27	159	2,790	1,721	-	-	-	-	-	-
	Light Truck		5,243	298	2,149	2,127	28	159	3,388	1,541	-	-	-	-	-	-
	Motorcycle	Novice	2,334	115	832	532	193	1,612	3,632	29,377 / 41,696	1.86	3.22	0.15 / 0.11	0.20 / 0.14	223%	369%
		Average								19,585 / 27,798			0.23 / 0.16	0.30 / 0.21		
		Skilled								9,797 / 13,899			0.43 / 0.31	0.59 / 0.42		
		Perfect								4,626 / 6,566			0.85 / 0.63	1.21 / 0.85		

*Note: Slash-separated cell data report helmeted / un-helmeted riders.