Exploring First-Order Approximation of Energy Equivalence of Safety at Intersections

Preprint

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Exploring First-Order Approximation of Energy Equivalence of Safety at Intersections

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ABSTRACT

Maintaining safety is the most critical issue for a transportation system. Other considerations, albeit of secondary importance to safety, include energy use and delay. Quantifying the economic and societal costs of traffic crashes is an important area of study, and covers financial, energy and human impact considerations. Consequences of crashes include losses associated with crash-induced congestion, costs due to equipment damage and loss, and human injury and death. This study establishes the GDP-weighted energy equivalence of safety—encompassing the energy consumption associated with crashes. It proposes a framework for this calculation by extracting an equivalency rate from national-level statistics on total energy consumption of the transportation sector. Combining this with estimates of total direct and indirect costs of all crashes permits an estimation of their total GDP-weighted energy equivalence. The framework is demonstrated with an example calculation for the U.S. highway system in 2010. The results imply the tremendous potential energy value of technologies that promise to reduce or eliminate crashes.

INTRODUCTION

Safety is the top priority for reliably servicing travel demand in transportation systems. All types of motor vehicle crashes, such as vehicle-to-vehicle, vehicle-to-pedestrian, or vehicle-to-roadside, can lead to severe consequences, including loss of life, injury, associated losses of productivity and quality of life, and property damage. Researchers have extensively studied crash impacts from the perspectives of crash prevention, collision response, and economic and societal impacts (Chang). Patterned after these works and relying on their results, this study establishes a framework for the energy equivalence of safety and applies it to develop an initial estimate of the total GDP-weighted energy equivalence.

Emerging technologies, such as connected and automated vehicles and enhanced spatial sensing at intersections, can help avoid the occurrence of collisions as well as promote efficient traffic flow by improving operations, resulting in economic and energy benefits. An estimate of the energy equivalence of safety is needed to fully understand the energy consequences of these technologies, similar to what has been achieved for understanding the economic and societal impacts of crashes. Of particular note, about 50% of all crashes occur at intersections, and intersections experience a higher number of severe crashes (such as right-angle crashes). At the same time, many new technologies are being introduced that are anticipated to considerably improve intersection operations and safety performance.

To this end, this paper introduces a framework for estimating the GDP-weighted energy equivalence of safety at intersections. This framework starts from economic loss estimates, which specify costs in terms of direct and indirect impacts. Direct impacts encompass activities induced by the crash within an immediate time frame (such as congestion and emergency response) along with the immediate consequences of the crash (such as vehicle loss or personal injury recovery).

Estimates of such costs are well documented. Indirect impacts are less tangible—these include personal pain and suffering, loss of quality of life, and willingness to pay to avoid crashes or reduce their severity. Although harder to calculate, such costs are a burden on society, and their value can be estimated. Meanwhile, the statistics on overall national energy consumption by different economic sectors offer a way to estimate the amount of energy per dollar that is consumed in the transportation sector. Combined with the economic value of crash impacts, it is possible to estimate the total energy costs related to all crashes, which can be further broken down by crash severity and location. This study proposes such a framework and applies it to obtain an initial estimate of the full energy impacts of crashes, which implies the potential for the full energy of impacts of technologies that improve roadway safety, should those technologies someday be able to eliminate crashes altogether.

MOTOR VEHICLE COLLISIONS AND IMPACT

Crashes disrupt the transportation system, causing traffic congestion, and result in potentially severe economic and societal consequences arising from fatalities, injuries, property damage, and loss of productivity, among other impacts. For example, in the United States in 2010, 32,999 people were killed, 3.9 million people were injured, and 24 million vehicles were damaged in crashes (Blincoe 2015). The direct economic cost of those crashes totaled $242 billion, accounting for about 1.6% of the U.S. gross domestic product (GDP) for the year (Blincoe 2015). In general, crash rates have declined over time, although there have been recent increases. Figure 1 shows crash rates per capita from 2003 to 2016, which shows that the overall numbers have decreased, but those improvements reversed in the last couple years (Rocky Mountain Insurance Information Association 2015).

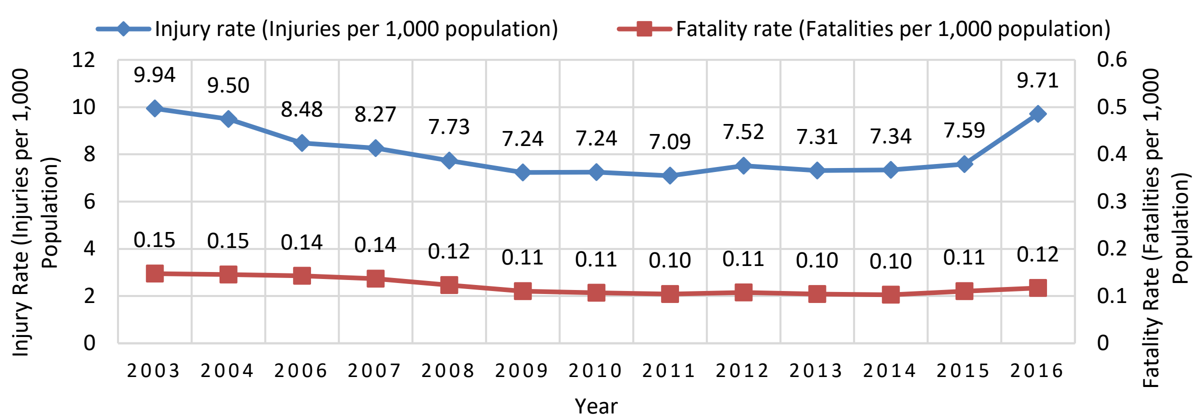

Figure 1. Injury and fatality rates over time.

Transportation agencies and research institutes have carried out abundant research to analyze the impacts of motor vehicle collisions on freeways and major arterials (Chang and Rochon 2009, De Leur 2010). In the United States, most motor vehicle crashes are reported in the National Highway Traffic Safety Administration (NHTSA) Fatality Analysis Reporting Systems (FARS) (NHTSA 2018a) or the National Automotive Sampling System General Estimate System (NHTSA 2018b). The economic cost of vehicle collisions has been studied extensively using data from these databases.

The economic impacts of crashes include both direct and indirect costs, as summarized in

Table 1.

- **Direct costs** refer to tangible and internal costs directly attributable to crashes, including costs related to property damage, medical rehabilitation, and induced congestion. These costs are relatively straightforward to estimate.
- **Indirect costs** are those costs *not* directly linked to crashes, usually including the following two components:
    - **Human capital** (HC) cost is the person-correlated cost associated with loss of long-term future net production (i.e., the difference between future production and future consumption (De Leur 2010)) due to the loss of work capability because of an injury or fatality. Human capital cost measures the value of a person's contribution to society through labor. The loss of human capital includes discounted future earnings and an estimate of the cost related to human suffering. Although challenging to estimate accurately due to the diverse social and economic characteristics of people, it is an agreed-upon method to evaluate the economic consequences of injury and death.
    - **Willingness-to-pay** (WTP) cost is the price that a society (or a person) is willing to pay to avoid the risk and occurrence of fatal and injury crashes. Its value depends on what kind of preventive measures will be applied to the transportation system and the cost of adoption for road users. The intangible WTP costs are estimated according to the value of a statistical life (VSL).

Table 1. Crash Economic Impacts Items and Their Types

Type	*Items*
Direct impacts	Medical costs
	Emergency medical services (EMS)
	Lost productivity (immediate)
	Workplace losses
	Insurance administration costs
	Legal and court expenses
	Congestion costs
	Property damage costs
Indirect impacts	HC cost
	WTP cost

Crashes can be categorized as fatal, injury, and property damage only (PDO) collisions. An example of the cost distribution across injury classes and direct or indirect cost types from a study from Alberta, Canada (De Leur 2010) is summarized in Table 2. Although this study is limited to a specific geographic region, some initial observations can be made. Generally, fatal crashes cost more than those of other types in both direct and indirect costs. Also, the indirect costs are significantly higher than the direct costs, especially for fatal collisions. The fatal crash indirect costs are one order of magnitude higher than the direct costs. For injury crashes, the indirect costs are several times higher than the direct costs. This indicates that the social and public cost of crashes cannot be ignored even though estimating indirect costs is challenging.

Table 2. Collision Cost Distribution across Collision and Cost Types for the Capital Region

	Fatal Collision	Injury Collision	PDO	Total
Collision frequency	43	8,517	51,822	60,382
Direct Cost	$181,300	$39,500	$10,900	$231,700
Indirect Cost (HC)	$1,669,100	$41,500	$0	$1,710,600
Indirect Cost (WTP)	$5,362,500	$95,000	$0	$5,457,500
Total	$7,212,900	$176,000	$10,900	$7,399,800

$: Canadian Dollar

A 2010 study by the National Center for Statistics and Analysis pointed out that the direct economic cost of all motor crashes in the United States totaled $242 billion while the comprehensive costs, including both direct and indirect costs, was equivalent to $836 billion (Blincoe 2015). The direct economic share for cost types is illustrated in Figure 2. Lost market and household productivity and property damage are the top two categories, together accounting for 63% of the total cost. Among direct costs, lost market and household productivity amounted to $77.4 billion while the property damage of all crash types totaled $76.1 billion. Congestion, including travel delay, excess fuel consumption, and emissions of greenhouse gases and criteria pollutants, accounted for $28 billion; medical expenses took $23.4 billion; and all others (including public revenue costs, average lifetime cost) totaled $37 billion (Blincoe 2015).

Several studies have estimated delay and waste of fuel due to congestion. In the United States, an average of 5.5 billion hours is wasted annually due to traffic congestion (recurring and non-recurring), which translates to about $121 billion in 2012 (Blincoe 2015). In 2015, congestion wasted 6.9 billion hours of driving and 3.1 billion gallons of fuel at the cost of $160 billion (Schrank 2015). Congestion related to bottlenecks and crash incidents respectively account for 40% and 25% of these costs.

Although costs due to congestion induced by crashes have been extensively investigated, the *overall* energy consequences of crashes (that is, going beyond the fuel wasted in the induced congestion) are not well understood. As shown in Figure 2, of the total economic impact of crashes, only 12% is associated with congestion impact, leaving 88% in non-congestion related costs. Similarly, the non-congestion-related energy saving associated with crash avoidance is not accounted for when estimating impacts of new technologies. As revealed by the figures from these previous studies, the energy saving from non-congestion-related categories may be substantial.

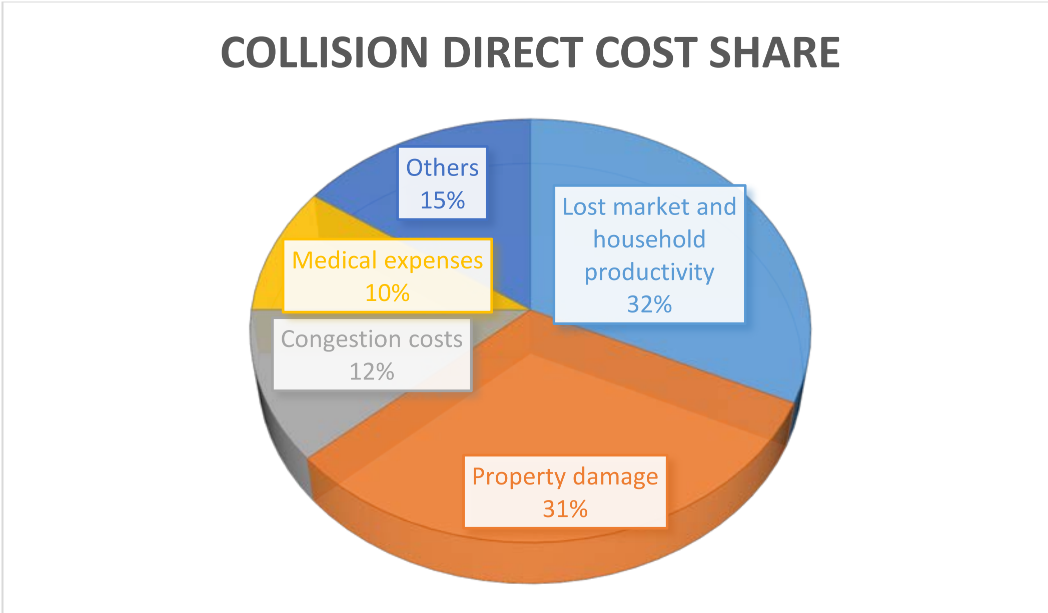

Figure 2. Collision direct cost share in 2010.

Three types of costs are carried forward in the energy equivalence of safety framework. Similar to economic impacts, the energy impacts are similarly framed as direct and indirect, with indirect costs attributed to HC and WTP.

Direct energy costs refer to the consequences directly linked to the crash, such as fuel wasted during induced congestion, energy expended to repair property damage or lost embedded energy of totaled vehicles, energy impacts of medical rehabilitation, including medical care, emergency medical services, and societal costs, such as insurance administration cost, and legal and court expenses. As with monetary costs, most direct energy impacts are straightforward to estimate, with many precedents in literature to draw from. In contrast, energy related to human rehabilitation is not as easy to estimate. This framework uses the same productivity assumptions as that of loss of HC, but in direct energy costs. This is energy devoted to rehabilitation activities that would have normally been applied to constructive productivity (rather than human recuperative productivity).

Indirect energy costs in the form of HC i.e., **HC energy costs,** reflect the energy equivalent productivity lost as a result of injury or death. In the case of injury, an HC cost is the economic equivalent of the reduced or lost human productivity during the rehabilitation procedure. The energy equivalent of such loss reflects the associated lost energy productivity, and the loss of quality of life (or correspondingly, the energy capital that would need to be spent to make up for the lost economic productivity). The initial estimate energy impact (or loss) due to indirect HC loss is made through known GDP to total energy consumed ratios.

Indirect energy costs in the form of WTP, i.e., **WTP energy costs**, indicate the energy equivalence of economic cost that society (or a person) is willing to pay to avoid the risk and occurrence of injury and fatality crashes. According to the definition of WTP, costs are estimated using the VSL. The monetary cost of WTP can be converted to WTP energy cost according to GDP to total energy consumed ratios.

The energy costs of crashes have not been thoroughly studied with respect to indirect costs of HC and WTP, although there are a few studies that mention energy equivalences of safety and traffic delay from various perspectives. Collision avoidance by adopting autonomous vehicles can lead to a 0% – 2% reduction in direct energy use for light-duty vehicles (Stephens 2016). A 3.25-liter-per-hour fuel consumption rate was used in a Canadian study (Vodden 2007) to convert congestion time delay due to vehicle collisions to the energy impact. Another study from the Ohio Air Quality Development Authority computed fuel consumption related to crash-induced congestion used a rate of 0.156 gallon of gas per hour for passenger cars and the rate of 0.85 gallon per hour for trucks (Lutsey 2004).

Crashes at Intersections

In the United States, nearly 50% of crashes occur at intersections (NHTSA 2018a, Thomas 2008). Intersection crashes caused 8,682 fatalities, over 2.2 million injuries, and over 10 million damaged vehicles in 2010 (Blincoe 2015). Crashes at intersections caused $120 billion in economic costs and $371 billion in societal costs and accounted for 50% of total economic costs (direct and HC costs) and 44% of societal costs (comprehensive cost, i.e., direct, HC, and WTP costs) nationwide in the United States (Blincoe 2015). A Georgia study demonstrated similar results in terms of collision location: from 2000 to 2005, of more than 300,000 annual crashes in Georgia, 47% occurred at intersections (Thomas 2008). The number of crashes and costs by types at intersections and at all roads in 2010 are summarized in Table 3.

Table 3. Statistics of Crashes and Economic Cost Types at Intersections and at All Roads (Blincoe 2015)

	Fatal Crashes	Injury Crashes	PDO Crashes	Economic Cost ($ billion)	Comprehensive Cost ($ billion)
All roads	32,999	3,900,000	24,000,000	242	836
Intersections	8,682	2,200,000	10,000,000	120	371
Intersection %	26	56	42	50	44

REDUCING COST OF COLLISIONS AT INTERSECTIONS

Crashes at intersections lead to substantial economic and societal costs, attracting applications of advanced technologies to reduce traffic collisions and improve traffic flow.

A performance and benefit evaluation study (Chang and Rochon 2009) of a motorist-assistance service operated in Maryland estimated that 8.2 million gallons of fuel were saved in 2016 through use of the service. These savings were attributed to accelerated incident response and timely removal of vehicles from travel lanes, mitigating congestion and preventing secondary crashes that may have otherwise occurred. These impacts would have been concentrated on the freeway system since that is where the service primarily operated.

Several advanced technologies are currently in development for improving the safety performance and efficiency of highways and urban streets. The technologies that are receiving perhaps the most attention at present are connected and automated vehicle technologies. Although these are expected to deliver substantial safety and efficiency benefits, it is unknown how long a high proportion of the vehicle fleet will be connected and/or automated, and such technology may never be able to capture all road users (i.e., non-vehicle users). Other technologies may offer similar promise in terms of outcomes. In particular, spatial sensing technologies (such as LiDAR sensing) have been discussed by various researchers (Edelstein 2017, Sun 2018, Trushinski 2018) as a means to identify not only vehicles but also pedestrians and bicyclists, while providing detailed trajectory information that could be used to support traffic control applications similar to those that would be enabled by vehicle-to-infrastructure communication.

Although there is a consensus that automated vehicles could improve traffic flow and reduce crashes, the effect of automated vehicles on transportation energy consumption is highly uncertain. The literature indicates that light-duty vehicle energy use in the United States could decrease by 60% or increase by 200% due to adoption of automated vehicles (Stephens 2016), and the period of payback, which is the time until savings are realized, could be decades away. Approaches like eco-routing (Zhu 2017, Zhu 2018), eco-driving, and traffic coordination (Rios-Torres 2015) have been studied to improve traffic performance, improve fuel economy, and mitigate congestion. A real-time optimization framework for smooth and energy-efficient coordination of automated vehicles in merging highways showed that the system could reduce fuel consumption by up to 50% and travel time by an average of 6.9% (Rios-Torres 2015) at freeway merge points. This does not consider the potential safety benefits of automation, whose value could greatly overshadow the efficiency benefits.

At signalized intersections, signal timing improvements yield economic and social benefits by reducing delay and improving safety. Traffic signal timing typically has a limited shelf life. The optimization is only effective if the underlying demand patterns remain similar to those for which the timing was designed. Although it is possible to develop robust plans that can serve a variety of conditions, ultimately changes in travel patterns necessitate the reevaluation and retiming of traffic signals, especially for locations where such patterns are rapidly changing due to growth and fluctuation of activity patterns. The Institute for Transportation Engineers suggests that traffic engineers should review signal timing plans annually and retime signals at least every three years (Miovision 2012).

A signal timing project in Boston (Boston Transportation Department (BTD) and Howard/Stein-Hudson Associates 2010) led to an 8% – 18% decrease in all types of intersection crashes, a 233 – 340 person-hour per day reduction in delay, and 155 – 211 gallons savings of fuel. A study in St. Augustine, Florida, in 2001 indicated that signal retiming reduced average arterial delay by 36%, arterial stops by 49%, and arterial travel time by 10%, resulting in estimated annual fuel savings of 26,000 gallons and overall annual cost savings of $1.1 million (Sunkari 2004). A study on a heavily traveled corridor in northern New Jersey showed a substantial benefit when signals were optimized —a total of 745 gallons of fuel per day were saved (Chien 2006). In 2016, the Maryland Department of Transportation Signal Retiming Program reduced traffic delay by 875,000 hours and saved 231,000 gallons of fuel (MDOT 2016). These numbers show the potential scale of improvement from individual projects. For the most part, these improvements have quantified fuel saving at intersections as a result of improving the efficiency of operations. Most studies quantify energy savings as a result from signal optimization, although it is unclear if this accounts for reduced crash-related congestion. However, no study accounts for indirect impacts, or direct impacts not directly related to traffic flow efficiency in and through the intersection. The latent value of avoided crashes is potentially an order of magnitude greater.

GDP-WEIGHTED ENERGY EQUIVALENCE OF SAFETY AT INTERSECTIONS

The proposed framework estimates the economic and societal costs of crashes using data available in public crash records together with reasonable assumptions of their economic and energy equivalence. Direct costs include the fuel wasted in congestion-induced by crashes; property damage; loss of productivity; vehicle loss; energy expended in repair of vehicles, roadways, and other assets; and other directly measurable quantities. Indirect costs include energy associated with the comprehensive costs from the HC and WTP perspectives, such as the discounted future earnings, value of suffering, cost to society of fatalities, and the magnitude of cost that people are willing to pay to avoid collisions or reduce their severity. These items are not directly measurable but can be estimated.

Energy Consumption and Gross Domestic Product Equivalence

The total U.S. GDP for 2010 was about $14.96 trillion (GDP United States 2010 2010). The total transportation sector GDP is about $1.32 trillion, or 8.8% of the total U.S. GDP (BTS 2016). Components in the transportation sector GDP comprise a range of products and services associated with transportation, including personal vehicle ownership costs, transportation infrastructure, relevant net exports, and government-related transportation purchases (USDOC 2017).

Energy statistics provide total energy consumption in British thermal units (BTU). In 2010, the total primary energy consumption in the United States was 98 quadrillion BTU across all sectors (e.g., residential, commercial, industrial, transportation, and electric power). The transportation sector consumed an estimated 27.4 quadrillion BTU, or 28% of all energy consumption; of that, 26.3 quadrillion BTU or 95.7% was obtained from fossil fuels (USEIA 2011).

Transportation energy consumption can also be quantified in gasoline gallon equivalence (GGEs), using the amount of energy contained in one gallon of gasoline. The GGE conversion factor is 114,000 BTU/GGE. Therefore, the total U.S. primary energy consumption in 2010 was equivalent to 859.6 billion GGE, and the transportation sector energy consumption was 240.3 billion GGE.

Using values for total U.S. energy consumption and GDP, the energy consumption equivalents for total U.S. energy consumption and for the transportation sector alone were calculated in terms of units of energy per unit of GDP. The results are listed in Table 4. The GDP-weighted energy equivalent rates of the transportation sector (0.182 GGE/$ or 20,754 BTU/$) are much larger than those of the overall national energy consumption (0.0574 GGE/$ or 6,549 BTU/$). This indicates that the transportation sector consumed more energy per unit of GDP than other sectors, such as the residential and commercial sectors.

Table 4. Energy Equivalent Rates, using 2010 GDP and Energy Consumption Data.

	National level	Transportation
GDP ($M)	14,964,400	1,320,200
Energy Consumption (Quadrillion BTU)	98	27.4
Energy Equivalent Rate (BTU per GDP)	6,549 BTU/$	20,754 BTU/$
Energy Consumption (Billion GGE)	859.6	240.3
Energy Equivalent Rate (GGE per GDP)	0.0574 GGE/$	0.182 GGE/$

Energy Equivalence from Economic Cost

The GDP-weighted energy equivalence of safety can be calculated from the **economic cost of safety** and the **energy equivalent rates**:

$$\begin{aligned} & Energy\ equivalence\ of\ safety \\ & \quad = Economic\ cost\ of\ safety\ (\$) \\ & \quad * Energy\ equivalent\ rate (BTU/\$\ or\ GGE/\$) \end{aligned} \tag{1}$$

As previously discussed, the economic costs (direct and HC cost) of collisions were estimated at $242 billion, and the comprehensive costs (direct, HC, and WTP) were estimated at $836 billion for the United States in 2010. Combining this information with the GDP-weighted energy equivalent rates shown Table 4 allows these costs to be converted into energy units. Thus, the economic energy equivalent is 1.6 quadrillion BTU, or 14 billion GGE (including direct and human capital cost), while the comprehensive energy equivalent is 5.5 quadrillion BTU, or 48 billion GGE (which also includes willingness to pay). To put this latter number into perspective, the United States energy consumption equated to about 860 billion GGE in 2010; the GDP weighted energy equivalent of crashes is therefore worth about 5.6% of the total U.S. energy consumption in GGE (though acknowledging that this calculation incorporates far more than gasoline consumption).

These overall numbers can be attributed to different crash and cost categories, as summarized in Table 5. The total energy costs tend to be lower for the more severe crash categories because those are less frequent events. However, costs *per crash* are much higher for the more severe crashes. This is especially true for combined direct and indirect costs. After HC and WTP energy costs are incorporated, the indirect costs dwarf the direct energy costs for collisions involving injuries and fatalities. This is not insubstantial considering that the direct costs themselves are already considerably large figures.

To compute the GDP-weighted energy equivalence of safety at intersections, crashes at intersections are estimated to account for 26% of fatal crashes, 57% of injury crashes, and 55% of PDO crashes. From this, the total GDP-weighted energy equivalence of safety at intersections can be calculated as 22 billion GGE in 2010 for the United States, which is equivalent to 9% of the total transportation sector energy consumption (again acknowledging that the calculation accounts for more than just transportation energy consumption).

Table 5. GDP-Weighted Energy Equivalence of Safety on All Roads and at Intersections.

All Roads

	Fatal	Injury	PDO
Number of crashes on all roads	30,296	2,969,963	10,565,514
Number of persons or vehicles on all roads *	32,999	8,504,771	18,508,632
Direct cost (million $)	5,799	88,459	70,369
HC cost (million $)	40,364	35,885	1,111
WTP cost (million $)	255,646	338,159	N/A
Direct Energy Cost (GGE)	332,862,600	5,077,546,600	4,039,180,600
HC Energy Cost (GGE)	2,316,893,600	2,059,799,000	63,771,400
WTP Energy Cost (GGE)	14,674,080,400	19,410,326,600	N/A
Direct Cost ($) per crash	$191,411	$29,785	$6,660
HC Cost ($) per crash	$1,332,321	$12,083	$105
WTP Cost ($) per crash	$8,438,276	$113,860	N/A
Direct Energy Cost (GGE) per crash	10,987	1,710	382
HC Energy Cost (GGE) per crash	76,475	694	6
WTP Energy Cost (GGE) per crash	484,357	6,536	N/A
Total Energy Cost (GGE) per crash	**571,819**	**8,939**	**388**

	Intersections		
# of person–vehicle crashes	8,682	4,829,008	10,127,014
# of crashes equivalence	7,971	1,686,345	5,780,930
% of crashes at intersections	**26%**	**57%**	**55%**
Direct cost (million $)	1,526	50,227	38,502
HC cost (million $)	10,620	20,375	608
WTP cost (million $)	67,260	192,007	N/A
Direct Energy Cost (GGE)	87,575,778	2,883,030,378	2,210,041,157
HC Energy Cost (GGE)	609,572,115	1,169,553,636	34,892,577
WTP Energy Cost (GGE)	3,860,734,144	11,021,181,221	N/A

* For fatal and injury crashes, the number of people in crashes; for PDO, the number of vehicles in crashes

CONCLUSIONS

Motor vehicle crashes lead to significant economic cost and societal harm, as has been abundantly documented in considerable research extending back many decades. However, the equivalent energy consumption of crashes and their induced impacts has not been extensively studied. It is necessary to assess these costs to develop a clearer understanding of the true value of potential safety improvement technologies that are expected to see increasing deployment in the near future. This study offers a framework to evaluate the full economic costs of safety and their GDP-weighted energy equivalences, including both direct and indirect costs. The indirect costs are broken down into HC and WTP components. These costs can be attributed to crashes of different severities (fatal, injury, and PDO), and the costs for crashes at intersections can be isolated. A first-order estimation of the energy costs per crash gives values of 571,819 GGE, 8,939 GGE, and 338 GGE for fatal, injury, and PDO crashes, respectively. The total GDP-weighted energy equivalent of all crashes on all roads is estimated at 48 billion GGE. For intersections alone, the GDP-weighted energy equivalent of crashes is 22 billion GGE, or 9% of total actual energy consumption of the transportation sector. These results show that the energy equivalence of safety is very substantial and that possible benefits of collision avoidance technologies have tremendous potential value.

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