DRAFT

The Energy Footprint of Automotive Electronic Sensors

ABSTRACT

Information and communication technologies (ICT) have emerged as one of the leading technologies to reduce global emissions, particularly in the mobility sector. Automotive electronics, such as sensors/actuators and microcontrollers (commonly known as electronic control units (ECU) which control one or more of the electrical systems or subsystems in a vehicle), play a key role in ICT. Sensors/actuators are key in electronic ICT devices, starting with the data collection and data communication with the internet. The latest two big trends of electrification and automation in vehicles, are projected to increase the use of worldwide automotive sensors from 7.5 billion units in 2017 to 11.0 billion units by the year 2024. A representative state-of-the art automotive sensor system, (i.e., an ultrasonic backup system), including the ECUs controlling the vehicle electrical systems/subsystems, has been considered to estimate the energy footprint in terms of manufacturing and operational energy of global automotive sensors use. A widely used life cycle energy assessment method (i.e., cumulative energy demand) was used as both direct and indirect (including the extraction, manufacturing, and disposal of the raw and auxiliary materials) energy use can be considered for the energy footprint estimation. The embodied manufacturing energy impacts of the system was estimated to be 559 MJ/system, compared to the 417 MJ/system for lifetime system power and additional gasoline use. The share of purchased energy to the embodied energy where the upstream energy isn't included in the former case, is less than 10% and ~ 85% for the component manufacturing and vehicle operation energy uses, respectively. As the purpose of this ultrasonic backup system is to prevent rear crashes, an estimated 1.0 MJ/system is avoided from reduced lifetime vehicular repairs (from an estimated 11% chance of requiring a rear bumper replacement). While all of this is small compared to the overall automotive manufacturing and use energy, the 11 billion automotive sensors expected to be produced in 2024 could require 1540 PJ for manufacturing and those sensors would require an additional 780 - 1150 PJ for lifetime energy use.

Keywords

Ultrasonic backup system, automotive sensors, embodied energy, automotive electronics manufacturing.

Introduction

Information and Communication Technology (ICT) development has spurred a growth in a sector-wide connected economy, with the creation of a tremendous value through the technology-enabled links between people, machines, and organizations. There are more than 31 billion global connected devices in 2018, of which 928 million devices are in automotive and transportation, with an anticipated growth of 21.4% Compound Annual Growth Rate (CAGR) during the 2013-2030 period [1]. It is projected that ICT can enable a 20% reduction of global CO_2e emissions by 2030, holding emissions at 2015 levels through improved efficiencies, lower use of resources, and behavior changes [2]. Sensors/actuators are the key

ICT electronic components for the initial stage of data collection and data exchange to the internet through other major electronic components of an Internet-of-Things (IoT) electronic device such as input/output module and controller in a connected economy [3]. Worldwide trends toward a more connected economy (such as connected or automated vehicles) are projected to increase energy consumption from the manufacturing and operation of connected IoT devices. Conversely, the growing availability of established and new services on *single* platforms or devices in addition to the availability of more efficient electronic devices may dampen this increasing energy consumption trend. A 2016 Swedish study on the energy and carbon footprint for the ICT sector (defined as all but ICT electronic devices used in the entertainment & media sector) indicates both footprints had peaked around 2010 and then started to decrease, despite growing number of usage (data traffic) [4].

A sensor is an electronic device that converts a physical or chemical stimulus into an electrical signal. That electrical signal is processed by an integrated circuit or microprocessor, transforming it into usable information for another system, such as an electronic control unit (ECU) and from there, an actuator, which can act and perform a function (e.g., turn on an alarm or open a window). The total global sensor market was $102 billion USD in 2015, and is expected to almost double in 6 years [4]. By end-use, consumer electronics is the top market, followed by the automotive industry. The automotive sensor market represents about one-quarter of the global sensor market [4] [5]. Within this, engine and drivetrain sensors dominates the market but safety and security related sensors have the highest growth [6]. Bosch and Denso were the main actors in the 2013 market with more than 25% market share [6]. Growth in 2015 was led by the IoT, though industry automation will be the top driver by 2022 [7].

Based on market projections, the global automotive sensors market is expected to register a CAGR close to 8% during the forecast period, 2018 to 2023, with total unit sales reaching 11.7 billion by 2023 [8]. The increasing demand for safety and security in the automobiles is the main factor that is playing a vital role for the growth of this market. The two big current trends for vehicles are electrification and automation; there is rapid integration of high value sensing modules like radio detection and ranging (RADAR), imaging, and light detection and ranging (LiDAR) in automotive systems. The adoption of electric vehicles will greatly change the amount and the sensor types, with increased emphasis on position, speed, temperature and pressure within the car, in the long term. Increasing demands for more vehicle infotainment (entertainment and informative features such as video players and GPS) and safety features (e.g., backup cameras and sensors) have also resulted in an increase in vehicle electronics (both sensors and ECUs). These new components account for about 30% – 35% of the total cost of a vehicle, and are expected to reach 50% by 2030 [9], [10]. The manufacturing of the microcontrollers (ECUs) for these new electronics will increase the total energy of vehicle manufacturing; however, electronics are more than just the microcontrollers. Electronics wiring has added 45 – 65 pounds to vehicles [11], which likely have significant manufacturing and use phase energy contribution. Overall, the number of sensors in vehicles is increasing each year, with more in higher class vehicles (a premium vehicle has more sensors than an economy class vehicle) [12]. Figure 1 shows the increase in both sensors and ECUs in vehicles over time and over vehicle class: Economy (E); Premium or Luxury (P); and Standard (S). This paper focuses on automotive sensors, but the analysis also includes the energy impact of the ECUs and wiring required for a full sensor system.

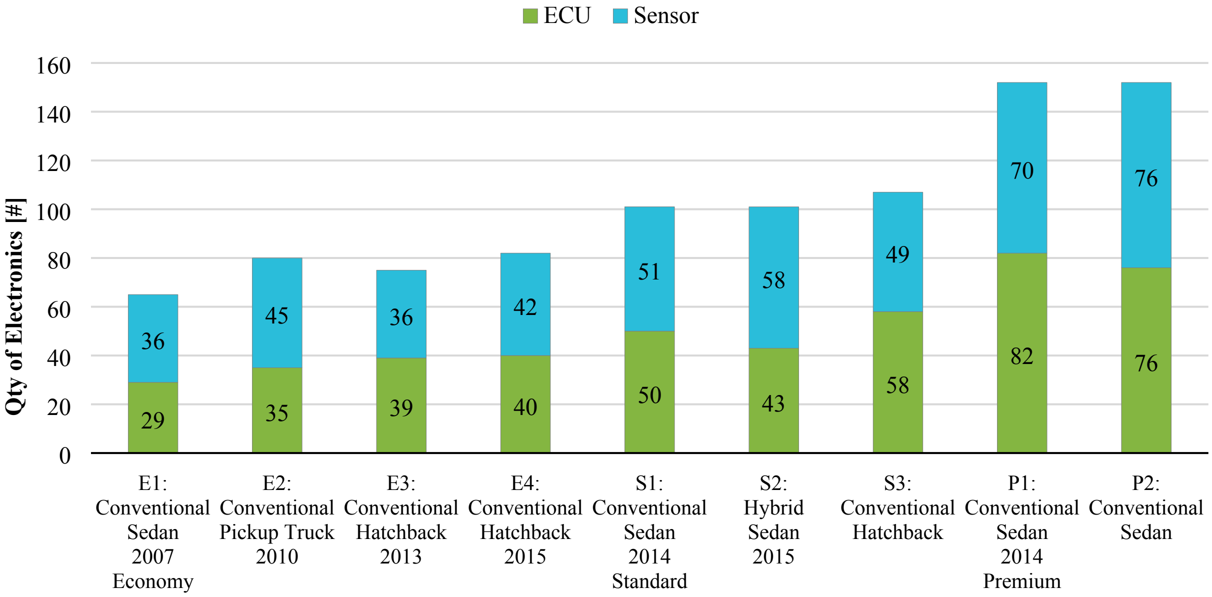


Figure 1. Number of vehicle sensors and ECUs for three classes of vehicle [12]

Automotive Sensors

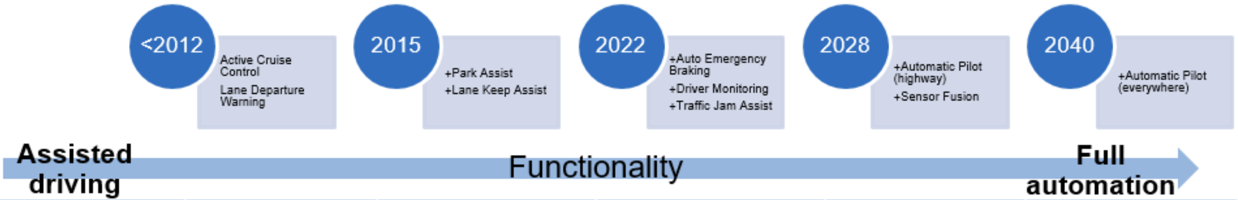
Automobiles utilize many sensors for a variety of applications, though one sensor can serve multiple electronic systems. They are often used for monitoring various systems, such as the engine or tires, so the system's computer can adjust parameters (e.g., the fuel-to-air ratio) or inform the driver of problems. Pressure and temperature sensors are the most common within a vehicle and have the most diversity. For example, there are four tire pressure sensors in a vehicle, to diagnose tire misalignments and monitor tire pressure. By maintaining proper tire pressure, higher fuel efficiency can be maintained (vehicle efficiency decreases 0.2% per psi drop [13]) and this type of system has been shown to improve the vehicle fuel economy by 0.6% [14]. Engine and transmission sensors require a higher level of accuracy and robustness; consequently, digital sensors are usually the type of sensor used. The most common technologies used in automotive sensors are micro-electromechanical systems (MEMS) with wired communication, consumer accuracy precision, smart signal processing, and an active input energy [15].

Table 1. Number of sensors within vehicle systems with examples [12]

Engine	Accessories	Body	Brakes	Transmission	Safety	Heating	Seats
0 - 18	0 - 15	1 - 10	4 - 8	0 - 8	1 - 6	1 - 6	0 - 5
• Cooling System • Engine Block • Fuel Injection System • Hybrid/ Electric System • Turbo/ Supercharge System	• Audio System • Blind Spot Detection System • Keyless Opening System • Park Assist System • Phone System	• Lighting • Opening Systems • Windshield Wiper	• Front Brakes • Hand Brake • Rear Brakes	• Gearbox • Shift Lever Mechanism • Transfer Case	• Airbags • Alarm Theft Protection Device • ESP System	• Front Air Duct • Front Lower Air Pipe	• Driver • Passenger
Electrical	**Exhaust**	**Fuel**	**Air System**	**Interior**	**Steering**	**Pedals**	**Suspension**
0 - 4	0 - 4	0 - 4	0 - 3	0 - 3	0 - 3	1 - 2	0 - 1
• Battery • Opening Switch	• Catalytic System • Pre-Catalytic Converter System	• Fuel Pressure • Fuel Tank System	• Air Flow System • Supercharge System • Intake Temperature	• Center Console • Cockpit	• Steering Shaft Assembly • Steering Wheel System	• Accelerator Pedal • Pedals (Break or Clutch)	• Wheels

An average new car has between 60 and 100 sensors, which could double within 6 years [16]. Table 1 provides examples of specific sensors in different vehicle systems and shows a range of the number of sensors found in each system [12]. Most sensors are in the engine, followed by accessories (such as keyless entry and parking assist), then brakes and transmission, though this varies with vehicle class (e.g., economy versus luxury) and maker. Engine sensors are not considered luxury or premium and have been considered “standard” for decades [17]. Safety and driver assistance sensors (found under “safety” and “accessories”) have previously been considered optional, but as costs of the sensors decrease and government regulations increase, these sensors are transitioning from luxury to standard or even required [18]. Additionally, many sensors are redundant to compensate for any sensor failures or counter the weaknesses associated with similar sensors (e.g. low range or accuracy, malfunction due to weather conditions).

The rise in the automotive sensor market is partially driven by the increasing number of associated regulations and desire for improved system control and automation. Proximity and image sensors (usually found within the safety or accessories systems) are experiencing a high quantity growth rates as shown in Figure 2. This is due to the increase in Advance Driver Assistance Systems (ADAS), in response to the desire to transition to autonomous vehicles [19]. ADAS includes sensors systems such as cameras, radio detection and ranging (RADAR), and ultrasonic proximity sensors. Over the next few decades, the quantity of electronics of these systems within vehicles is expected to increase, and ultrasonic sensors are projected to have the highest growth and final quantity per vehicle [19]. Ultrasonic or ultrasound sensors are often used for proximity sensing, specifically, the backup/reversing obstacle detection system or Parking-Assist System of the vehicle.



# of Types of Proximity Sensor	3	4	9	9	9
Total #	6	17	29	29	32

Figure 2: Advance Driver Assistance Systems (ADAS) and the projected increase in number of sensors per vehicle (adapted from [20])

Ultrasonic Backup/Reversing Systems – A Representative Automotive Sensor

The ultrasonic backup/reversing system allows the driver to hear or visualize how near an object is to the rear of their vehicle. It works using high frequency sound waves for echolocation, allowing them to respond to fully transparent objects, such as glass, and respond to objects in the dark. Figure 3 illustrates, step-by-step, how an ultrasonic backup/reversing system works. The system should respond with high accuracy when the objects are closer to the vehicle (0-2.5 m) [21], and not respond over long distances (e.g., 50 m). Although cameras are better for detecting objects in motion and verifying the presence of obstacles, ultrasonic sensors respond to objects and conditions that are more difficult to view via cameras (e.g., transparent or object in the dark). Additionally, camera systems' interactions with the driver are more passive than ultrasonic systems: the ultrasonic system has an alarm or LED warning display if it detects an object, a camera relies on the user watching the screen.

In addition to their ADAS system use, ultrasonic sensors are used for gas tank level sensors. Beyond automotive applications, ultrasonic sensors are used for fetal detection images, food quality inspection, and even in construction concrete diagnosis.

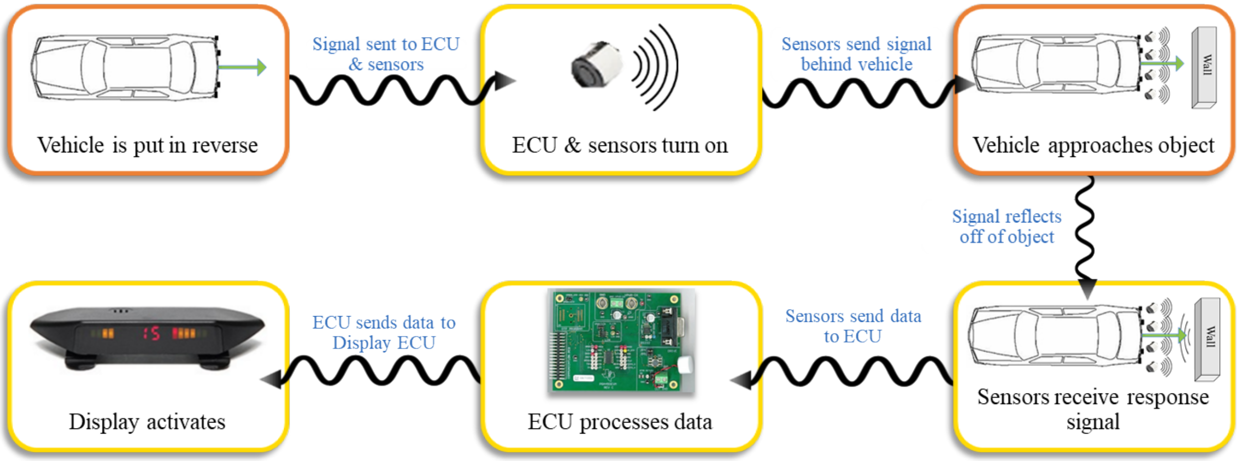


Figure 3. Ultrasonic backup/reversing system simplified diagram [22], [23]

The ultrasonic sensor system is not representative of all sensors in the vehicle. As stated above, many "standard" sensors are pressure or temperature sensors. They are likely fully powered whenever the vehicle is powered, internal to the vehicle, must handle extreme operating conditions (e.g., corrosive exhaust fumes, high temperatures) and are relatively close to their (likely multi-use) ECUs and actuators. Conversely, the ultrasonic system is only on while the vehicle is in reverse and has two dedicated ECUs, which are not near the sensors (rear of the vehicle and center console). Additionally, the ultrasonic sensors are external or near external, implying less harsh operating conditions, but more likely to require replacement if the vehicle is in a crash. All these differences will affect the vehicle energy footprint, mostly in the manufacturing and use phases. However, it is likely that the ultrasonic sensors are representative of newer sensors that will be used for ADAS, as these are also likely to be external or near external and not constantly powered. As vehicles move closer to autonomy, more sensors, ECUs, and wiring will be required, drastically increasing vehicle weight unless these systems transition to sharing ECUs and wireless transmission [11].

Energy Footprint of Automotive Sensor

As discussed, the potential increase in automotive sensor incorporation, specifically in ADAS systems, establishes the need to understand the energy impacts of the inclusion of these sensors, especially with respect to the manufacture and use of these systems. While not a complete life cycle assessment of ADAS sensors, this work discusses how the energetic impact of these sensors could be considered in future life cycle analyses.

The manufacturing and use energy footprint of automotive sensors is estimated based on the cumulative/primary energy demand of a representative automotive ultrasonic backup/reversing system. Cumulative energy demand, widely used in life cycle assessment, is an appropriate metric to quantify the energy use impacts of a product as it represents the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials. Additionally, energy impact estimates are readily available via resources such as SimaPro software and the Ecoinvent databases [24], [25]. The unit sensor system considered for the energy impacts analysis is one automotive ultrasonic backup/reversing system, consisting of several sub-components (i.e., sensors, wiring and connectors, rubber components, an ECU, and a Light Emitting Diode (LED) display module), as a part of a U.S. light-duty vehicle (1,776 kg) [26] and considers no other proximity sensing (e.g., cameras, radio detection and ranging (RADAR)). This analysis is based on the U.S. market and includes two major energy use stages: manufacturing and use/operation. Figure 4 illustrates the major contributions to the energy demand of vehicular sensors, including the impact of the sensors’ purpose (in this case, preventing low speed rear crashes) and lifetime sensor replacement.

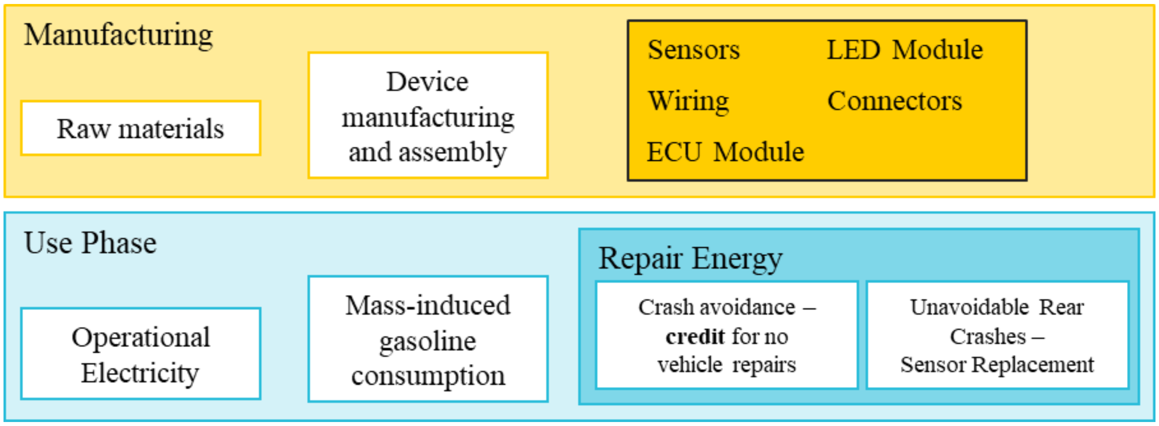


Figure 4. Components of Manufacturing and Use Phase Energy

When moving toward smarter systems, whether it is in manufacturing or vehicles, several challenges exist in terms of what other key aspects beyond the sensors must be taken into account and how they are to be quantified while defining the sensor energy system boundary [27]:

- Sense (What can be sensed?)
- Collect (How is sensor data collected? Is there local processing?)
- Connect (How do they connect and transmit data?)
- Store (How and where is the data stored?)
- Analyze (What insights can be drawn from the data?)
- Action (What actions should be taken, based on the data?)

In this analysis, the sensors are only monitoring for an object behind the vehicle, during a backup. The system has two processor units (ECU and LED modules), which are connected by ethernet cables; there is no long-term data storage. Figure 5 illustrates these aspects for this system, and what energy use phases they impact and how.

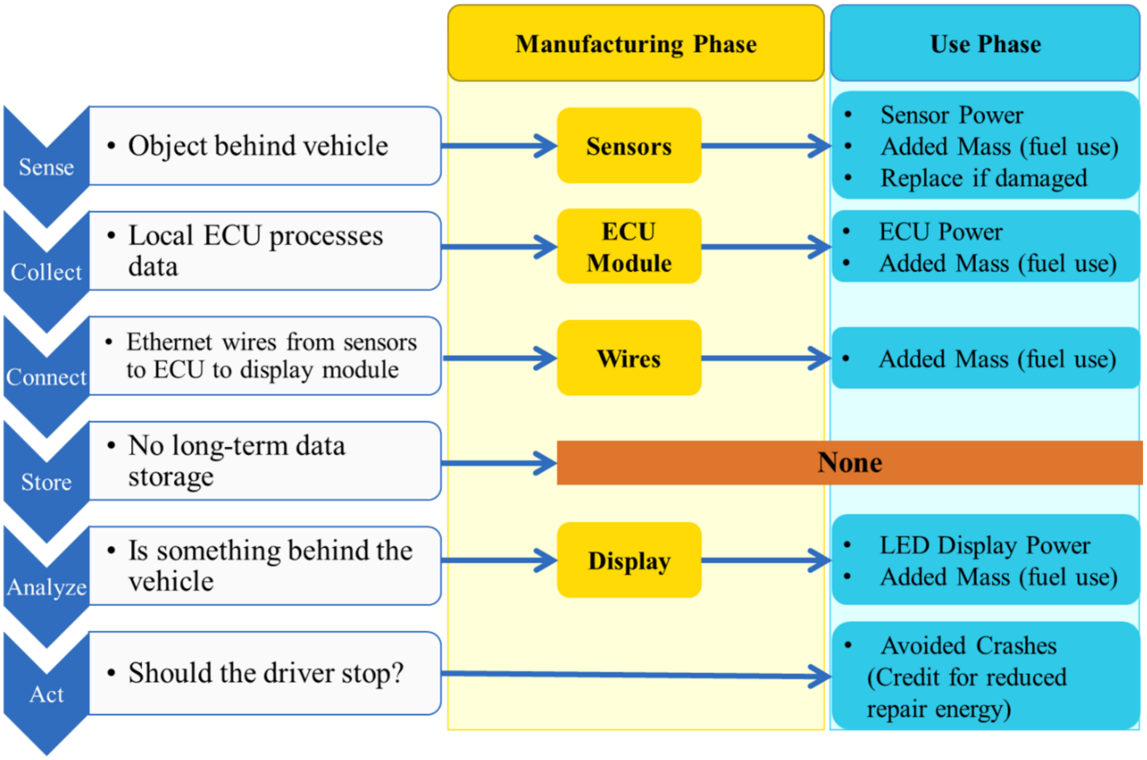


Figure 5. Energy impacts of smarter vehicle systems

Manufacturing

The materials and manufacturing of the ultrasonic backup/reversing system includes the wiring (i.e., four 4.5” sensor wires, a 12’ power wire, a 66’ trigger wire, and a 14” display wire) and connectors, four ultrasonic sensors with four rubber grommets, the main module and the display module [21] as shown in Table 2. The embodied energy in this table accounts for the energy put in the final products, from the energy required to extract the raw materials to the energy purchased to manufacture the final item, and was estimated using similar items within the Ecoinvent database (assuming manufacturing in the U.S.) [24]. Overall, the purchased energy is a small fraction of automotive manufacturing (for example, steel stamping is 5 MJ / kg [28] compared to 50 – 90 MJ/kg embodied energy for stainless steel [29]), the majority of the energy embodied in the system is embodied in the materials (e.g., material extraction). The total manufacturing impact was estimated to be 559 MJ for one ultrasonic backup/reversing system. The ECU and LED modules have the individual highest impacts (115 MJ per unit, each), but the largest overall contribution is from the wiring (189 MJ per system), while the sensors themselves (86 MJ per system) are also significant. Potential damage and replacement are not accounted for in this stage, however, they are accounted for during the use-phase of the system in the vehicle.

Table 2. Ultrasonic sensor component breakdown [21], [23]

	Quantity	Total Mass (kg)	Embodied Energy [24]	Energy Contribution (MJ)
Sensors	4	0.17	506 MJ/kg	86
ECU module	1	0.23	506 MJ/kg	115
LED module	1	0.23	506 MJ/kg	115
Wiring	24.6 m	2.2 kg [30]	7.70 MJ/m	189
Wiring Connectors	6	---	0.99 MJ/unit	6
Rubber Grommets	4	0.23	94 MJ/kg	21
Molding	1	0.23	117 MJ/kg	27

Use Phase

For this analysis, the use phase was separated in three phases: electricity consumption, mass-induced gasoline consumption, and sensor replacement caused by vehicle use rear-end crashes. Electricity is provided to the sensor system using gasoline via the alternator and the battery. The mass-induced gasoline consumption is the additional fuel is needed to compensate for the fuel efficiency reduction caused by additional mass of the system. Finally, the purpose of the system is to avoid rear-end crashes; the probability of these accidents and the embodied energy (i.e., from ground to vehicle) of the replaced parts was determined and converted into an energy avoidance for the system. However, not all rear-end crashes will be avoided, so the energetic cost of replacing the sensors was also included.

Electricity consumption

The electricity consumption of the ultrasonic backup/reversing system ($E_{Electricity}$, calculated with Equation 1 was determined from the system operating current (I) and working voltage (V), and the approximate lifetime operation time in which the power is being used (t); idle power draw was assumed to be negligible.

$$\boldsymbol{E_{Electricity} = I \times V \times t} \qquad \textbf{(1)}$$

$$\boldsymbol{t = Bm \times Tpd \times 365 \left[\frac{days}{Year}\right] \times Lt_{yr}} \qquad \textbf{(2)}$$

Table 3. Sensor system electricity consumption calculation parameters

Variable	Description	Value (unit)	Reference
I	Current	150 mA	[21]
V	Voltage	10.5 V	[21]
Bm	Time spent per backup	10 s	Assumed
Tpd	Vehicle-trips per day	2.7 trips / day	[31]
$\boldsymbol{Lt_{yr}}$	Lifetime of the vehicle	11.9 years	[31]

The lifetime operating time (t) and system electricity consumption ($E_{Electricity}$) were determined using Equations 1 and 2 using the parameters found in Table 3. This resulted in the system being powered for 32.6 hours over the vehicle lifetime and, combining this with Equation 1, a total of 51.3 Wh electricity is required.

For conventional internal combustion engine (ICE) vehicles, engine losses and alternator inefficiency result in only about 21% of the gasoline's energetic content to be converted into the electricity to power the sensor system (40% engine efficiency, 98% belt efficiency and 55% alternator efficiency [9]). The gasoline energy use of the sensor system over the lifetime of a vehicle is 0.86 MJ. Using a higher heating value of 120,439 BTU/gal (33.568 MJ/L) [32] and a well-to-wheel embodied energy of 39.6 MJ/L [33] results in a total embodied energy contribution of 1.0 MJ for sensor electricity use.

Mass-induced gasoline consumption

The added weight of the ultrasonic backup system (3.05 kg) increases vehicle fuel consumption, resulting in additional use phase energy use (E_{mass}). The relationship between mass, fuel consumption, lifetime mileage, and well-to-wheel embodied energy of gasoline is shown in Equation 3 [33]–[35],and the values used are described in Table 4.

$$\boldsymbol{E_{mass} = m_{sys} \times F_{co} \times Lt_{mi} \times E_{gas}} \tag{3}$$

Table 4. Sensor system mass-induced additional fuel consumption calculation parameters

Variable	Description	Value (unit)	Reference
$\mathbf{m_{sys}}$	Mass of the sensor system	3.05 kg	[21]
$\mathbf{F_{co}}$	Fuel Consumption Parameter	$\frac{0.161\,L}{100\,kg\,\times\,100\,km}$	[34]
$\mathbf{Lt_{mi}}$	Lifetime of the vehicle	214,493 km	[35]
$\mathbf{E_{gas}}$	Higher Heating Value of Gasoline	33.568 MJ / L gasoline	[32]
	Well-to-wheel embodied energy of gasoline	39.6 MJ/ L gasoline	[33]

Using Equation 3 and the parameters outlined in Table 4, the additional 3.05 kg requires an additional 10.5 L or 352 MJ of gasoline over the lifetime of the vehicle, adding 417 MJ to the embodied energy of the sensor system.

Vehicle repair energy

According to the National Highway Transportation Safety Administration (NHTSA) [36], a vehicle will have a rear bumper crash about once over its lifetime, installation of the ultrasonic sensor system might prevent this. This phase was sub-divided into three portions: avoided accidents, not avoided accidents and unavoidable accidents. Avoided accidents result in an energy credit for avoiding rear-end repairs and the associated energy. Not avoided and unavoidable accidents result in replacing sensors that would not otherwise have to be replaced.

Energy credit: Avoided crashes

Using the NHTSA methodology, accident probabilities (including the probabilities for driver error and sensor failure) for given accident speeds [36] and the embodied energy of a standard fiberglass bumper, the costs of avoided crashes was estimated using Equation 4. The lifetime chance of a vehicle being in a crash while backing-up at low speed is about 25% (see Table 5). This type of crash is what can be avoided by the use of an ultrasonic sensor system, however, the sensors and drivers do not react perfectly in every situation, represented by the sensor avoidance probability ($p_{A,i}$), based on the vehicle speed at the time of crash (i.e., the crash severity in Table 6). Damage from rear crashes of this type could include bumper replacement, depending on the speed of the crash and the bumper material. Steel bumpers weigh between 22 and 44 lb (ranging between passenger cars and pickup trucks), while lightweight composite bumpers are between 5 and 11 lb [37]. A Glass Fiber-Reinforced Plastic (GFRP) bumper was used for this analysis, as it was assumed a steel bumper would not need replacement due to these types of crashes. Argonne’s GREET modeler [32] assumes 3.01 MMBTU per ton of GFRP (SMC) for producing a GFRP part and 1.14 lb of GFRP per 1 lb of final GFRP part. This results in approximately 9.05 – 19.9 MJ per bumper, and a negligible avoidance of 1.0 MJ per vehicle lifetime. Successfully avoiding a crash would also avoid the energy of repairs and the end-of-life of the damaged bumper, but those are not included in this analysis.

$$\boldsymbol{E_{Avoided} = p_{LS-B} \times 9.05\frac{MJ}{bumper} \times \sum_{L,M,H}(p_i \times p_{A,i})} \tag{4}$$

Table 5. Details of crash probability parameters [36]

Parameter	Probability
Lifetime probability of low speed avoidable back-up crash (p_{LS-B})	25%
Lifetime probability of low speed rear-ended crash (unavoidable) (p_{LS-R})	75%
Lifetime probability of high speed rear-bumper crash (unavoidable) (p_{HS})	9%

Table 6. Parameters for lifetime backup crash repair cost estimation [36]

Low Speed Crash Severity	Fraction of Low Speed Crashes (p_i)	Sensor Avoidance Probability ($p_{A,i}$)	Number of sensors that would need to be replaced (n_i)
Light (L)	75%	49%	0
Medium (M)	18%	26%	1
Heavy (H)	7%	13%	3

Sensor replacement: Not avoided and unavoidable crashes

However, in the more likely cases of not avoided and unavoidable crashes, the sensor replacement also must be taken into consideration. Not avoided crashes are the same type of accident as avoided crashes (low-speed backing-up crashes), but either the sensor system failed to alert the driver, or the driver failed to heed the warning. In a vehicle accident where the rear bumper is damaged, the number of sensors needing to be replaced depends on the severity of the crash. Equation 5 calculates the not avoided crash energy ($E_{Not\ Avoided}$), is similar to Equation 4. However, it only considers the number of sensors damaged for a given accident rating (ni) and the sensor manufacturing energy (86 MJ for 4 sensors) and does not consider the bumper replacement (as the bumper would have to be replaced regardless of the presence of the sensors).

$$\boldsymbol{E_{Not\ Avoided} = p_{LS-B} \times 21.5\frac{MJ}{sensor} \times \sum_{L,M,H}(p_i \times (1 - p_{A,i}) \times n_i)} \tag{5}$$

Unavoidable crashes are accidents that the sensors could not help the driver avoid; either the vehicle was moving backwards too fast for the sensors or driver to react, or another vehicle impacted the rear bumper of the primary vehicle. The NHTSA estimated the lifetime probability of a low-speed rear-ended accident to be 75% and that of a high-speed rear-bumper crash to be 9% (rear crashes resulting in the totaling of the primary vehicle were not included). These probabilities were used in conjunction with the sensor manufacturing energy and the number of sensors needing to be replaced (Equations 6 and 7) to estimate energy impacts, i.e., $E_{Unavoidable-LS}$ and $E_{Unavoidable-HS}$ due to low- and high-speed rear-end crashes, respectively.

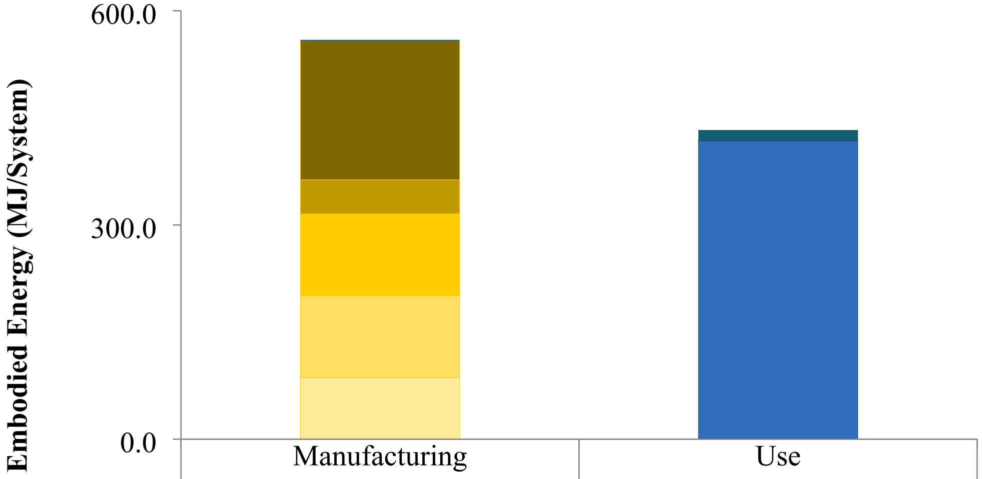
$$\boldsymbol{E_{Unavoidable-LS} = p_{LS-R} \times 21.5\frac{MJ}{sensor} \times \sum_{L,M,H}(p_i \times n_i)} \tag{6}$$

$$\boldsymbol{E_{Unavoidable-HS} = p_{HS} \times 21.5\frac{MJ}{sensor} \times 3\ sensors} \tag{7}$$

The inclusion of replacing sensors due to rear-end accidents resulted in an additional energy demand of 13.7 MJ per system (this does not include any energy for installation).

Energy Use Summary

The total manufacturing and use lifetime energy contribution is 991 MJ per vehicle lifetime of a sensor system consisting of four sensors (Figure 6). The largest contributors to energy use are the mass-induced gasoline consumption (417 MJ), the total wiring (189 MJ) and the two ECUs (115 MJ each). Gasoline for electricity use (1.0 MJ), lifetime sensor replacement (13.7 MJ) and avoiding the replacement of a rear bumper (1.0 MJ) were significantly lower energy impacts.



	Manufacturing	Use
■ Sensor Replacement	0.0	13.7
■ Avoided Crash Repair Costs	0.0	1.0
■ Gasoline (Mass Change)	0.0	417.0
■ Gasoline (Electricity)	0.0	0.9
■ Wiring & Connectors	195.4	0.0
■ Rubber	47.9	0.0
■ LED Module	114.8	0.0
■ ECU Module	114.8	0.0
■ Sensor	86.0	0.0

Figure 6. Energy Contributions (MJ) of an Ultrasonic Backup Sensor System

Future Energy Use Implications

As shown in Figure 2, types of proximity sensors per vehicle are expected to increase from four to nine by 2040, with the number of sensors increasing from 17 in 2015 to 32 [20]. Assuming "# of Types of Proximity Sensor" is analogous to the number of sensor systems, and that the ultrasonic backup sensor system is a representative ADAS system, just the manufacturing and use energy of ADAS systems contribute 4.0 GJ to the lifetime energy use of a 2015 vehicle (four systems of 991 MJ each). This could increase to 8.9 GJ (nine systems of 991 MJ each) or more (as the number of sensors will increase seemingly independently of types of sensors) for a 2040 vehicle.

If we expand these findings to estimate the additional energy burden of all new automotive sensors, the impact grows. For a rough estimate, it was assumed that all automotive sensors have a similar energy burden (excluding lifetime replacement and any energy credits for their inclusion). By 2024, the sales for automotive sensors will reach 11 billion units (up from 7.5 billion units in 2017); this will increase the total automotive sensor manufacturing energy from approximately 1050 PJ (2017) to 1540 PJ (2024) assuming the energy estimates shown in Figure 6 for four sensors in an ultrasonic backup sensor system (Table 7). This increase in sensors will also increase the total lifetime use energy from 780 PJ to 1150 PJ. The Use phase energy is likely to be higher, given that many of the sensors continuously use energy when the vehicle is running. The Gasoline-for-Electricity contribution of the Use phase energy increases from 0.54 MJ to 106 MJ if the time-on changes from 10 s per trip to the entire trip (assuming an average trip time of 20.6 min [31]). This would increase the total automotive sensor lifetime use energy to 980 PJ (2017) and 1440 PJ (2024). A more inclusive estimate would also consider energy credits due to avoided repairs (like the ultrasonic backup system) or from contributions to vehicle efficiency, decreasing the Use phase energy, but this would be highly dependent on each sensor's function.

Table 7. Estimation of increasing sensor energy burden

	2017	2018	2019	2020	2021	2023	2024
Sales (B units) [20]	7.5	7.9	8.2	8.6	9.5	10.3	11
Manufacturing Energy (PJ)	1050	1100	1150	1200	1330	1440	1540

Conclusion

The ultrasonic backup/reversing system is a proximity sensing technology that enables the driver to be more aware of objects and people behind the vehicle. Back-over crashes kill approximately 228 people per year and injure over 17,000. Unfortunately, ultrasonic sensors are not likely to prevent more than 3 fatalities and approximately 200 injuries over the vehicle lifetime [38]. The sensors are both unlikely to "see" people behind the vehicle and even if they do alert the driver to an obstacle, if the driver cannot see it, via mirrors or a camera, they are unlikely to stop. However, safety consideration is an implicit driver for the utilization of ultrasonic sensors, by providing parking assistance and because they are considered a step in the autonomous vehicles roadmap [20]. Given the expected prevalence of this system, the additional embodied energy added to vehicles should be considered when determining the lifetime energy use of a vehicle.

Automotive ultrasonic backup/reversing system does not provide energy savings to the vehicle's embodied energy, but from a social perspective it is a desirable feature capable of improving the driver's reaction to rear objects and people, and therefore avoiding vehicular accidents. Given the total embodied energy of vehicle manufacturing is approximately 157 GJ per vehicle [26], the ultrasonic sensors system represents approximately an additional 0.36% of the vehicular manufacturing energy (559 MJ / 157 GJ). While this is quite small, this is only one new sensor system; as discussed above, there are several other sensor systems in the ADAS category that are expected to be added to standard vehicles in the near future, further increasing vehicle manufacturing energy. Including the other ADAS sensor system increases the energy contribution to closer to 1.0%, which could more than double by 2040. Additionally, the trend of increasing electronics is adding significant weight to the vehicle (especially from the ECUs and wiring) and is competing with another major vehicular trend, lightweighting. As overall vehicle weight decreases, the increase in electronics weight will have a relatively greater impact. At this time, the total number of ECUs and wiring that these new systems will require together is unknown; systems may be able to combine ECUs and some systems may transition to wireless in-vehicle communication, making projections for the manufacturing and use-phases different.

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Supplementary Information

Life Cycle Assessment of the Ultrasonic Backup System

The following tables provide the Bill of Materials used for this work. All data is from secondary sources, such as the Ecoinvent databases. Data about the ultrasonic backup sensor comes from the seller [23] and it was assumed that no materials were wasted or broken during assembly or replacement. It was also assumed that the manufacturing location had the same Emission Factor (EF) as that in the source.

Table 1. Bill of Materials for Manufacturing (1)

Contribution	*Amount per FU*	*Source & method for amount*	*EF*	*Source & rationale for EF*	*CED [MJ]*
Sensor	0.17 kg	1 sensor (1.5 oz.) x 4 per system [23], [39]	506 MJ/kg	Electronics for control units, at RER, with US electricity U.S.. [24]	86
Sensor's Wiring	0.457 m	1 wire (4.5 in) x 4 per system [23], [40]	7.7 MJ/m	Cable, connector for computer, without plugs, at plant, at GLO S. [24]	3.52
Module (ECU)	0.227 kg	1 module (ECU) (8oz) [23], [40]	506 MJ/kg	Electronics for control units, at RER, with US electricity U. [24]	115
Module's Sensor to Control Box	3.66 m	1 power wire (12 ft) [41]	7.7 MJ/m	Cable, connector for computer, without plugs, at plant, at GLO S. [24]	28
Module's Control Box to Interior	20.1 m	1 trigger wire (66 ft) [42]	7.7 MJ/m	Cable, connector for computer, without plugs, at plant, at GLO S. [24]	155
Module's Power Wiring Connector	2 Unit	2 Plugs (in & out) for the power wire [23], [40]	0.99 MJ/unit	Plugs, inlet and outlet, for network cable, at plant, at GLO S. [24]	1.98
Module's Trigger Wiring Connector	2 Unit	2 Plugs (in & out) for the Module's Trigger Wiring [23], [40]	0.99 MJ/unit	Plugs, inlet and outlet, for network cable, at plant, at GLO S. [24]	1.98

Table 8. Bill of Materials for Manufacturing (2)

Contribution	*Amount per FU*	*Source & method for amount*	*EF*	*Source & rationale for EF*	*CED [MJ]*
LED Module Display	0.227 kg	1 Display module (8oz) [23], [40]	506 MJ/kg	Electronics for control units, at RER, with US electricity U.S. [24].	115
Display's Wiring	0.356 m	1 wire (14 in) [23], [40]	7.7 MJ/m	Cable, connector for computer, without plugs, at plant, at GLO S. [24]	2.74
Display's Wiring Connector	2 Unit	2 Plugs (in & out) for the Display wire [23], [40]	0.99 MJ/unit	Plugs, inlet and outlet, for network cable, at plant, at GLO S. [24]	1.98
Rubber Grommets	0.227 kg	1 grommet (2oz) x 4 per system [23], [40]	94 MJ/kg	Synthetic rubber, at plant [24]	21
Rubber Molding	0.227 kg	1 grommet (2oz) x 4 per system [23], [40]	117 MJ/kg	Polypropylene injection molding E. [25]	27

The total mass of wiring (2.2 kg) was estimated using a linear density of 5.015 lb/1000 ft (18 AWG wire)[30].

Table 2. Bill of Materials for Use Phase

Contribution	***Amount per FU***	***Source & method for amount***	***EF***	***Source & rationale for EF***	***CED [MJ]***
Gasoline for Electricity	0.18 MJ	Operating Voltage (V): 10.5V [23] Operating Current (I): 150 mA [23] Trips per day: 2.7 Trips [31] Time on per Trip: 10 s (assumed) Vehicle Lifetime: 11.9 yr [35] Operating Time (t) = time on per trip x trips/day x vehicle lifetime Electric Energy = V x I x t	5.47 MJ/MJ	Engine Efficiency: 40% [43] Belt Efficiency: 98% [44] Alternator Efficiency: 55% [44] Energy per L for gasoline: 39.59 MJ/L Petrol, 5% ethanol by volume from biomass {GLO}. [24] Higher Heating Value: 120,439 Btu/lb [32] (39.59 / 33.568) MJ/MJ/(0.4 x 0.98 x 0.55)	1.01
Gasoline (mass-induced to vehicle)	21.44 L	Added Mass: 3.05 kg Mass Factor: 0.161 L/100km100kg [34] Annual Milage:11,200 mi [35] Lifetime distance = 214,493 km Gasoline Consumption = (3.05 kg) * (0.161 L/100km100kg) * 214,493 km	39.59 MJ/L	Petrol, 5% ethanol by volume from biomass {GLO}. [24]	417
Avoided Crash Repair Costs	5 lb	Avoided bumper replacement weight [37]	1.81 MJ/lb	1.14 lb GFRP per 1 lb GFRP part (Tons Needed per Ton of Final Transformed Product) 3.01 MMBtu/ton GFRP (Energy Use of Plastic) [32]	-1.01
Unavoidable Backup Sensor Replacement	0.0425 kg	1 sensor (1.5 oz.) [23], [39] replaced	506 MJ/kg	Electronics for control units, at RER, with US electricity U. . [24]	1.7
Unavoidable struck-from-rear crashes	0.1275 kg	3 sensors (1.5 oz.) [23], [39] replaced	506 MJ/kg	Electronics for control units, at RER, with US electricity U. . [24]	12.0

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