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Parking infrastructure: energy, emissions, and automobile life-cycle environmental accounting

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Abstract
The US parking infrastructure is vast and little is known about its scale and environmental impacts. The few parking space inventories that exist are typically regionalized and no known environmental assessment has been performed to determine the energy and emissions from providing this infrastructure. A better understanding of the scale of US parking is necessary to properly value the total costs of automobile travel. Energy and emissions from constructing and maintaining the parking infrastructure should be considered when assessing the total human health and environmental impacts of vehicle travel. We develop five parking space inventory scenarios and from these estimate the range of infrastructure provided in the US to be between 105 million and 2 billion spaces. Using these estimates, a life-cycle environmental inventory is performed to capture the energy consumption and emissions of greenhouse gases, CO, SO_2, NO_X, VOC (volatile organic compounds), and PM_{10} (PM: particulate matter) from raw material extraction, transport, asphalt and concrete production, and placement (including direct, indirect, and supply chain processes) of space construction and maintenance. The environmental assessment is then evaluated within the life-cycle performance of sedans, SUVs (sports utility vehicles), and pickups. Depending on the scenario and vehicle type, the inclusion of parking within the overall life-cycle inventory increases energy consumption from 3.1 to 4.8 MJ by 0.1–0.3 MJ and greenhouse gas emissions from 230 to 380 g CO_2e by 6–23 g CO_2e per passenger kilometer traveled. Life-cycle automobile SO_2 and PM_{10} emissions show some of the largest increases, by as much as 24% and 89% from the baseline inventory. The environmental consequences of providing the parking spaces are discussed as well as the uncertainty in allocating paved area between parking and roadways.

Keywords: parking, passenger transportation, life-cycle assessment, cars, automobiles, energy, emissions, greenhouse gases, criteria air pollutants

S Online supplementary data available from stacks.iop.org/ERL/5/034001/mmedia

1. Introduction

The infrastructure required for automobile transportation is extensive with many vehicle, infrastructure, and fuel supply components (Chester and Horvath 2009). Parking is the result of land area needs for vehicles when they are not moving. With roughly 250 million vehicles in the US and an emphasis on providing abundant free parking (Shoup 2005 using the National Household Travel Survey determines that 99% of automobile trips do not pay for parking directly), the parking infrastructure is often disregarded by many private trip takers

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(BTS 2009). The ability to properly value parking is of great interest to planners to aid in decisions which may promote or discourage automobile travel over public transit or walking and biking. The availability and private cost of parking influences a trip taker's behavior (Hess 2001, Wilson and Shoup 1990), but little information is available to determine the environmental and other external costs associated with paved surface areas, building code parking space requirements, or the indirect effects of encouraging automobile travel by planning to provide parking spaces for drivers. One such cost is the energy requirements and resulting emissions from parking space construction and maintenance. The environmental effects of parking are not just from encouraging the use of the automobile over public transit or walking and biking (thus favoring the often more energy-intensive and polluting mode), but also from the material and process requirements in direct, indirect, and supply chain activities related to building and maintaining the infrastructure (Chester and Horvath 2009). The emissions from these activities result in human health and environmental impacts and could be included in the costs of automobile travel. They are part of a suite of impacts which also include the urban heat island effect (dark-colored pavements help increase urban temperatures triggering additional energy demand for cooling and strain on the electricity grid) and impediment of natural water flows (parking pavements can create impervious surfaces altering hydrologic flows reducing local water accessibility) (Albanese and Matlack 1999, Santero and Horvath 2009, EPA 2005). A parking space inventory estimate is important for understanding the energy requirements and air emissions associated with the parking infrastructure allowing for more comprehensive evaluation of automobile total costs.

Estimates of the number of parking spaces in the United States vary significantly (Manville and Shoup 2005). Parking spaces are typically grouped into on-street (metered and road shoulders) and off-street (surface lots, parking garages/structures, and private homes or apartments). Consideration should also be given to home driveways. No nationwide inventory of US parking exists, but several estimates have been performed for different geographic regions. Approaches vary from estimating building code parking requirements (number of spaces per building area to total US building area) (Delucchi 1997) to conducting surveys (Davis *et al* 2010, Shoup 2005) to evaluating satellite imagery (Akbari *et al* 2003). There are many difficulties in evaluating the US parking inventory which include scaling of regional-specific surveys, attribution of roadway shoulders, and estimation of private residential spaces (e.g., driveways and apartment building garages).

The studies that have evaluated parking inventories often focus on specific space types including on-street, surface lot, multi-story garage or structures, and private, and do not provide assessments of larger regional impacts. An accurate estimate is critical in valuing the total cost of automobile travel (Delucchi 1997, Litman 2009). Using census data, Delucchi (1997) estimates that there were between 125 and 200 million non-residential off-street parking spaces in the United States in 1991. Litman (2009) points out this may be an underestimate considering that the growth rate of commercial floor area has outpaced population and vehicle growth and Delucchi (1997) excludes some significant parking supply land use categories. Using total floor area and parking spaces per unit floor area estimates, Litman (2009) goes on to provide his own estimate of 220 million commercial parking spaces in the US for 2003. The International Parking Institute, an association of parking professionals, reports 105 million US parking spaces, likely an estimate of the number of for-pay parking spots (IPI 2009). Furthermore, a survey by Davis *et al* (2010) reports that in Tippecanoe County, Indiana, there are approximately 2.2 parking spaces per registered vehicle, and Shoup (2005) estimates approximately three to four spaces per vehicle in particular urban settings.

The number of parking spaces in the United States is important for evaluating the extent of transportation infrastructure investment, and the corresponding environmental inventory should be understood for evaluating associated human health and environmental impacts. The goal of this study is to estimate the energy and emissions associated with the US parking infrastructure, and evaluate these environmental requirements in the context of vehicle travel. We estimate the range of the number of parking spaces in the US from existing literature highlighting the uncertainty with this inventory. Given the space inventory range, we show the corresponding energy requirements and emissions in producing and maintaining this infrastructure component. Lastly, to provide perspective on the extent of this infrastructure, we normalize the energy and emissions estimates per passenger kilometer traveled (PKT) for automobile travel (while acknowledging the allocation challenges in charging all of the environmental effects to the automobile instead of other sectors or decisions that induce travel). The environmental impacts from transportation infrastructure often go unaccounted (Chester and Horvath 2009), and the development of comprehensive energy and emissions inventories are necessary to understand the full impacts of parking infrastructure investment.

2. Parking space inventory methodology

Multiple scenarios are evaluated to capture the wide range of estimates of parking infrastructure. For each of the parking space estimate scenarios, the energy and emissions from parking lot construction and maintenance and their contribution to automobile life-cycle environmental performance are computed using the same methodology as in Chester and Horvath (2009). Maintenance effects are small (around 10%) compared to construction (Caltrans 2007, PaLATE 2004). The construction of each inventory should capture the energy consumption and emissions associated with raw material extraction, processing, transport, and placement including direct, indirect, and supply chain effects.

Parking space terminology varies depending on factors such as location, cost structure, and privatization. For this assessment, the following nomenclature is used for three primary groupings: on-street, surface, and structure (also known as multi-story garage, parkade, or ramp). On-street spaces are within a road's right-of-way and are either priced (metered) or free (such as a roadway shoulder). Surface spaces are built directly on land and used for commercial parking lots, building on-site parking (but not structures), and private home spaces. The structure spaces can be priced or free, and are either free-standing or serve as the bottom levels of buildings.

Five scenarios are evaluated to capture the range in estimation methodology.

- Scenario 1 captures the 105 million for-pay parking spaces reported by the International Parking Institute (IPI 2009).
- Scenario 2 evaluates the paid spaces from scenario 1 plus square foot commercial estimates, a home space, and a work space for each vehicle. Scenario 2 is intended to capture the conservative 'known' inventory and does not foray into estimates of on-street non-metered parking.
- Scenario 3 adds urban on-street parking to scenario 2 based on AASHTO (2004) roadway design specifications.
- Scenario 4 uses a 3.4 to 1 spaces per car ratio from survey data.
- Scenario 5 evaluates the extreme upper limit where the rule-of-thumb 8–1 spaces per car ratio is employed. When this ratio is cited it is often implied that both designated and non-designated parking spaces are included capturing all potential parking area.

For each scenario, parking spaces are disaggregated by space type (on-street, surface, and structure) for evaluation. For scenario 1, of the 105 million metered parking spaces, 34 million are estimated for structures based on the number of structures and average size (ME 2001, TRB 1991). Of the remaining spaces it is assumed that one-half are on-street and the other half surface lots. Scenario 2 supplements scenario 1 by including the Litman (2009) square foot estimates for off-street non-residential spaces of 220 million and a home spot and work spot for each of the 250 million US vehicles (BTS 2009). Of the 220 million commercial spaces, it is assumed that 20% overlap with the metered spaces. It is also assumed that 20% of these commercial spaces are met by on-street free spaces. Home spaces are assumed to be a mix of 5% on-street, 90% surface (capturing the dominating share from home driveway and private garages as well as apartment building surface lots), and 5% garage. The work spaces are specified with a 5% on-street, 80% surface, and 15% structure mix, and 20% of work spaces are assumed to overlap with metered and commercial spaces. Based on these estimates, there are 730 million spaces in scenario 2. The general dominance of surface spaces in the percentage breakdowns is based on qualitative indicators from the literature suggesting preferential construction of surface-type spots. Scenario 3 builds on scenario 2 adding AASHTO (2004) design guideline parking areas for urban arterial, collector, and local roadways to capture on-street spaces. Bridge (150 million m^2) and tunnel (2.6 million m^2) potential parking area has been excluded (FHWA 2010, 2003, 2003). Furthermore, ramp area is removed. The New Jersey Department of Transportation reports 8300 lane miles of highway system in the state including 900 lane miles of ramps (roughly 11% of total highway area) (NJDOT 2008). Given the roadway density of New Jersey and assuming that fewer ramps exist on arterial, collector, and local roadways, an additional 5% of on-street potential parking area is removed. Of the remaining potential parking area, it is assumed that one-half is actually designated as such, and of the remaining urban roadways one-half have two parking lanes and the remainder one parking lane (producing 180 million on-street spaces). Because scenario 2 already captures 92 million on-street spaces, scenario 3 adds roughly 90 million spaces. Scenario 4 uses a 3.4 to one space-to-registered-car ratio for the US to produce an 840 million space inventory. A four-to-one ratio has been observed for urban environments which account for roughly 70% of vehicle kilometers traveled (VKT) for the private fleet and a 2.2-to-one ratio has been observed for rural environments (Davis *et al* 2010, FHWA 2007, Shoup 2005). The percentage of VKT urban and rural travel is assumed to be strongly positively correlated to registered vehicles. For every car, it is assumed that there is a home and work space with the same distributions specified in scenario 2. For the remaining spaces per car, the 220 million spaces from the square foot estimate in Litman (2009) including 34 million structure spaces are specified, with the remainder assumed to be on-street. The difficulty of estimating the number of on-street parking spaces remains a challenge for those evaluating the extent of the parking infrastructure. Data are sparse and methods for attributing roadway shoulders as potential parking spaces remain unclear. An often cited figure is that there are approximately eight spaces per car (Crawford 2000, Eckersley *et al* 2001), however, this 'rule-of-thumb' estimate has not been substantiated. Scenario 5 uses the eight-to-one ratio to capture the potential upper bound of the US parking inventory. While this ratio has not been verified, it is assumed to provide a more liberal assessment of on-street parking capturing spaces that scenarios 1–4 may miss. Following similar assumptions to scenario 4, Scenario 5 includes a home and work spot with the remaining spaces apportioned assuming 370 million surface, 69 million structure, and the remainder on-street (resulting in a total estimate of 2 billion spaces). Table 1 provides a summary for each of the scenarios of the number of parking spaces by type.

Several common factors are used across the scenarios. A parking space size of 17 m^2 (180 ft^2 at 9 ft by 20 ft) per space is used and 44% (the fraction of large vehicles in the private vehicle fleet, BTS 2009) of surface lot spaces have been adjusted to reflect an increase in paved area of 20% from typical transportation engineering design codes to accommodate SUVs, pickups, and vans (Litman 2008). The 76 million single-family detached and attached (i.e., town and row houses) homes account for 66% of the housing stock (US Census Bureau 2005). These homes are used in scenarios 2–5 to evaluate 220 million (90% of home spaces for the 250 million cars) private home spaces including driveways (private home garage structures are excluded) reported in the total surface spaces. For the 66% of private homes, 60% of these spaces are assumed to be asphalt and the remainder concrete, and driveways are included adding an estimated 25 m^2 (270 ft^2) per space.

Table 1. Parking spaces, annualized energy, and annualized emissions inventories. (Note: all results are rounded to two significant digits. Totals may not sum due to rounding.)

		Spaces (10^6)	Energy (PJ)	GHG (Tg CO2e)	CO (Gg)	SO_2 (Gg)	NO_X (Gg)	VOC (Gg)	PM_{10} (Gg)
Scenario 1	On-street	35	33	2.6	10	5.2	37	42	19
	Surface	36	26	2.0	7.5	4.0	29	32	15
	Structure	34	48	5.9	42	30	35	1.6	4.9
	Total	105	110	10	59	39	100	75	39
Scenario 2	On-street	92	88	6.8	26	14	99	110	51
	Surface	520	450	37	190	140	400	370	180
	Structure	110	150	19	130	97	110	5.2	16
	Total	730	690	63	350	250	610	490	250
Scenario 3	On-street	180	180	13	52	27	200	220	100
	Surface	520	450	37	190	140	400	370	180
	Structure	110	150	19	130	97	110	5	16
	Total	820	780	70	370	260	710	590	300
Scenario 4	On-street	150	140	11	42	23	160	180	83
	Surface	610	510	42	210	140	470	440	210
	Structure	84	120	14	100	74	86	4.0	12
	Total	840	770	67	350	240	710	630	310
Scenario 5	On-street	1100	1000	78	300	160	1100	1300	580
	Surface	790	640	52	240	170	610	610	290
	Structure	120	160	20	140	100	120	5.6	17
	Total	2000	1800	150	690	430	1900	1900	890

3. Parking spaces construction energy and emissions

To estimate energy consumption and emissions from parking construction, the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is used. PaLATE computes the direct and indirect energy and emissions from construction of asphalt or concrete surfaces using hybrid life-cycle assessment (PaLATE 2004, Hendrickson *et al* 2006). Hybrid life-cycle assessment uses process-based approaches to capture the direct effects of major processes and sub-processes such as the emissions from diesel equipment when placing asphalt. Additionally, economic input–output life-cycle assessment (EIO-LCA) is used to determine some indirect and supply chain effects such as emissions from mining aggregate for asphalt material components (Hendrickson *et al* 1998). PaLATE employs the hybrid approach to draw upon the benefits of process and EIO-LCA assessment and has been used in many environmental assessments (Sathaye *et al* 2010, Nathman *et al* 2009, Facanha and Horvath 2007, Carpenter *et al* 2007).

The physical characteristics of each parking space type are important when determining environmental effects. On-street and surface lot spaces are specified as asphalt and structure spaces as concrete. The on-street and surface spaces are assumed to have two 7.6 cm (3 inch) asphalt wearing layers and a 30 cm (12 inch) aggregate subbase, similar to a collector or local roadway. The lifetimes for the two space types are 10 (corresponding to the expected lifetime of an asphalt roadway) and 20 years. All surface spaces are estimated to produce an additional 50% area in access lanes. The structure spaces are assumed to sit on a 15 cm (6 inch) concrete slab. Because PaLATE captures the construction of only surface layers, additional information was supplemented for the structure. Guggemos and Horvath (2005) evaluates the energy and emissions in the life-cycles of steel and concrete building structures. The PaLATE concrete surface estimates are combined with the energy and emissions of structural components (assuming half of structures are steel structures and the other half concrete, and both have 30 year lifetimes) to determine the total structure spaces environmental inventory. Parking structure sizes and number of spaces are determined from TRB (1991) which reports that the average structure is roughly 14 000 m^2 and 500 spaces per floor. Similar to surface layers, all structure spaces are assumed to produce an additional 50% in access lanes. The supplementary data (SD) (available at stacks.iop.org/ERL/5/034001/mmedia) includes additional detail of the parameters used in PaLATE as well as the allocation of the life-cycle inventory (LCI) to passenger and freight vehicles.

4. Inventory results

The environmental inventory for the scenarios includes energy consumption and emissions of greenhouse gases (GHG), CO, SO_2, NO_X, VOC, and PM_{10}. GHG emissions include CO_2, CH_4, and N_2O emissions, summed using 100 year CO_2-equivalence (CO_2e) factors (with weightings of 21 for CH_4 and 310 for N_2O). The contribution of PM emissions to climate impacts has not been included. Table 1 details the annualized construction and maintenance requirements from PaLATE for each of the scenarios over the specified lifetimes.

The life-cycle energy and emission effects of parking space construction are dominated by several components. Energy consumption, GHG, CO, and SO_2 emissions are dominated by petroleum production for bitumen (the binder, or glue, that holds the aggregate together) in oil and gas extraction, transport, and refining (mostly related to the wearing layers). The majority of NO_X emissions are produced by diesel vehicles transporting materials in the asphalt production supply chain. Furthermore, significant SO_2 and

Table 2. Typical sedan energy and emissions inventory for varying parking space estimates. (Note: all results are rounded to two significant digits.)

		Operational inventory		LCI for scenario 1 (105×10^6 spaces)		LCI for scenario 2 (730×10^6 spaces)		LCI for scenario 3 (820×10^6 spaces)		LCI for scenario 4 (840×10^6 spaces)		LCI for scenario 5 (2000×10^6 spaces)	
		VKT	PKT	VKT	PKT	VKT	PKT	VKT	PKT	VKT	PKT	VKT	PKT
Sedan	Energy (MJ)	3.3	2.1	4.9	3.1	4.9	3.2	5.0	3.2	4.9	3.2	5.1	3.3
	GHG (g CO2e)	230	140	360	230	370	240	370	240	370	240	380	250
	CO (g)	11	7.2	12	7.7	12	7.7	12	7.7	12	7.7	12	7.8
	SO_2 (mg)	13	8.1	320	200	340	230	340	230	340	230	370	250
	NO_X (mg)	630	400	1000	640	1100	710	1100	720	1100	720	1200	870
	VOC (mg)	720	460	1200	730	1200	780	1200	800	1200	800	1400	970
	PM_{10} (mg)	79	50	230	150	250	170	260	180	260	180	340	260
SUV	Energy (MJ)	4.9	2.8	6.9	3.9	6.9	4.0	6.9	4.0	6.9	4.0	7.1	4.2
	GHG (g CO2e)	300	170	470	270	480	280	480	280	480	280	490	290
	CO (g)	13	7.6	14	8.2	14	8.2	14	8.2	14	8.2	14	8.3
	SO_2 (mg)	17	10	400	230	430	260	430	260	430	260	450	280
	NO_X (mg)	780	450	1200	720	1300	780	1300	800	1300	790	1500	960
	VOC (mg)	850	490	1300	780	1400	830	1400	850	1400	850	1600	1000
	PM_{10} (mg)	79	45	250	140	270	170	280	180	280	180	370	270
Pickup	Energy (MJ)	5.2	3.5	7.0	4.8	7.1	4.9	7.1	4.9	7.1	4.9	7.3	5.1
	GHG (g CO2e)	380	260	550	380	560	380	560	390	560	380	570	400
	CO (g)	17	12	18	12	18	12	18	12	18	12	18	12
	SO_2 (mg)	22	15	380	260	410	290	420	300	410	290	440	330
	NO_X (mg)	1000	710	1500	1000	1500	1100	1600	1100	1600	1100	1800	1300
	VOC (mg)	1400	960	1900	1300	1900	1300	2000	1400	2000	1400	2200	1600
	PM_{10} (mg)	78	53	240	160	270	200	280	210	280	210	380	310

NO_X emissions result from electricity production for material processing. When asphalt is placed, some of the petroleum-based ingredients volatilize (EPA 2001). The volatile organic diluents in asphalt are responsible for the majority of VOC emissions. With concrete, the organics released in cement production are the major VOC contributor. PM_{10} is produced in large part by the hot-mix asphalt plant during mixing of aggregates with other materials in creating the asphalt product, and in placement. Including these components in transportation inventories calls for new system-wide reduction policies and decisions that move beyond considering the tailpipe exclusively. The SD (available at stacks.iop.org/ERL/5/034001/mmedia) provides additional discussion of the significant life-cycle processes in parking space construction and maintenance as well as a sensitivity analysis and validation of key factors.

5. Automobile energy and emissions inventory effects

The addition of the environmental effects from parking to the automobile's LCI can be used for identifying the broader impacts associated with transportation infrastructure investment. Several studies have evaluated parking externalities within economic frameworks when evaluating the total cost of driving (Litman 2009, Shoup 2005, Delucchi 1997). It should be acknowledged, however, that the theoretical allocation of these effects can be split between vehicle use and the decisions and activities which generate travel.

Flow patterns in transportation networks (i.e., volumes on links and associated travel times) are the result of an equilibrium between the demand for travel (itself derived from the demand for activities) and the supply of transportation infrastructure and services. Thus, the supply of parking spaces is a determinant of the amount of automobile travel in a city or region (e.g., the provision of parking spaces by a shopping mall incentivizes automobile travel). On the other hand, observed flow patterns influence decisions by developers, businesses, and government agencies. Thus, high automobile flows lead developers to increase the supply of parking spaces. Because causality between parking supply and automobile travel flows occurs in both directions it is not possible to determine the allocation of environmental effects between the automobile and the decisions and activities that generate travel. This is important when assigning the environmental effects of parking to the automobile (or any other life-cycle component which indirectly exists because of automobile travel).

With total energy and emissions for each scenario (table 1), results are normalized per VKT and PKT to compare against other automobile life-cycle components presented in Chester and Horvath (2009). The annualized energy and emissions factors are divided by yearly US vehicle (sedan, pickup, SUV, motorcycle, bus, and freight truck) travel for each space type (see the SD for additional allocation detail available at stacks.iop.org/ERL/5/034001/mmedia). The infrastructure construction and operation components in Chester and Horvath (2009) include urban roadway parking area based on AASHTO (2004) design guidelines. This area has been removed from the Chester and Horvath (2009) infrastructure life-cycle component so that on-street parking can be evaluated independently in the scenarios. Additionally, Chester and Horvath (2009) automobile fuel economies have been updated. The per VKT factors are further normalized to PKT using the passenger occupancy levels identified in Chester and Horvath (2009).

Table 2 illustrates how the environmental effects of parking space construction appear when included in the

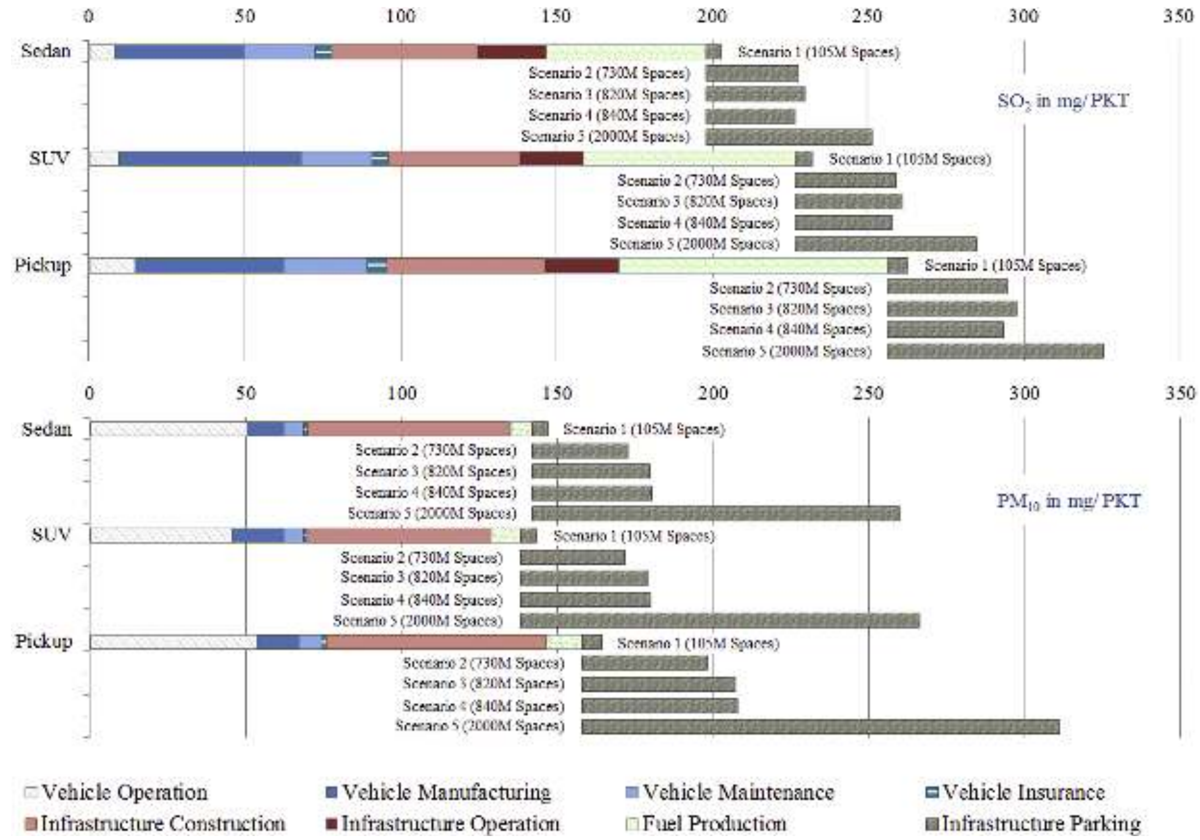

Figure 1. SO_2 and PM_{10} Automobile life-cycle emissions increases with parking scenarios. (Note: chart scales differ.)

automobile's LCI. We acknowledge that with an allocation methodology parking energy and emissions are split between decisions and activities that generate parking as well as vehicle use. The energy and emissions contributions from parking construction to automobile life-cycle performance in Chester and Horvath (2009) are based on scenario 1's 105 million spaces and are estimated to be at the low end of the space inventory. Table 2 summarizes the operational and life-cycle energy and emissions performance of sedans, SUVs, and pickups per VKT and PKT for each scenario.

The life-cycle factors include vehicle (manufacturing, operation, maintenance, and insurance, but not end-of-life shredding, see Boughton and Horvath 2006), infrastructure (construction, operation, maintenance, and insurance), and fuel (production and distribution) components. Each of these components is detailed extensively in Chester and Horvath (2009) (e.g., the energy and emissions associated with vehicle maintenance are determined from vehicle parts replacement as well as tire replacement, which have their own respective inventories), including the methodology used to calculate total energy and emissions and normalize per VKT or PKT. The operational factors are a composite of warm running mode, cold start mode, brake wear (PM), tire wear (PM), and evaporative losses (VOCs). Chester and Horvath (2009) provides a disaggregation of these operational factors for each vehicle type.

6. Discussion

The changes in automobile LCIs for the five parking scenarios are significant. Figure 1 shows the changes in sedan, SUV, and pickup SO_2 and PM_{10} life-cycle emissions when the different parking scenario inventories are applied. We have shown before that for some emissions (e.g., criteria air pollutants), life-cycle component contributions are much larger than fuel combustion emissions (Chester *et al* 2010, Chester and Horvath 2009). While scenario 1 shows small but non-negligible contributions to life-cycle SO_2 and PM_{10} emissions, scenarios 2–5 produce much larger effects. This highlights the importance of proper external valuation of air emissions to automobile travel. Energy consumption related to parking increases from 14–18 kJ/PKT in scenario 1 to 240–310 kJ/PKT in scenario 5. GHG emissions increase from 1.3–1.7 g CO_2e/PKT in scenario 1 to 19–25 g CO_2e/PKT in scenario 5. For NO_X and VOCs in scenario 5, the contribution of parking accounts for up to 27% of life-cycle emissions. Parking construction emissions externalities are not included in any known study to date and figure 1 shows that they can constitute a significant portion of an automobile's life-cycle emissions, ultimately increasing the total cost of driving.

Each of the scenarios represents a specific commitment level to automobiles by providing a level of parking service. Under-priced parking induces further dependence on the

Table 3. Parking infrastructure commitment by land area and spaces. (Note: fraction of total US surface area covered includes road and parking surface area and is adjusted for multi-story structures. All results are rounded to two significant digits.)

	10^9 m^2 of parking	m^2 of parking per 100 m^2 of roadway	Number of parking spaces per road km	Land area covered (roadways + parking) 10^9 m^2	Fraction of total US surface area covered (roadways + parking) (%)
Scenario 1	2.5	6.3	25	42	0.46
Scenario 2	21	51	170	60	0.64
Scenario 3	22	55	200	62	0.66
Scenario 4	23	58	200	63	0.68
Scenario 5	44	110	470	84	0.90

automobile (Hess 2001, Wilson and Shoup 1990). The amount of paved surface in a city compared to total land area has been evaluated (Shoup 2005). By comparing the total parking area against the total paved road area, the range of parking space inventories in the scenarios highlights the parking infrastructure commitment. In the US in 2005, there were approximately 13 million lane kilometers: 420 thousand interstate, 1.6 million arterials, 2.6 million collectors, and 8.8 million local (FHWA 2007). This results in an area of 40 billion m^2 (approximately 0.44% of total US land area) which includes roadway shoulders which may double as parking. For scenario 1, 2.5 billion m^2 of parking area is produced so that for every 100 m^2 of roadway an additional 6.3 m^2 of parking exist. The paved parking surface is only exacerbated in the larger inventories, as shown in table 3. Scenario 2 produces 51 m^2 of parking for every 100 m^2 of roadway, scenario 3, 55 m^2, scenario 4, 58 m^2, and scenario 5, 110 m^2. While this average assessment does not capture the higher concentrations of parking in urban environments, scenario 5 illustrates that a larger infrastructure is required for parking than for moving automobiles. Including the additional surface area covered by parking results in between 0.46% and 0.90% of US land area covered (including roadway and parking paved area). Additionally, the range in inventory estimates can be evaluated by normalizing the number of parking spaces per kilometer of roadway (ranging from 25 to 470).

Scenario 5 is intended to capture the extreme upper limit of the parking inventory and results should be evaluated acknowledging its underlying assumptions and potential of capturing incidental parking area. The accuracy of scenario 5's eight spaces per automobile ratio can be evaluated through estimates of curbside parking from roadway lengths. The rule-of-thumb approach represents an extreme upper bound is thought to capture home, work, and commercial spots as well as the mixed use portion of roadways which often serve as parking. There are about 4.1 million km of urban and rural roadway in the US classified as minor arterial, collector, or local (FHWA 2007). Scenario 3 evaluates this roadway's potential on-street parking eliminating a large fraction of the area due to bridges, tunnels, ramps, and an assumption for actual designated spaces. Using AASHTO (2004) rural shoulder and urban parking lane specifications (see the SD available at stacks.iop.org/ERL/5/034001/mmedia) without assumptions for area actually designated as parking, 820 million on-street parking spots are produced (excluding bridges, tunnels, and ramps). Adding these spaces to scenario 2's inventory (which includes one home and work spot per automobile, for-pay spaces, and commercial square foot spaces) results in an inventory of 1.5 billion total parking spaces (although paved area that is only sometimes used for parking is counted and minimum residential road widths are often tied to emergency vehicle requirements). This estimate does not include additional paved surface or unpaved fields that can be pressed into temporary service. The challenge of using the curbside inventory and the eight-to-one ratio is related to the difficulty in assessing the multiple functions of roadway shoulders (i.e., parking, driving, and serving the additional functions of pedestrian and cyclist access ways). While many roads have clearly marked parking spaces (with either paint or signage) and are not used for traffic, other road shoulders can and sometimes do accommodate parking, and traffic adjusts to avoid the vehicle (e.g., cul-de-sacs).

The effect of the parking inventory added to an automobile's life-cycle energy consumption and emissions is significant. For some emissions, the increase from scenario 1 to scenario 5 is significant even when normalized per PKT. The externalities of this increase are important when attempting to capture the total costs of private vehicle use (Delucchi 1997, Litman 2009, Shoup 2005). Estimating the extent of paved roadway and parking area is critical when evaluating the total costs of transportation.

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