Citywide Impacts of E-Commerce: Does Parcel Delivery Travel Outweigh Household Shopping Travel Reductions?

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ABSTRACT

E-commerce has facilitated online ordering of goods by households in recent years. This technological advancement has disrupted shopping related transportation. While the National Household Travel Survey (NHTS) [1] finds that household shopping frequency has declined in the last 10-20 years, deliveries by parcel delivery trucks and vans [2] have increased. However, the net effect of these phenomena on overall trip making, vehicle-miles traveled (VMT) and fuel consumption has not been quantified. From a regional planning perspective, understanding the net effect is important for informing city policies—for example, in regards to land use and transportation planning.

The objective of this research is to address this gap. In this study, the net regional impacts of e-commerce on “last mile” transportation and fuel consumption are evaluated.

The approach relies on a powerful, agent-based modeling framework (POLARIS) [3] that models decisions made by individual household and commercial agents. E-commerce demand is modeled for each household using a bilevel multinomial probit structure that evaluates e-commerce participation and ordering frequency. Last-mile delivery tours were constructed using GIS-based tools and information from a major parcel delivery company [4]. After integrating the resulting supply and demand models with all other passenger and commercial traffic within POLARIS, a traffic simulation was performed and subsequently VMT and energy consumption were analyzed.

The study finds that while e-commerce has generated an increase in parcel truck delivery trips, the net effect of e-commerce is a reduction in VMT and fuel consumption due to major reductions in these quantities via shopping trip reductions.

SCC '19, September 10–12, 2019, Portland, OR, USA

https://doi.org/10.1145/3357492.3358633

CCS CONCEPTS

• Social and professional topics → Sustainability • Electronic commerce • Online shopping • Routing and network design problems

KEYWORDS

E-commerce, net effect, vehicle miles traveled, VMT, energy, delivery, truck, shopping, NHTS, POLARIS, region, city

ACM Reference format:

Monique Stinson, Annesha Enam, Amy Moore and Joshua Auld. 2019. Citywide Impacts of E-Commerce: Does Parcel Delivery Travel Outweigh Household Shopping Travel Reductions? In *Proceedings of ACM SCC 2019 conference (SCC'19). ACM, New York, NY, USA, 7 pages.* https://doi.org/10.1145/357492.3358633

1 Introduction and Background

Generally speaking, city planning and policy measures aim to promote economic health, mobility, energy efficiency, and other desirable urban traits that enhance quality of life for residents. Access to shopping and low levels of congestion typically are considered desirable features in a metropolitan area.

In recent years, however, travel by motorized vehicles has grown to such levels that congestion is a top concern in many cities. At the same time, accessibility to shopping has been enhanced in a new way with the emergence of e-commerce, which has grown from less than 1% of US retail purchasing in 2000 to about 10% in 2018 [5]. Traffic by parcel delivery trucks, which transport deliveries from fulfillment centers and other e-commerce distribution points to homes and businesses, has grown accordingly [6]. Simultaneously, on the whole individuals are making fewer shopping trips, with about 700 annual one-way shopping trips per person in 2001 and 580 in 2017 for a 17% reduction [7].

Based on these statistics, it is reasonable to claim that delivery trips are replacing shopping trips to some extent. However, it is not known whether this replacement is making congestion and energy use worse or better—after all, parcel delivery trucks consumer more energy than passenger cars, but they typically operate in an efficiently designed tour rather than in out-and-back trips (e.g., home-store-home). Understanding the net effects of e-commerce in a way that accounts for such nuances is important for cities and government agencies in general as they develop plans and policies around e-commerce.

Questions regarding the overall effects of e-commerce on transportation mobility and energy have been circulating since the advent of e-commerce (for example, see [8] and [9]). Since those early years, researchers and practitioners have recognized that e-commerce seems to reduce demand for shopping trips while increasing the supply of delivery trucks throughout the roadway network. The main question, then, is: what is the net effect of e-commerce on regional mobility and energy consumption? Increased activity in online shopping, which generates more delivery trips, should generate at least some reduction in brick-and-mortar shopping trip rates and vice versa (see Figure 1). Therefore, to answer this question, both shopping trips and delivery trips must be accounted for to obtain a complete picture of the impacts of e-commerce on VMT and energy.

Figure 1. Interaction of e-commerce delivery rates and shopping trips rates.

Several studies have explored this topic for a specific industry. For example, [10], [11] and [12] study home meal delivery find that shopping for meal ingredient typically has more negative effects on VMT, energy and emissions than the meal delivery system.

However, very few studies have addressed this question at the system level by including all types of retail purchasing. To be sure, it is included in frameworks such as [13]; however, [13] does not model the trips made by delivery trucks (although their importance is recognized) and therefore is unable to estimate net effects. Similarly, a study using 2009 NHTS data [14] develops quantitative estimates of the number of e-commerce deliveries made to households in a large region in upstate New York, but is limited to the household demand perspective due to lack of data on delivery tours.

From the household demand perspective, Cao et al. [15] explore the impact of shopping accessibility on e-shopping frequency for Minneapolis and St. Paul metropolitan areas of Minnesota using structural equation model. They note that the effect varies by the location of the household. High shopping accessibility seems to increase the e-shopping frequency for the urban households, while the opposite seems to be true for exurban households. For suburban households, a conclusive effect was not found. Comi and Nuzzolo [16] deploy a nested logit formulation to quantify the demand for in-store and online shopping for Rome, Italy. They highlight demographic variables such as gender, age and employment status to be important determinants of e-shopping and propensity in general. However, the study does not comment on the impact of transportation accessibility on e-shopping frequency.

As a result of these limitations, there is still a major question regarding the net impact of e-commerce on cities. This study aims to address this gap. To the knowledge of the authors, this is the first study of its kind to address the passenger shopping/parcel delivery tradeoff question in detail. Quantifying this tradeoff and its net effects on VMT and energy use is the main contribution of this study. Other contributions include the development of an innovative, econometric model of e-commerce demand at the household level, which addresses some of the limitations of earlier work. Additionally, this study develops and demonstrates a methodology that can be used in other areas to model parcel delivery trips, household e-commerce demand, and their combined effects.

This study focuses on a localized and important part of the journey of retail goods. Many retail goods travel for very long distances around the globe or across a nation before reaching their final destinations with the consumers who purchase them. The long haul portion is not included in this study, as the focus is on e-commerce effects in urbanized areas. Within the region, transport between regional distribution centers and stores may take place. Changes in this portion of retail goods transport are not included in the current work, but are being included in ongoing extensions of this work. This study focuses entirely on the journey of retail goods to the final consumer and the two main options for this journey. First, a traditional shopping trip can be generated by the consumer as s/he picks up the goods from a store. Second, a parcel delivery truck can deliver goods from the depot to the home or business location of the consumer.

2 Approach

2.1 Activity-based model with dynamic traffic assignment

The main analysis platform is an agent-based modeling platform, POLARIS [3], which models the decisions of all individuals and households in the Chicago region. Further, the platform performs Dynamic Traffic Assignment (DTA), using mesoscopic traffic simulation procedures to find optimal transportation paths for agents as they move through the system in pursuit of activities. To support studies that analyze transportation and its impacts on energy use, dozens of passenger vehicle classes, which are distinguished by body types, fuel types, and powertrain configurations, are used within POLARIS.

Until recently, freight transportation in POLARIS was modeled using estimates of generic Medium Duty Truck (MDT) and Heavy Duty Truck (HDT) trips between traffic analysis zones (TAZ) in the region. A more detailed process was required to model trips that are made by parcel delivery trucks, which for this study are all assumed to be MDT (Class 3-6) vehicles [17]. Furthermore, detailed truck classes previously were not included in the simulation framework, which limited its ability to support freight-related transportation and energy analysis. As such, the first part of approach involves developing a model that (a) leverages the finely detailed geographic, network, and traffic capabilities of POLARIS and (b) utilizes the comprehensive nature of the POLARIS platform to model household e-commerce demand, parcel delivery truck supply, and their interaction in a dynamic traffic environment. While the entire modeling effort includes introducing all types of commercial vehicles into POLARIS, this discussion focuses only on the aspects that pertain to e-commerce.

2.2 Scenarios

The next step is to establish average rates of household demand for e-commerce deliveries. Data from the 2017 National Household Travel Survey (NHTS) [1] are used to establish a baseline rate. According to the survey, individuals over 16 years old on average generated an online order 2.5 times in the last 30 days, which is equivalent to 0.08 deliveries per person-day. Two scenarios were developed to test a more aggressive rate as well as a "corner case" (Table 1). The more aggressive rate is 0.20 orders per person per day while the corner case rate is 0.50 orders per person per day. Based on an average household with two adults [1], these rates are equivalent to about one household order per week, three per week, and seven per week, respectively. The corner case is designed as a "What if?" scenario to test the extreme (though perhaps unlikely) possibility that e-commerce orders replace all regular shopping trips. Major shopping trips, which involve shopping for goods such as appliances and cars, are not adjusted.

Scenario	Year	Household E-commerce Rate (Approx. Deliveries per Week)
Baseline	2020	1
C	2040	3
B		7

Table 1. Scenarios with different e-commerce demand rates.

2.3 High/low technology scenarios

Within each of the e-commerce scenarios (C and B), two variations were tested: one with low-tech vehicle options and another with high-tech vehicle options. The main difference is that, for the high-tech scenarios, more electrification is assumed to occur across fleets. Both of these scenarios assume a long-range timeframe (2040). Vehicle technology assumptions are documented in [18].

2.4 Household-level e-commerce demand model

A household-level e-commerce model is developed to generate demand for delivery stops within POLARIS (Table 2) using data from [19]. The first model identifies whether or not a household participates in e-commerce. Subject to the participation decision, the second model quantifies the ratio of delivery to retail shopping for that household. When the model is implemented, POLARIS then evaluates for every household whether it participates in e-commerce and, if it does, how frequently it participates (in other words, how many orders it makes per week). The weekly e-shopping deliveries then replace physical shopping trips in the model. The baseline model produces the 0.08 rate in aggregate over the Chicago area population as required for the baseline scneario. To meet the specified rates for future scenarios (0.20 and 0.50), the model parameters are adjusted.

The estimated model parameters are intuitive as they indicate the following. Households with more children participate are more likely to participate in e-commerce than households with fewer children. Households with high incomes are more likely to participate in e-commerce compared to households with low incomes. In addition, households that are located farther from transit are more likely to participate in e-commerce compared to households with closer transit service. This finding supports the efficiency hypothesis proposed by Anderson et al. [20], according to which people with low shopping accessibility tend participate more in e-commerce.

Among households that participate in e-commerce, relatively high income tends to increase the delivery to retail ratio, while high numbers of adults and vehicles tend to decrease the ratio. Households with good walk accessibility have a lower delivery to retail ratio. This observation indicates that better shopping accessibility is conducive to brick-and-mortar retail shopping and tends to discourage high rates of e-shopping.

Binary Choice: Whether Participates in E-commerce or not		
Variables	Estimates	t-stat
Constant	-0.103	-1.64
# of HH Children	0.104	1.39
HH income less than 25k	-0.459	-2.33
HH income between 25k and 50k	-0.54	-3.37
HH income between 50k and 100k	-0.154	-1.41
HH income greater than 200k	0.355	3.32
Distance to nearest transit stop from home (in 100th of miles)	0.077	1.18
Ratio of Delivery to Retail Shopping		
Parameters to the latent propensity		
Constant	2.882	11.7
# of HH Adults	-0.146	-2.49
HH income greater than 200k	0.369	3.29
Walk Score (Range 0 to 10)	-0.057	-3
# of HH Vehicle	-0.18	-2.8
Threshold Parameters		
Theta 0	-ve Infinity	Fixed
Theta 1	0	Fixed
Theta 2	1.576	11.86
Theta 3	2.162	15.74
Theta 4	2.738	19.23
Theta 5	3.482	22.34
Theta 6	+ve Infinity	Fixed
Summary		
Number of Observations	971	
Final Log-likelihood	-1362.45	

Table 2. Household-level e-commerce demand models.

The model can be extended in future efforts by using different e-commerce adoption and frequency rates based on residential location. For example, city dwellers may in fact be more technologically savvy than suburban residents, therefore they may be more inclined to replace shopping trips with deliveries. However, due to data limitation this potential distinction of tech savviness variation by geography could not be included.

2.5 Model of MDT parcel delivery tours

Parcel delivery tours of MDT vehicles that serve the household e-commerce delivery demand are generated. The total number of stops that are made by the tours is adjusted to match the household-level delivery demands.

For the baseline, tours are generated as follows. A model that was previously developed using actual UPS truck GPS traces in Columbus, Ohio [4], is adapted for the Chicago metropolitan region. In the previous work, truck GPS traces were obtained for a representative portion of the delivery truck fleet. Delivery locations were extracted from the traces. Socioeconomic and land use data were used in conjunction with the delivery locations to develop a delivery demand estimation model, which provides delivery estimates for the entire Columbus MSA. Using an adapted version of the Columbus model, numbers of deliveries in each of the nearly 2,000 TAZs in the Chicago Metropolitan Statistical Area (MSA) were estimated and used to create a randomized point layer to represent estimated delivery locations within each TAZ. These points are then grouped according to proximity to UPS depots to represent service areas. These service area groups are arranged using a sorting algorithm in ArcGIS, which uses a peano curve to list, in tabular format, nearest neighbor points relative to the previous point. Once the service areas are sorted, sets of 120 points are created to form MDT delivery tours (the 120 points correspond to 120 stops, which is the average number of stops per tour found in the previous study). Finally, a traveling salesman algorithm is applied to generate the tour with a list of stops ordered by stop sequence.

The randomly distributed stop locations then are assigned to the closest location in the POLARIS network. Each location typically corresponds to one parcel of land. This process results in a set of baseline delivery tours with MDT vehicles traveling between delivery stops in an efficient, peddling fashion.

Lastly, the number of MDT trips is adjusted for each scenario so that the total is consistent with the e-commerce demand that is produced in the household model. This adjustment makes total supply and demand consistent at the regional level. However, one limitation of this process is that demand and supply at the TAZ level are not entirely synchronized. A process to achieve this is currently being implemented. Nevertheless, while this will alter subregional patterns of MDT delivery tours, it is not expected to have much impact on the total estimates of VMT and energy.

2.6 Start times for delivery tours

The start time of each MDT trip must be specified, as this is not included in the above process. An algorithm is developed to assign each trip and tour to specific start times throughout the day. Start times of individual trip segments on parcel truck tours are assumed to be uniformly distributed between 9 AM and 5 PM (i.e., parcel trucks are assumed to leave the depot in the morning and to make deliveries around the region throughout the day, returning to the depot before 6 PM). This is important for POLARIS because it simulates traffic flows in 6-second intervals.

2.7 Calibration and validation

Calibration and validation are performed to ensure that the model produces reasonable results. Total freight VMT by MDT and Heavy Duty Trucks (HDT) combined is about 8%, which is comparable the 10% estimated in national studies [21]. The same report indicates that freight trucks consume about 30% of transportation energy; the model produces 36%, which likewise is comparable. By construction, total e-commerce demand matches the e-commerce rates that were obtained from the NHTS.

2.8 Integration and simulation in POLARIS

The e-commerce supply and demand models are fully integrated in POLARIS. This permits the MDT delivery trucks to be routed in the traffic network alongside passenger shopping trips, other passenger trips, and other commercial trips, providing a complete picture of MDT delivery truck VMT and energy consumption in a congested travel network.

The simulated network flows by MDT delivery trucks and passenger shopping trips are subsequently analyzed to evaluate their net VMT and energy use. To illustrate the efficiency of MDT delivery tours, Figure 2 shows a tour that is generated by this process and assigned by the DTA. As expected, the tour originates at a depot belonging to a parcel carrier; travels out to the delivery neighborhood; makes dozens of deliveries in the concentrated delivery area; then travels back to the depot.

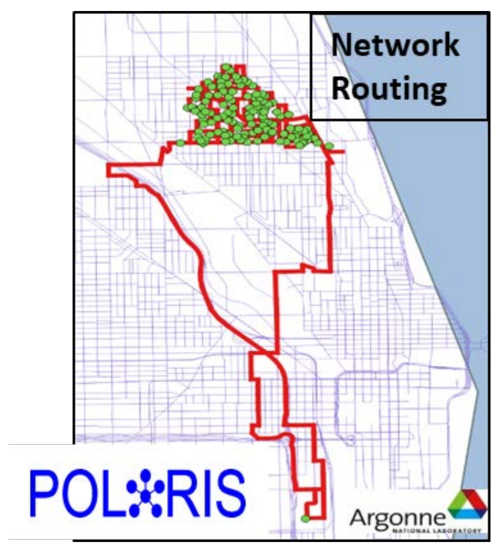

Figure 2. Example e-commerce tour (red) and individual stops (green) from the POLARIS DTA following routing on the congested transportation system.

3 Data

This section describes each data source and how the data were used in the study. Data are obtained from the following sources: the 2017 NHTS, a major parcel carrier (UPS), the WholeTraveler survey, and a study in Seoul, South Korea.

The 2017 NHTS [1] provides information on person-level e-commerce ordering rates. Responses to the question "In the past 30 days, how many times did you purchase something online and have it delivered?" were used to establish the baseline ordering rate per person over 16. For one future scenario, a rate of 0.20 deliveries per person per day is used based on a study of residents of Seoul, South Korea [22]. For the other future scenario, which assumes that each household generates one order per day, a rate of 0.50 per person per day is used based on average household size information from the NHTS [1].

Data from the WholeTraveler survey [19] are used in this study to estimate parameters of the household-level e-commerce demand model. The survey includes questions on how frequently the household made e-commerce orders in the last week and information on household sociodemographics.

Parcel delivery truck data, which include information on both vehicle tours and delivery stops, were provided by UPS in an earlier study and used to inform the delivery tour estimates that are modeled in this study. Data sources for the previous study are described in more detail in [4]. Population, employment, and other land use data from [23] are used to adapt the model to the Chicago region. The randomly distributed stops within each TAZ are assigned to a specific POLARIS location using land use data [23].

4 Results

This section discusses the results of the study. First, activity and mobility shifts that are predicted by the household e-commerce model are reviewed. Second, the impacts of e-commerce on VMT and energy use are presented and discussed. Findings are presented for passenger shopping trips, MDT delivery trips, and the net effects of the two types of trips. The baseline is discussed first followed by scenario-specific results.

4.1 Activity/mobility shifts

In the baseline scenario, about 50% of the households participate in e-commerce and the per-capita rate of delivery is about 0.08 deliveries per day. In the moderate e-commerce scenario, per-capita delivery is increased to 0.20 per day and household e-commerce participation correspondingly is increased to about 75%. In the corner case scenario, all households are assumed to participate in e-commerce and per capita delivery is increased to 0.50 per day, replacing the non-major shopping trips of all households.

4.2 Baseline VMT

Figure 3 shows the baseline VMT accrued by passenger shopping trips, other passenger trips, MDT parcel delivery (e-commerce retail) trips, and other types of MDT and HDT trips. Passenger shopping in the baseline constitutes about 18.2 million miles in the Chicago region, which is about 6% of all Chicago-area VMT. The potential to reduce overall VMT by replacing these trips with a more efficient retail system therefore is substantial. Figure 3 also shows that the baseline MDT parcel trips only generate 0.4 million miles, which is a small percentage of total baseline VMT.

4.3 VMT and Energy Analysis by Scenario

In general, more e-commerce shopping leads to more MDT trips and fewer passenger car trips due to reductions in physical shopping trips by households. At the same time, it reduces total retail-based fuel consumption for the last mile to consumers.

Figures 4-6 and Table 3 show the estimated VMT, fuel and total energy results that are attributable to retail purchasing. Results are differentiated for MDT delivery vehicles and passenger shopping vehicles, which are all light duty vehicles (LDV). In bar charts, the results are stacked so that the total VMT and energy can be seen in addition to the amount that is attributable to each vehicle type.

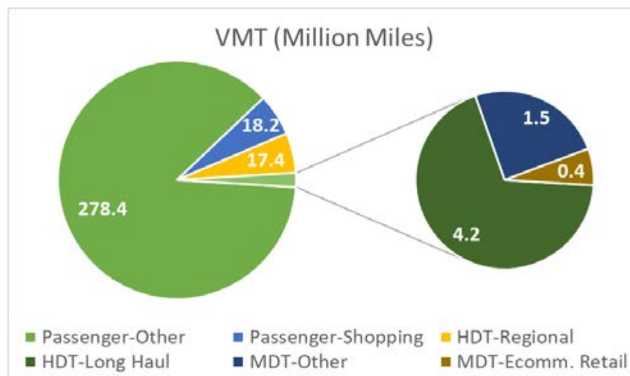

Figure 3: Modeled VMT by various vehicle types and trip purposes in the Chicago metropolitan region

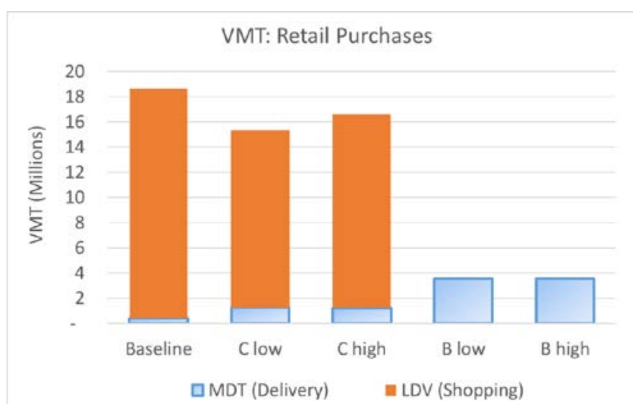

Figure 4. Retail VMT by parcel delivery MDT and passenger shopping LDV

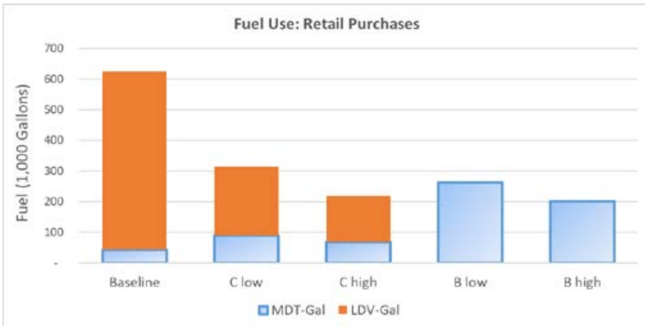

Figure 5. Retail-driven fuel consumption by parcel delivery MDT and passenger shopping LDV

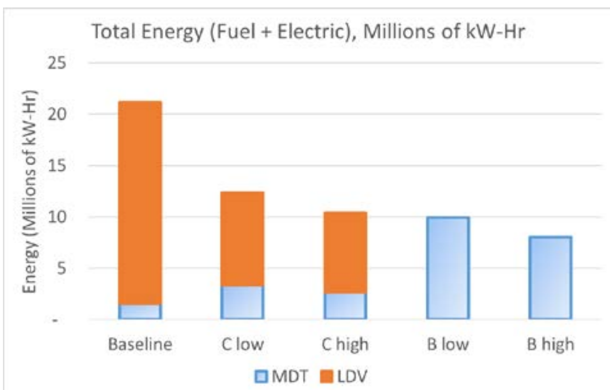

Figure 6. Retail-driven total energy consumption by parcel delivery MDT and passenger shopping LDV

Metric	Unit	Base-line	Δ C-low to base	Δ C-high to base	Δ B-low to base	Δ B-high to base
VMT: MDT (Delivery)	a	0.4	211%	207%	781%	783%
VMT: LDV (Shopping)	a	18.2	-23%	-16%	-100%	-100%
VMT: Total	a	18.6	-18%	-11%	-81%	-81%
Fuel consumption: MDT (Delivery)	b	0.0	110%	60%	517%	372%
Fuel consumption: LDV (Shopping)	b	0.6	-61%	-74%	-100%	-100%
Fuel consumption: Total	b	1	-50%	-65%	-58%	-68%
Total Energy	c	21	-42%	-51%	-53%	-62%
Electricity: MDT (Delivery)	c	0.0	0.2	0.2	0.4	0.8
Electricity: LDV (Shopping)	c	0.0	1.4	2.6	0.0	0.0
Electricity: Total (Deliv. + Shopping)	c	0.0	1.5	2.8	0.4	0.8

Units: a=Million miles, b=Million gallons, c=GWh

Table 3. Summary of regional VMT, fuel, electricity and total transportation energy impacts of e-commerce.

In Scenario C, where the delivery rate is about 2.5 times that of today, shopping VMT decreases by about 20% while parcel MDT VMT doubles. A net reduction of about 15% in retail VMT occurs. However, as significant advances in technology are assumed to occur for passenger vehicles in both the low- and high-tech cases, fuel consumption is forecast to be much lower than today's consumption with a net reduction of about 50%-65%. In other words, while the increase in e-commerce creates a net VMT savings of 15%, the percentage of fuel saved is much greater based on assumptions around vehicle technology improvements. Similarly, total reduction in net energy (fuel and electricity combined) is sizeable at about 40%-50%, which is again attributable the combined effect of less driving overall and improvements in vehicle technologies. Total energy is computed by assuming that gasoline has 33.7 kWh per gallon and diesel 37.1.

In accordance with Table 1, in Scenario B all daily shopping needs of households are satisfied with e-commerce, thereby eliminating the need to travel to stores. As such, Scenario B provides a glimpse into the maximum potential system efficiency that can be gained by a wholescale replacement of shopping trips by e-commerce deliveries. Given that the average shopping trip is about 7 to 8 miles long [7] and that regular shopping constitutes about 6% of all vehicle miles in POLARIS, the potential VMT reduction is substantial. Based on the results of this study, the potential savings is about 80% of retail-based VMT, about 60%-70% of retail-based fuel consumption, and 55%-60% of total energy.

At first glance, it may seem surprising that the reduction in fuel and total energy consumption is not higher in Scenario B, given that the reduction in VMT is dramatically higher than that in Scenario C. This is explained by the preponderance of LDV in Scenario C, which are assumed to be much more fuel efficient than the MDT fleets that generate all of the retail VMT in Scenario B. Both LDV and MDT vehicles are assumed to become more efficient in future years, but the adoption rates of energy-efficient technologies are assumed to be higher among LDV customers than MDT customers. Overall, the net effects on fuel and energy consumption is about the same between the Scenarios B and C for this reason.

5 Conclusions

This study analyzes the net effect of e-commerce on VMT and transportation energy consumption in a metropolitan area, accounting for both reductions in passenger car shopping trips and increases in MDT delivery truck trips. The study develops new methods to conduct this analysis. As part of this, an innovative model for modeling e-commerce demand at the household level is developed. The model is implemented along with a parcel delivery touring model in an agent-based platform. Traffic is simulated for all travel in the region, then the net effects of e-commerce demand and e-commerce supply are evaluated.

The study finds that increasing rates of e-commerce have net benefits on the transportation system and energy use. As more households adopt e-commerce and e-commerce is used for a greater percentage of retail shopping occasions, substantial savings in VMT and fuel consumption result. This phenomenon is explained mostly by the characteristics of LDV shopping trips and the MDT parcel delivery tours that replace them. Passenger LDV shopping trips currently generate about 6% of VMT in the Chicago region and each shopping trip is about seven or eight miles on average. Replacing one of these trips with an extra stop on a delivery tour generates a small increase in MDT VMT every time a much longer LDV trip is replaced.

Adoption of vehicle electrification technology improvements generates additional fuel savings. However, the e-commerce energy savings benefit is constrained by availability and/or adoption of efficient MDT vehicle technologies.

Overall, increases in e-commerce adoption as well as improvements in MDT vehicle technologies present a major opportunity for VMT and energy efficiency to be improved in metropolitan areas.

ACKNOWLEDGMENTS

The submission has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne") and UT-Battelle, LLC, Operator of Oak Ridge National Laboratory ("ORNL"). Argonne, a U.S. Department of Energy Office of Science laboratory, is funded and operated under Contract No. DE-AC02-06CH11357. ORNL, a U.S. Department of Energy Office of Science laboratory, is funded and operated under Contract No. DE-AC05-00OR22725. The following Department of Energy project managers played a role in guiding this work: David Anderson and Prasad Gupte. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government. Argonne National Laboratory's work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Office

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