Collaborative Sciences Center for ROAD SAFETY

FINAL REPORT

Urban Freight and Road Safety: Trends and Innovative Strategies

October 2021

Noreen McDonald
Torrey Lyons
Jueyu Wang
University of North Carolina, Chapel Hill

Christopher Cherry
Mojdeh Azad
Saurav Parajuli
University of Tennessee, Knoxville

Offer Grembek
University of California, Berkeley

The University of Tennessee Knoxville | Berkeley University of California | FAU Florida Atlantic University | Duke University | The University of North Carolina at Chapel Hill

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Acknowledgement of Sponsorship

This project was supported by the Collaborative Sciences Center for Road Safety, www.roadsafety.unc.edu, a U.S. Department of Transportation National University Transportation Center promoting safety.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CSCRS-R30		

4. Title and Subtitle: Urban Freight and Road Safety: Trends and Innovative Strategies	**5. Report date** December, 2021
	6. Performing Organization Code
7. Author(s) Noreen Mcdonald; Torrey Lyons; Jueyu Wang; Christopher Cherry; Mojdeh Azad; Saurav Parajuli; Offer Grembek	**8. Performing Organization Report No.** CSCRS-R30
9. Performing Organization Name and Address University of North Carolina, Chapel Hill, NC University of Tennessee, Knoxville, TN University of California, Berkeley, CA	**10. Work Unit No.**
	11. Contract or Grant No. Collaborative Sciences Center for Road Safety R30
12. Sponsoring Agency Name and Address Collaborative Sciences Center for Road Safety 730 Martin Luther King Jr. Blvd., Suite 300 Chapel Hill, NC 27599-3430	**13. Type of Report and Period Covered** Final Report (June 2019-June 2021)
	14. Sponsoring Agency Code

15. Supplementary Notes

Conducted in cooperation with the U.S. department of transportation, federal highway administration.

16. Abstract

The increasing freight demand in recent decades has posed road safety threats on urban local communities. This project addresses the urban freight road safety issues by 1) using data from NC and TN surveillance systems to evaluate the impacts of urban freight on road safety through detailed spatial and longitudinal analyses; 2) reviewing novel last-mile delivery options and identifying the advantages and disadvantages of these options in improving road safety. The spatial and longitudinal analyses reveal a statistically significant increase in the number of crashes between vulnerable road users and commercial vehicles in both North Carolina and Tennessee and find that light trucks and vans are less likely to produce severe and fatal compared to large commercial vehicles variables crashes. These results highlight the critical role of goods movement in road safety outcomes and the safety benefits of adopting smaller vehicles for last-mile delivery. The systematic review reveals that very limited studies have looked at the safety impacts of last-mile strategies, highlighting research needs on assessing safety impacts of these last-mile delivery strategies.

<table>
<tr><td colspan="2">17. Key Words

Last-mile delivery strategies; Urban freight; crashes; Literature review; Vulnerable road users</td><td colspan="2">18. Distribution Statement

No restrictions. This document is available through the collaborative sciences center for road safety (roadsafety.unc.edu), chapel hill, NC.</td></tr>
<tr><td>19. Security Classif. (of this report)

Unclassified</td><td>20. Security Classif. (of this page)

Unclassified</td><td>21. No. Of Pages

58 pages</td><td>22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Contents

Tables

Figures

Executive Summary

Changing consumer preferences and technological advances have created greater demand for freight. Such growth in freight demand has posed greater challenges on last-mile delivery and road safety threats on urban communities. Last-mile delivery, a term used to describe the last stretch of the supply chain between a final distribution center and the desired destination point, is considered the most costly and inefficient portion of the supply chain. The frequent movement of freight vehicles for last-mile delivery has also caused increasing concern over road safety. Logistic firms usually use freight vehicles to move goods from warehouse and distribution centers to businesses and households. These freight vehicles usually have larger size and are difficult to maneuver. As freight movement has becoming prevalent in urban communities, where Vulnerable Road Users (VRU), including pedestrians and bicyclists are concentrated, freight vehicles for the last mile delivery cause growing concern over road safety. This project aims at

- Using data from NC and TN surveillance systems to evaluate the impacts of urban freight on road safety through detailed spatial and longitudinal analyses.
- Reviewing novel last-mile delivery options and identifying the advantages and disadvantages of these options in improving road safety.

Corresponding to the two key objectives of this project, this report describes work in two parts:

Part I: "Exploring the Determinants of Crash Severity for Incidents Involving Vulnerable Road Users and Commercial Vehicles in North Carolina and Tennessee" explores the spatial and temporal patterns of freight vehicle interactions with VRU in urban areas of North Carolina and Tennessee. We find a statistically significant increase in these crashes in North Carolina and Tennessee, highlighting the importance of looking at VRU-commercial vehicle crashes to improve traffic safety. This section also examines the impacts of crash-level characteristics on the severity of crashes. It reveals that the small vehicles for last-mile delivery are less likely to produce crashes causing severe injuries or fatalities. If carriers continue their trend of using smaller vehicles for last-mile delivery, there is evidence to suggest that crashes between VRUs and this type of delivery vehicle are less likely to cause severe injuries or fatalities.

Part II: "Last Mile Strategies for Urban Freight Delivery" presents a systematic review of the literature to identify last-mile delivery strategies and determine how those strategies have been evaluated. Specifically, we identify four types of last-mile delivery strategies: innovative vehicles, urban goods consolidation, technological and routing advancements in city logistics, and emerging planning tools and policies. Many studies have evaluated these strategies from the perspective of operational, environmental, social, and economic impacts. However, limited studies have examined the effects of those proposed strategies on safety outcomes, highlighting research needs on assessing safety impacts of these last-mile delivery strategies. This section also assesses the advantages and disadvantages of e-cargo bikes to address last-mile delivery in urban communities. The assessment shows that e-cargo bikes have lower vehicle and maintenance costs, lower parking costs, the potential of higher speed in traffic congestion, fewer driver training requirements, and lower negative environmental impacts, but still have limitations in terms of security issues, limited capacity, or range, seasonality, managing trailer locations, stability, route scheduling, and labor cost (Mayor of London, 2009, Behnke, 2019, Blazejewski et al., 2020).

These studies contribute to a better understanding of research issues related to improving urban freight road safety and last-mile delivery strategies. The research results could inform policymaking to improve road safety associated with last-mile delivery and VRU. They also elaborate on the existing novel last-mile delivery strategies that logistics firms and public agencies could compare and adopt to promote efficient and safe last-mile delivery. They also identify research directions for freight researchers to improve the understanding of different last-mile delivery strategies.

Part I: Exploring the Determinants of Crash Severity for Incidents Involving Vulnerable Road Users and Commercial Vehicles in North Carolina and Tennessee

Introduction

Trends in consumer preference and retail have led to a boom in e-commerce. Impacts of this change are felt widely but are especially apparent in the transport sector. This new model of consumption has increased the volume of heavy and light goods vehicles in urban areas including residential areas. Transportation planners, local officials, the public, and the media have been debating the impacts of our increased reliance on commercial vehicles for last-mile delivery. Researchers have analyzed congestion impacts, air pollution and greenhouse gas emissions, noise pollution, road safety, and curb management strategies to increase delivery efficiency (Allen et al., 2017; Callahan, 2019; Duhigg, 2019; Giordani et al., 2018; Ranieri et al., 2018).

Recent media coverage of the impacts of online delivery has highlighted conflicts between freight vehicles and vulnerable road users – pedestrians and bicyclists (Callahan, 2019; Haag & Hu, 2019; Gilbert, 2020). Researchers and planners have long advocated for policies and infrastructure investments that promote bicycling and walking as alternatives to automobile transport, citing reductions in externalities related to automobile travel such as air pollution, carbon emissions, congestion, and noise (Pucher & Buehler, 2017; Cavill et al., 2006; Godlee, 1992; OECD, 2004). Research suggests that targeted efforts to promote active transportation are changing travel behavior, at least in areas where these policies are present (Ogilivie et al., 2004). While we know that the potential for interactions between commercial vehicles and vulnerable road users is rising, there has been little empirical work examining safety issues specifically between these cohorts within metropolitan areas.

This study describes the spatial and temporal patterns of freight vehicle interactions with VRU in urban areas of North Carolina and Tennessee to provide a knowledge base and assess strategies to reduce risks for VRU and freight vehicle drivers. We focus on the following research questions:

- What are the spatial and temporal trends in VRU/freight vehicle crashes?
- What are the crash-level characteristics associated with VRU/freight crashes?

Background

Changing consumer preferences and the accompanying proliferation of e-commerce are leading to a new landscape in urban freight delivery. While retail has only shown modest growth globally, online retail has exploded, demonstrating a 14.8% increase in just a five-year period from 2007 to 2012 (Hutchings et al., 2013). This trend is even more pronounced more recently in the US where the proportion of e-commerce with respect to all US retail sales increased 65% from 2009 and 2014. Possibly even more illustrative of this phenomenon is the growth in sales revenue of the largest online retailer. Amazon reported net sales revenue of $7 billion in 2004, and an astonishing $107 billion in 2015 (Giuliano et al., 2018). Across the entire US retail sector, the proportion of retail sales attributable to e-commerce has increased from just under 1% in 2000 to 9.4% in 2018 (McGowan, 2019).

Higher demand for freight facilities has accompanied the change in consumer demand, resulting in a tripling in the number of freight facilities in the Atlanta region (Dablanc & Ross, 2012). Visser et al. (2014) suggest that e-commerce will only keep growing as demographics and societal norms continue to trend favorably for the practice. Additionally, they suggest that e-commerce will outcompete brick and mortar retail through economic shocks, the practice of online shopping will penetrate new markets, and smartphone technology will continue to reduce barriers to online shopping. Giuliano et al. (2018) confirm that continuing demographic shifts will favor e-commerce dominance and resulting urban freight patterns. As freight activity moves closer to urban centers, there will be increased competition for space between passenger vehicles, transit vehicles, and pedestrians and bicyclists (Sedor & Caldwell, 2002; Gao & Ozbay, 2016l Giuliano et al., 2018). Such competition can lead to further issues of urban congestion but also has the potential to increase conflicts between vulnerable road users and freight vehicles.

As freight volumes and patterns change, researchers are considering the effects that these trends are having on freight vehicle safety. Giuliano et al. (2013) found that in 2009, 9.6% of all motor vehicle fatalities involved large trucks. More recently, McDonald et al. (2019) reported a 17% increase in fatalities for urban freight-related crashes, compared to a much more modest 3% increase in all traffic fatalities from 2009-2015. Interestingly, McDonald et al. (2019) also observed even larger increases in non-fatal urban freight crashes during this period. Supporting the hypothesis that spatial patterns are changing, they find that urban freight crashes are occurring more often on local roads and arterials as opposed to interstates. This is especially concerning when we consider that local roads are also where vulnerable road users are most likely to be traveling as well. When coupled with the Giuliano et al. (2013) observation that one third of fatal truck accidents occur in urban areas, there is some agreement that increases in e-commerce and urban freight activity are leading to growing safety concerns in this arena.

Vulnerable Road User Safety

Vulnerable road users are users of transport networks that are not protected by a physical shield, thus making them more prone to injury in traffic accidents (OECD, 1998). As Constant & Lagarde (2010) put it, “They constitute with almost no exception the weak party in a road traffic crash.” With that in mind, vulnerable road users (VRUs) unsurprisingly account for half of the world’s road fatalities every year, according to the World Health Organization (WHO, 2009). Accounting for such a large proportion of traffic fatalities, VRUs have received a commensurate level of attention in the transportation safety literature. Studies have focused on four broad categories of determinants of crash severity for VRUs: 1) Individual (victim) characteristics; 2) Infrastructure characteristics; 3) Crash mechanics; and 4) Colliding vehicle characteristics. Researchers have identified individual characteristics of bicyclists and pedestrians that lend to more severe accidents with motor vehicles such as age, sex, and intoxication (Kaplan et al., 2014; Ma et al., 2014; Clifton et al., 2009; Al-Ghamdi, 2002; Baltes, 1998; Nicaj et al., 2006; Zeeger et al., 1993; Lee & Abdel-Aty, 2005; Hebert-Martinez & Porter, 2004). The infrastructure present, and to a lesser degree, the surrounding built environment has also been shown to influence the severity of VRU crashes. This includes cycling paths and medians, speed limits, streetlights, transit access, pedestrian connectivity, and the density and style of urban development (Kaplan et al., 2014; Ma et al., 2014; Clifton et al., 2009; Conway et al., 2016; Dunbaugh et al., 2013; Dunbaugh & Rae, 2009; Sze & Wong, 2007). Additionally, the way in which VRUs and motor vehicles interact with the infrastructure, or each other, can affect the severity of the crash. Some studies have pointed to the position of bicyclists within the blind spot of vehicles or the specific way in which the bicyclist is struck can be exacerbating factors in crashes (Kaplan et al., 2014; Ma et al., 2014; Johannsen et al., 2015; Seiniger et al., 2015). Others suggest that the position of the bicyclist within the context of the block (segment or intersection) can contribute to the likelihood of a more severe crash outcome (Kaplan et al., 2014; Clifton et al., 2009). Finally, Clifton et al. (2009) found that compliance with traffic laws by VRUs is an effective indicator of crash severity.

Research regarding VRU safety has recently responded to the trends of increased urban freight and competition for space between VRUs and freight vehicles on urban roads. This work indicates that larger vehicles can exacerbate the consequences of crashes for pedestrians (Dill et al., 2009; Roudsari et al., 2004). Roudsari et al. (2004) find that light trucks are three times more likely to cause severe injury to pedestrians than regular passenger vehicles. Dill et al. (2009) also find that heavier vehicles (trucks, vans, buses, and emergency vehicles) are more likely to cause injury or death in pedestrian crashes. Heavy vehicles, although not consistently defined, have been identified as an aggravating factor for VRU crash severity by many authors (Kaplan et al., 2014; Manson et al., 2013; Ma et al., 2014; Johannsen et al., 2015; Seiniger et al., 2015; McCarthy & Gilbert, 1996). Many of these studies relate heavy vehicles to fatality among VRUs, McCarthy & Gilbert (1996), for example, claim that crashes with heavy trucks were the most common bicycle accident leading to death in London. Pokorny et al. (2018) highlight the danger of this type of collision, saying "truck-bicycle accidents are considered as one of the most serious type of event a cyclist can experience." Pokorny et al. (2018) show that accidents with trucks are fatal at a rate of 10% for bicyclists, compared to a rate of just 1% for all reported bicycle accidents in Norway. They find that while these truck-bicycle accidents were occurring at relatively slow speeds, the mass of the trucks exposed bicyclists to such great risk that it outweighed many other crash factors that might seem countervailing.

This burgeoning focus on the interaction between heavy vehicles and VRUs is promising as it provides the potential for transportation planners and engineers to respond to concerns related to increasing urban freight traffic. While the factors influencing VRU crash severity more broadly are well-established at this point, we still know little about the nuances of the determinants of crash severity for incidents between commercial vehicles and VRUs. Pokorny et al. (2018) have helped to shed light on some of the determinants of heavy truck-bicycle crash severity, but their findings are limited in their generalizability to all VRUs, especially in a US context. This study will help to fill this gap, looking at a relatively large sample of VRU-freight vehicle crashes with recent US data. We take lessons from the literature to include as many of the determinants of crash severity as possible, while also including novel variables. This study will continue to advance knowledge of how transportation officials can anticipate safety concerns related to expanding urban freight.

Analysis in North Carolina

Study Area

For this analysis we focus on non-interstate crashes involving vulnerable road users and commercial vehicles that occur within census-defined urbanized areas in North Carolina. We focus on non-interstate urban areas because the policy discussion of how to decrease dangerous interactions between VRU and freight vehicles has focused on these environments. We selected North Carolina as a convenience sample where the research team had strong knowledge of and access to road safety data. However, North Carolina represents a wide range of environments which will provide important context for broader interpretation of our results.

Data and Methods

Data

For the purpose of this study, we have defined vulnerable road users (VRUs) as bicyclists and pedestrians. Some authors have been more inclusive with their definition of VRUs, sometimes including motorcycles, mopeds, and other non-enclosed modes of transport (Constant & Lagarde, 2010; WHO, 2009). We believe that motorized modes are categorically different than bicyclists and pedestrians, and as such, conclusions from a combined sample would be difficult to interpret for meaningful policy or infrastructure interventions.

We define likely freight vehicles as those categorized in police crash reports as light trucks (mini-van/panel), single unit trucks (2-axel, 6-tire), single unit trucks (3 or more axels), tractor/doubles, tractor/semi-trailers, truck/tractors, truck/trailers, unknown heavy trucks, and common cargo vans. While recent innovations in last-mile delivery have greatly expanded the variety of vehicles used for commercial purposes, we limited our van category to cargo-style models that are not likely to carry passengers. This included 16 sub-models by four automakers that we identified via their vehicle identification numbers (VIN). The other vehicle type classifications are made by police officers on the scene, and do not necessarily reflect a scientific designation protocol. Previous studies have focused on large freight vehicles, typically heavy trucks (Roudsari et al., 2004; Kim et al., 2006; Ma et al., 2014; McCarthy & Gilbert, 1996; Pokorny et al., 2017). We include a broader range of commercial vehicles with the knowledge that changing delivery patterns and practices requires a broader operationalization of freight vehicles. Recent research by Lyons & McDonald (2020) shows that freight carriers are increasingly using delivery vans and other smaller vehicles for urban freight delivery.

Our data are a sample of crashes throughout North Carolina from 2007 to 2018. Each observation in our sample represents a single crash. There are associated crash characteristics that relate to vehicles and individuals, but the observation, frequencies, and visualizations represent crashes. The sample has been limited to crashes between vulnerable road users and commercial vehicles, as defined above. We select crashes that occur on non-interstate roads within urban areas. Our sample of VRU-cargo van crashes has a more limited temporal extent, representing only 2011-2018. Because of the more recent addition of these types of vehicles to the commercial fleet, and also based on our analysis of the data, we expect that our sample contains most of this type of accident occurring in North Carolina. The data come from digitized crash reports that have been geocoded by the Institute for Transportation Research and Education at North Carolina State University. The data include crash-specific variables that measure aspects of the individuals involved, the vehicles, the crash site and immediate surroundings, and the conditions at the time of the crash. From 2007-2018 there were 33,707 crashes between pedestrians and all vehicles and 11,266 crashes between bicyclists and vehicles during this same period. When we identify crashes between commercial vehicles and VRUs the figure is limited to 1,126 for pedestrians and 318 for bicyclists. Finally, we selected only VRU-commercial vehicle crashes that occurred on non-interstate roads in urban areas, leaving 825 crashes with pedestrians and 251 crashes with bicyclists. There were an additional 51 crashes between qualifying cargo vans and VRUs that met all the above criteria.

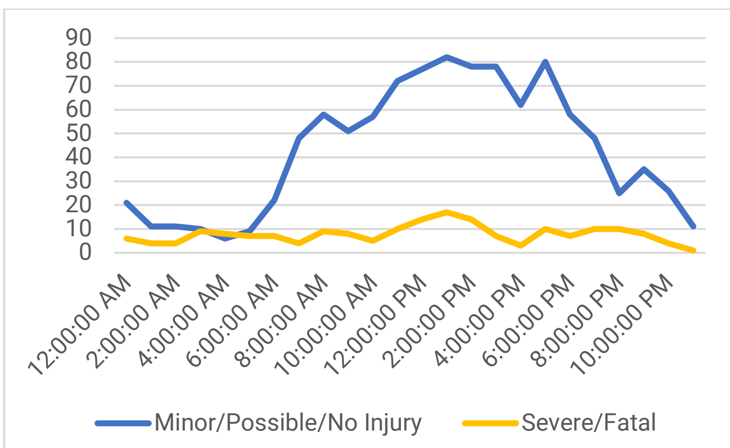

Figure 1: Crash Frequencies by Crash Hour

This chart of crash hour and crash severity indicates that there is a higher frequency of minor crashes in the 12-hour period from 8:00 AM to 8:00 PM. More serious crashes involving suspected serious injuries or fatalities are more evenly spread throughout the 24-hour period, with the distribution most even for fatal crashes. Below, Figure 2 describes yearly crash counts by crash severity.

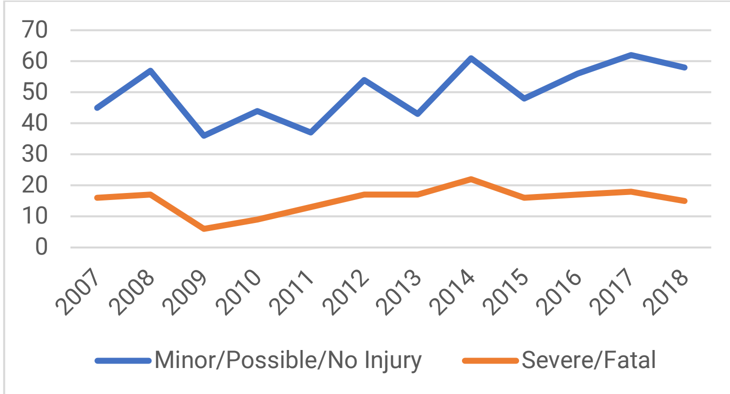

Figure 2: Crash Frequencies by Severity and Year

This chart allows us to observe crash severity frequencies over time. We see somewhat discernible upward trends in both minor crashes and severe crashes, with higher values and variability among minor crashes. Below, Table 1 examines crash counts among cargo vans in our sample.

Table 1: Cargo Van Crashes by Year and Model

Model	2011	2012	2013	2014	2015	2016	2017	2018	Total
NV Cargo	0	0	0	1	1	2	2	5	11
ProMaster	0	0	0	0	2	0	2	2	6
Sprinter	1	1	1	1	1	0	1	1	7
Transit	0	0	0	1	2	13	7	2	25
Total	1	1	1	3	6	15	12	10	49

The sixteen most common cargo vans can be grouped into four similar make/models: NV Cargo Van by Nissan, ProMaster by Dodge, Sprinter by Mercedes, and Transit by Ford (Table 1). The above table includes multiple similar submodels that have been aggregated together for ease of interpretation. The most common freight van in terms of VRU crashes is the Ford Transit, accounting for more than half of all these crashes. More than half of the Ford Transit-VRU crashes happened in 2016. The next most common freight van crash involved the NV Cargo Van. This was the only model to demonstrate an increase in crash frequency from 2017 to 2018. From 2011 through 2018 there were a total of 49 freight van-VRU crashes, with a peak in 2016. Although we cannot infer a trend from these limited data, there seems to be a downward trajectory in freight van-VRU crashes after the peak in 2016. The decrease, however, does not match in magnitude the increase observed from 2013 to 2016.

Methods

We begin by exploring the data using descriptive analysis. We map crashes to observe spatial patterns for certain crash types. Specifically, we map crashes between VRUs and commercial vehicles for the two largest North Carolina regions: Charlotte, and Raleigh/Durham/Chapel Hill. We also use crosstabulations and pivot tables to observe patterns and associations between specific variables of interest. Given the limited size of our sample, some relationships will not demonstrate significant relationships in inferential models, but trends and associations can still provide meaningful context.

We also estimate a logistic regression model to assess the determinants of crash severity in crashes between VRUs and commercial vehicles. Severe crashes are those in which the VRU was classified in the crash report as a “Suspected Serious Injury” or “Killed.” Given the fact that crash reports are completed on the scene or shortly thereafter, it is possible that some crashes categorized as “Suspected Serious Injury” could have resulted in a subsequent fatality, where the victim later died as a result of injuries from the crash. We select our logistic regression model using a stepwise model selection process considering model fit, face validity, and significance of relationships as criteria for inclusion of independent variables.

Results

Spatial Analysis

We map VRU-commercial vehicle crashes for the two largest regions in North Carolina below. We have shaded census tracts by population density and freight jobs to explore whether there are observable patterns in crash frequency for areas with high freight-producing economic activity or high general trip-producing activity. We use the Work Area Characteristics subset of Longitudinal Employer-Household Dynamics (LEHD) Origin Destination Employment Statistics to determine the number of freight-producing jobs per census tract. Of the 20 employment categories provided by the LEHD data, we include jobs from the following four categories: Manufacturing; Wholesale Trade; Retail Trade; and Transportation and Warehousing.

Across the state of North Carolina, the correlation between freight jobs and VRU/commercial vehicle crashes is moderate ($r=0.23$, $p<0.001$). Population density and VRU crashes also have a moderate correlation using data from the state of North Carolina ($r = .25$, $p<.001$). Figures 8 and 9 highlights the patterns in the Charlotte and Raleigh-Durham areas.

Charlotte Raleigh Durham

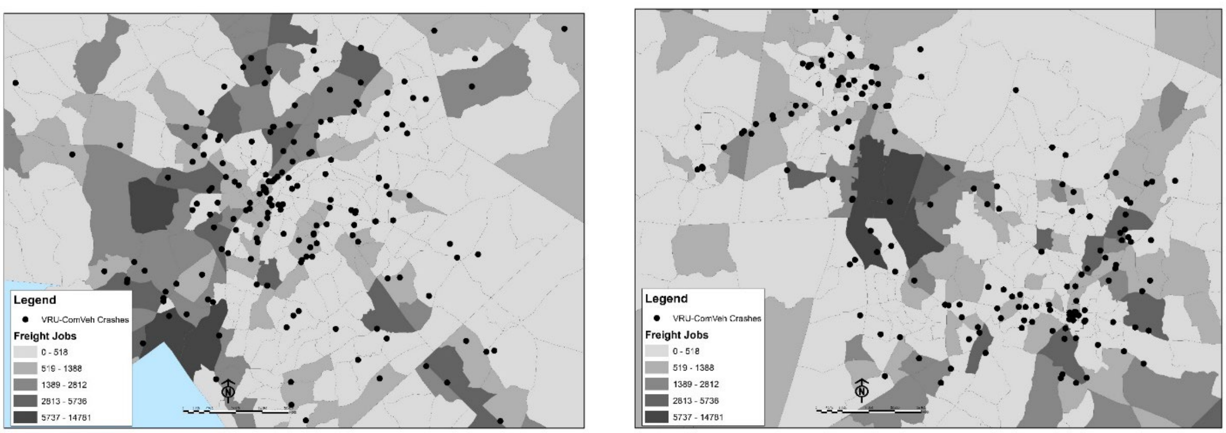

Figure 3: VRU-Commercial Crashes and Freight Jobs in Charlotte and Raleigh-Durham

Charlotte Raleigh Durham

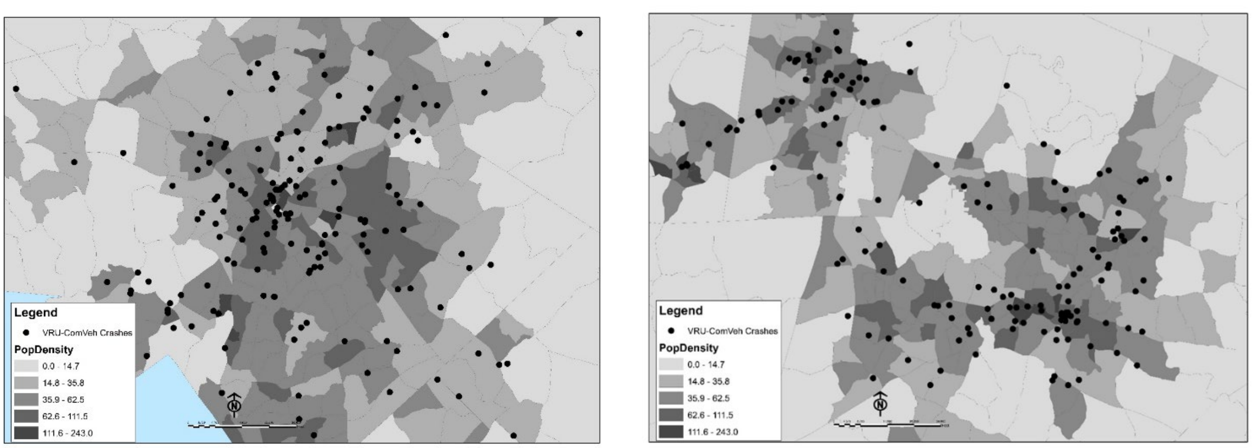

Figure 4: VRU-Commercial Crashes and Population Density in Charlotte and Raleigh-Durham

Descriptive Analysis

We start by presenting crosstabulations of characteristics of the crash, local environment, and individuals with crash severity. The unadjusted results show the strongest relationships between crashes that involved a severe or fatal injury and vehicle type, road speed limit, and local built environment.

Table 2: Prevalence of Injury Severity for Vulnerable Users by Individual, Crash, and Environmental Characteristics

		Category Frequency	Frequency (Severe+Fatal)	Frequency (Fatal)
VRU Characteristics			Count (Percent)	Count (Percent)
Age	Chi Square		(c^2=10.44, p=0.06)	(c^2=4.58, p=0.47)
	0-15	123 (0.11)	22 (0.12)	7 (0.06)
	16-29	296 (0.27)	59 (0.20)	30 (0.10)
	30-49	348 (0.31)	88 (0.25)	29 (0.08)
	50-69	248 (0.22)	62 (0.25)	18 (0.07)
	70+	77 (0.07)	25 (0.32)	7 (0.09)
	Unknown	19 (0.02)	2 (0.11)	0 (0.00)
Race	Chi Square		(c^2=8.41, p=0.08)	(c^2=0.82, p=0.94)
	Black	366 (0.33)	74 (0.20)	29 (0.08)
	Hispanic	70 (0.06)	16 (0.23)	5 (0.07)
	Other/Mixed	120 (0.11)	34 (0.28)	10 (0.08)
	Unknown/Missing	39 (0.03)	4 (0.10)	2 (0.05)
	White	516 (0.46)	130 (0.25)	45 (0.09)
Sex	Chi Square		(c^2=1.75, p=0.42)	(c^2=2.76, p=0.25)
	Male	734 (0.66)	165 (0.22)	56 (0.08)
	Female	353 (0.32)	85 (0.24)	31 (0.09)
	Unknown	24 (0.02)	5 (0.21)	4 (0.17)
Crash Characteristics				
VRU Position	Chi Square		(c^2=22.74, p=0.00)	(c^2=9.93, p=0.08)
	Crosswalk	92 (0.08)	14 (0.14)	3 (0.03)
	Non-roadway	327 (0.29)	74 (0.23)	37 (0.11)
	Other/Unknown	54 (0.05)	9 (0.17)	3 (0.06)
	Road Side	38 (0.03)	8 (0.21)	4 (0.11)
	Sidewalk/Path	83 (0.07)	8 (0.10)	4 (0.05)
	Travel Lane	509 (0.46)	145 (0.28)	40 (0.08)
Crash Group	Chi Square		(c^2=7.21, p=0.71)	(c^2=10.18, p=0.43)
	Ped in RtofWy	124 (0.11)	28 (0.23)	10 (0.08)
	Backing Vehicle	142 (0.13)	32 (0.23)	11 (0.08)
	Bike Maneuver	13 (0.01)	1 (0.08)	0 (0.00)
	Bike Fld to Yld	34 (0.03)	10 (0.29)	4 (0.12)
	Crossing RtofWy	246 (0.22)	61 (0.25)	25 (0.10)
	Dash/Dart Out	60 (0.05)	17 (0.28)	5 (0.08)
	Mtrst Fld to Yld	55 (0.05)	14 (0.25)	3 (0.05)
	Mtrst Ovrtkng Bk	40 (0.04)	4 (0.10)	6 (0.15)

	Mtrst Turn	32 (0.03)	8 (0.25)	1 (0.03)
	Non-roadway	109 (0.10)	17 (0.16)	4 (0.04)
	Other/Unusual	256 (0.23)	39 (0.15)	22 (0.09)
Vehicle Type	Chi Square		(c^2=16.68, p=0.00)	(c^2=39.93, p=0.00)
	Single Unit Truck	308 (0.28)	88 (0.29)	31 (0.10)
	Large Truck	204 (0.18)	59 (0.29)	37 (0.18)
	Light Truck	549 (0.49)	104 (0.19)	23 (0.04)
	Van	50 (0.05)	7 (0.14)	1 (0.02)
Speed Limit	Chi Square		(c^2=20.12, p=0.00)	(c^2=8.83, p=0.12)
	5-15	185 (0.17)	23 (0.12)	9 (0.05)
	20-25	183 (0.16)	49 (0.28)	20 (0.11)
	30-35	355 (0.32)	49 (0.14)	27 (0.08)
	40-45	193 (0.17)	28 (0.14)	22 (0.11)
	50+	71 (0.06)	6 (0.09)	3 (0.04)
	Unknown	124 (0.11)	30 (0.24)	10 (0.08)
Environmental Characteristics				
Road Class	Chi Square		(c^2=2.67, p=0.61)	(c^2=2.11, p=0.71)
	State Scndry Route	62 (0.06)	13 (0.21)	3 (0.05)
	Local Street	609 (0.55)	145 (0.24)	55 (0.09)
	Prvt Rd/Driveway	44 (0.04)	6 (0.14)	4 (0.09)
	Pblc Veh Area/Other	300 (0.27)	72 (0.24)	21 (0.07)
	US Route	96 (0.09)	22 (0.23)	8 (0.08)
Development	Chi Square		(c^2=12.58, p=0.00)	(c^2=25.12, p=0.00)
	Commercial	624 (0.56)	136 (0.22)	56 (0.09)
	Industrial/Institutional	43 (0.04)	7 (0.16)	0 (0.00)
	Residential	389 (0.35)	92 (0.24)	22 (0.06)
	Rural	55 (0.05)	23 (0.42)	13 (0.24)

Regression Results

We fit a logistic regression model to our dataset of crash-level characteristics. We test one outcome variable: Likelihood that a crash will result in a severe injury or death for the vulnerable road user, which we will call our "Severe Model." We use the sample of crashes from 2007-2018 that also includes cargo vans. We also tested this model with our sample that leaves out cargo vans, but they were not meaningfully different, so we just present the model from the complete dataset here.

Table 3: Severe Model Results

Variable	Estimate	S.E.	z value	p
Intercept	-2.130	0.495	-4.305	0.000
VRU Age Grp (ref.=30-49)				
VRU Age Grp 0-15	-0.315	0.287	-1.099	0.272
VRU Age Grp 16-29	-0.377	0.202	-1.867	0.062
VRU Age Grp 50-69	0.029	0.203	0.142	0.887
VRU Age Grp 70+	0.572	0.299	1.911	0.056
VRU Age Grp Unknown	-1.039	0.796	-1.305	0.192
VRU Race (ref.= African Americans)				
VRU Race Hispanic	0.250	0.330	0.760	0.447
VRU Race Other/Mixed	0.279	0.286	0.978	0.328
VRU Race Unknown/Missing	-0.749	0.565	-1.325	0.185
VRU Race White	0.334	0.175	1.904	0.057
VRU Position (ref.=Sidewalk/Path)				
VRU Position Crosswalk	0.243	0.496	0.490	0.624
VRU Position Non-Roadway	0.816	0.414	1.970	0.049
VRU Position Other/Unknown	0.489	0.539	0.907	0.364
VRU Position Road Side	0.853	0.573	1.489	0.137
VRU Position Travel Lane	1.308	0.399	3.278	0.001
Development (ref.=Commercial)				
Development Industrial/Institutional	-0.552	0.446	-1.236	0.216
Development Residential	0.108	0.168	0.641	0.521
Development Rural	1.012	0.314	3.228	0.001
Crash Group (ref. =Ped in R to fWy)				
Crash Group Backing Vehicle	0.123	0.316	0.388	0.698
Crash Group Bicycle Maneuver	-1.086	1.094	-0.993	0.321
Crash Group Bicycle Fld to Yld	0.408	0.478	0.853	0.394
Crash Group Crossing Rt of Wy	0.068	0.280	0.242	0.809
Crash Group Dash/Dart-Out	0.263	0.378	0.695	0.487
Crash Group Motorist Fld to Yld	0.336	0.406	0.827	0.409
Crash Group Motorist Ovrtkng Bike	-0.129	0.471	-0.273	0.785
Crash Group Motorist Turn	0.221	0.487	0.453	0.651
Crash Group Non-Roadway	-0.159	0.345	-0.462	0.644
Crash Group Other/Unusual	-0.224	0.281	-0.796	0.426
Driver Vehicle Type (ref.=Single-unit truck)				
Driver Vehicle Type Large Truck	-0.011	0.215	-0.051	0.960
Driver Vehicle Type Light Truck	-0.588	0.177	-3.322	0.001
Driver Vehicle Type Van	-0.880	0.443	-1.985	0.047
Speed Limit (ref.=30-35)				
Speed Limit 20-25	0.557	0.224	2.492	0.013
Speed Limit 40-45	0.195	0.234	0.831	0.406
Speed Limit 5-15	-0.449	0.261	-1.720	0.085
Speed Limit 50+	-0.446	0.383	-1.165	0.244
Speed Limit Unknown	0.436	0.258	1.695	0.090

The above logistic regression predicts the likelihood of a crash resulting in a severe injury or fatality based on seven crash-level predictors. The model is significant, and we used pseudo R-squared values, AIC values, and BIC values to compare models and select the best performing iteration. Additionally, VIF values for all variables are below five, indicating that there is no issue of multicollinearity between the independent variables.

The first variable in the model, VRU age group, includes five age categories for VRU parties involved in a crash. The regression table reports just four age categories as one category is held as a base case for the other categories to be compared against. We see that the log odds that a crash will result in a severe injury or fatality for the age group of 70+ are positive and nearly significant with a p value just over 0.05. By exponentiating the log odds presented as the coefficient estimate, our model indicates that crashes involving VRUs 70 years old or older are just less than twice as likely to result in a severe injury or fatality compared to the base case. Additionally, the log odds of a severe or fatal crash are negative and nearly significant for those involving VRUs from the age group 16-29. We can interpret this as meaning that compared to the base case of age group 30-49 (the age category missing from the regression output), crashes involving the 70+ group are more likely to produce a severe injury or fatality and less likely for the 16-29 group. This result is intuitive and is line with findings from Clifton et al. (2009). For this variable and all others, we chose the base case in order to optimize our ability to make meaningful comparisons between categories.

The crash group variable did not prove significant. We allowed the crash group variable to remain in the model for its effect on model performance as well as for our confidence in its theoretical importance. Our hypothesis was that certain crash mechanics, as in the way that VRUs were struck or the maneuvers performed by VRUs or commercial vehicles would lead to varying probabilities of crash severe crash outcomes. This theory was not significantly validated by this model.

Driver vehicle type represents the classification of the motor vehicle involved in the crash. Based on the literature (Dill et al., 2009; Roudsari et al., 2004), we would expect that crashes involving larger commercial vehicles would lead to increased probabilities of severe outcomes. Not surprisingly, when compared to the base case of single unit trucks (which could be described as medium-sized commercial vehicles), light trucks and vans significantly reduce the probability of severe or fatal accidents. Previous findings from Dill et al. (2009) and Roudsari et al. (2004) found that larger vehicles like trucks and vans were more likely to lead to severe accidents, but this was when comparing them to all vehicle types. We see that when the sample of crashes is reduced to just commercial vehicles, the relationship between vehicle size and crash outcome persists.

The speed limit variable demonstrates somewhat surprising results. Compared to the base case of speed limits of 30-35 mph, the slower limits of 20-25 mph are a little less than twice as likely to produce a severe or fatal crash. This finding is unexpected and contrary to what has been previously established in the literature. However, the slowest speed limit, 5-15 mph, demonstrates a negative relationship with the likelihood of a severe or fatal crash. These two findings suggest that there is more nuance to the effect of speed on crash severity with crashes between commercial vehicles and VRUs.

The variable that produced the largest log odds ratio was the VRU position. This variable depicts the position of the VRU within the road cross section at the time of the crash. Crashes in which the VRU was in the travel lane were more than three and a half times more likely to produce a severe or fatal outcome than the base case of sidewalk or path location. While it is not surprising that the travel lane is more dangerous for VRUs than a sidewalk or path, the level of responsiveness to this location is notable. The non-roadway VRU position was also positively related to the likelihood of a severe or fatal crash, although the relationship was less responsive.

The development that surrounded the crash was an environmental variable that proved to predict the likelihood of crash severity. Crashes between commercial vehicles and VRUs that occurred in rural settings were nearly three times as likely to produce a severe or fatal outcome. This result, while somewhat novel in the context of the literature, is not surprising as we would expect commercial vehicles to be traveling at higher speeds in rural areas. Additionally, commercial vehicle operators might also be less likely to expect to encounter VRUs in such a setting.

Finally, we observe that VRU race is an indicator of the likelihood of a severe or fatal crash. When compared to the base case of black VRUs, white VRUs are somewhat more likely to be severely or fatally injured in a collision with commercial vehicles. It is not necessarily intuitive that race would factor into crash severity outcomes, although other safety research has found that non-white pedestrians often demonstrate higher rates of traffic injury (Steinbach et al., 2010). However, as Steinbach et al. (2010) suggest, race might be more closely related to environmental factors affecting the crash like infrastructure, lighting, etc., instead of having a direct relationship to crash outcomes.

Analysis in Tennessee

Study Area

Similar to the analysis in North Carolina, we focus on non-interstate crashes involving vulnerable road users and commercial vehicles that occur within urban areas of fourteen counties in Tennessee. Figure 5 illustrates the study area of the project for fourteen urbanized counties in Tennessee.

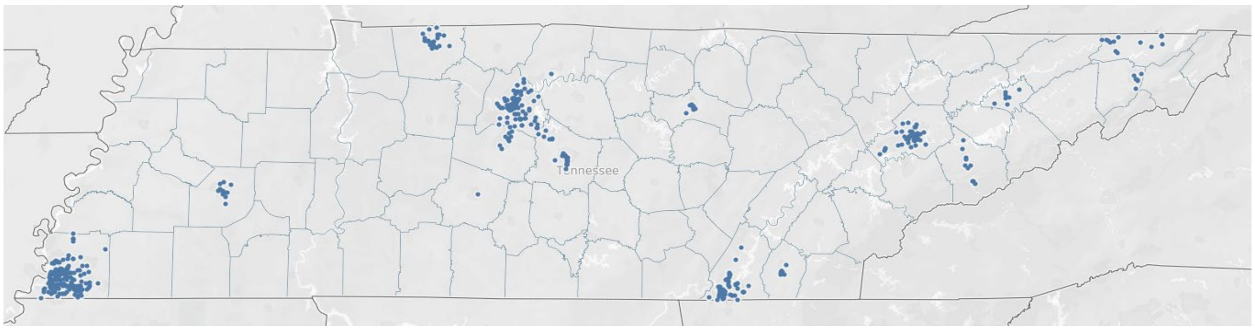

Figure 5: Study Area

Data and Methods

Data

Data are extracted from the TITAN database with entries from 2009 to 2019. We used a comprehensive approach to determine the commercial vehicles within the TITAN database. Although the database has an indicator for commercial vehicles, the police officer enters it at his/her discretion. Several instances where rental cars and governmental vehicles were classified as commercial vehicles and only relying on commercial reporting by officers were not enough. Thus, we decided to categorize the commercial vehicles and non-commercial vehicles in a relatively consistent way using the body types of the vehicle units and various forms of reporting such as commercial reporting, body weight, cargo-body type, gross vehicle weight rating, particular use, HAZMAT indicator, VIN code information, manual checking of owner's address, and so on. In this way, we have determined that large vehicles such as trucks and vans have a greater likelihood of being commercial vehicles. Out of 19388 VRU entries, we found 593 victims of commercial crashes, 105 bicyclists, and 488 pedestrians.

Major cities of Tennessee have a higher number of commercial VRU crashes (Figure 5). Figure 6 represents the yearly trend of fatal and total crashes from 2009 to 2018. We can see an overall increasing trend for both criteria.

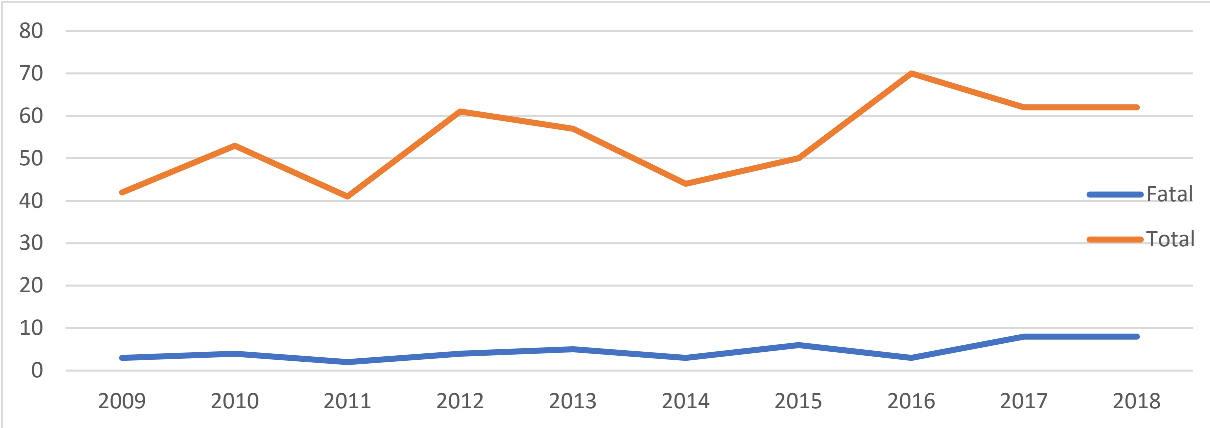

Figure 6: Yearly Trends for Fatal and All Commercial VRU Crashes in Tennessee

Yearly trends of individual commercial vehicle types suggest that only large vans follow the decreasing trends while light trucks have been showing an upward trend over the ten years. Despite a relatively less steep increase, large and composite trucks and other vehicles comprising mainly minivans, SUVs, and pickup-sized vehicles are also increasing trend over the years.

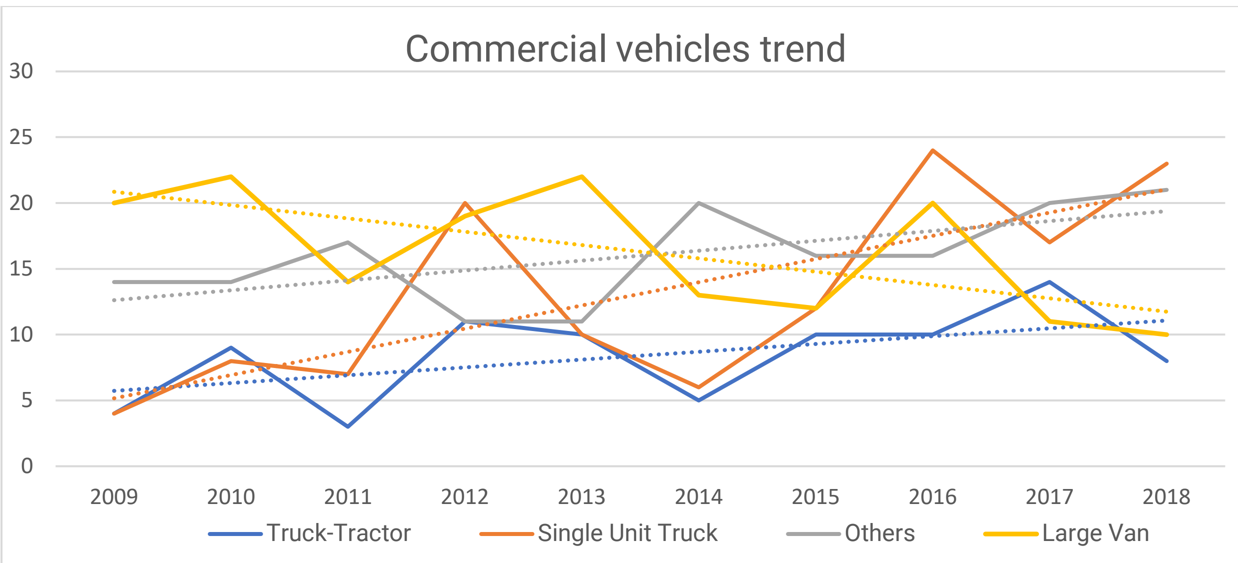

Figure 7: Yearly Crash Trends of Individual Commercial Vehicle Types in Tennessee

Methods

We begin studying the characteristics of commercial VRU crashes, we performed two cross-tabulation analyses: the first is to examine the disparities in determining factors between non-commercial and commercial VRU crashes and the second is to examine the disparities in characteristics of the crash, local environment, and individuals associated with different level of crash severity.

Next, we also fitted a binomial logistic model using nine significant variables from the crosstabs with the commercial indicator as a dependent variable.

Results

Descriptive Statistics

The variation for the most determining factors for commercial vehicles, such as time of the day, weekends, driver gender, etc., are statistically significant as per the cross-tabulation analyses done for these variables for both commercial and non-commercial vehicles. We also determined important variables by performing another cross-tabulation analysis that involved different levels of injury outcome. Variables such as alcohol presence, posted speed limit, etc., are essential variables affecting injury outcomes.

Table 4: Cross-tabulation Analyses of Crashes in Tennessee

Variables	Values	Commercial Indicator		Injury Severity				
		Non-Commercial	**Commercial**	**No**	**Possible**	**Minor**	**Serious**	**Fatal**
Age Category	15 years and younger	3213 (17)	77 (13)	12 (20)	28 (14)	29 (16)	7 (7)	1 (2)
	16-39 years	7900 (42)	218 (37)	27 (45)	83 (40)	61 (34)	33 (34)	14 (28)
	40-54 years	4027 (21)	155 (26)	12 (20)	44 (21)	54 (30)	29 (30)	16 (32)
	55 years and older	3654 (19)	143 (24)	9 (15)	52 (25)	34 (19)	29 (30)	19 (38)
	χ^2 - value/ p-value	**21.864**	**.000**		**χ^2 - value/ p-value**		**28.659**	**.004**
Alcohol or Drug Presence	No or Unknown	17842 (95)	561 (95)	57 (95)	204 (99)	173 (97)	88 (90)	39 (78)
	Yes	954 (5)	32 (5)	3 (5)	3 (1)	5 (3)	10 (10)	11 (22)
	χ^2 - value/ p-value	**0.123**	**.726**		**χ^2 - value/ p-value**		**40.107**	**.000**
Gender	Female	6797 (36)	195 (33)	16 (27)	84 (41)	51 (29)	23 (23)	21 (42)
	Male	11999 (64)	398 (67)	44 (73)	123 (59)	127 (71)	75 (77)	29 (58)
	χ^2 - value/ p-value	**2.68**	**.102**		**χ^2 - value/ p-value**		**13.869**	**.008**
Race	Black	6009 (32)	196 (33)	15 (25)	78 (38)	56 (31)	28 (29)	19 (38)
	White	7821 (42)	270 (46)	23 (38)	77 (37)	87 (49)	59 (60)	24 (48)
	Other	4966 (26)	127 (21)	22 (37)	52 (25)	35 (20)	11 (11)	7 (14)
	χ^2 - value/ p-value	**7.809**	**.020**		**χ^2 - value/ p-value**		**26.734**	**.001**
Weekend	No	13691 (76)	464 (82)	51 (85)	170 (82)	137 (77)	77 (79)	42 (84)
	Yes	4259 (24)	105 (18)	9 (15)	37 (18)	41 (23)	21 (21)	8 (16)
	χ^2 - value/ p-value	**8.516**	**.004**		**χ^2 - value/ p-value**		**3.152**	**.533**
Time of Day	00:00 - 06:00	1604 (9)	48 (8)	2 (3)	17 (8)	16 (9)	12 (12)	6 (12)
	06:00 - 12:00	3469 (19)	167 (29)	16 (27)	56 (27)	57 (32)	27 (28)	18 (36)
	12:00 - 18:00	7218 (40)	225 (40)	29 (48)	92 (44)	67 (38)	31 (32)	13 (26)
	18:00 - 24:00	5659 (32)	129 (23)	13 (22)	42 (20)	38 (21)	28 (29)	13 (26)
	χ^2 - value/ p-value	**42.277**	**.000**		**χ^2 - value/ p-value**		**14.712**	**.258**
Route Signing	County Route	763 (4)	18 (3)	3 (5)	6 (3)	5 (3)	5 (5)	0 (0)
	Municipal Route	9947 (55)	292 (51)	30 (50)	110 (53)	88 (49)	46 (47)	27 (54)
	Other	4718 (26)	177 (31)	21 (35)	68 (33)	65 (37)	31 (32)	3 (6)
	State Route	1312 (7)	36 (6)	2 (3)	14 (7)	9 (5)	4 (4)	8 (16)
	US Route	1210 (7)	46 (8)	4 (7)	9 (4)	11 (6)	12 (12)	12 (24)
	χ^2 - value/ p-value	**10.273**	**.036**		**χ^2 - value/ p-value**		**48.079**	**.000**
Trafficway Type	Private/Parking	3678 (20)	155 (27)	16 (27)	61 (29)	56 (31)	28 (29)	5 (10)
	Trafficway	14271 (80)	414 (73)	44 (73)	146 (71)	122 (69)	70 (71)	45 (90)
	χ^2 - value/ p-value	**15.306**	**.000**		**χ^2 - value/ p-value**		**9.385**	**.052**
Weather	Clear	14600 (81)	468 (82)	53 (88)	177 (86)	147 (83)	75 (77)	39 (78)

	Cloudy	1201 (7)	50 (9)	2 (3)	15 (7)	17 (10)	11 (11)	6 (12)
	Other	421 (2)	7 (1)	3 (5)	2 (1)	1 (1)	1 (1)	0 (0)
	Rain	1728 (10)	44 (8)	2 (3)	13 (6)	13 (7)	11 (11)	5 (10)
	χ^2 - value/ p-value	**8.68**	**.034**		**χ^2 - value/ p-value**		**17.791**	**.122**
First Impact	Front End	7456 (42)	186 (33)	21 (35)	57 (28)	58 (33)	44 (45)	18 (36)
	Left Side	2327 (13)	63 (11)	1 (2)	25 (12)	23 (13)	8 (8)	8 (16)
	Non-Collision	348 (2)	16 (3)	0 (0)	4 (2)	5 (3)	3 (3)	5 (10)
	Other	2683 (15)	87 (15)	3 (5)	30 (14)	31 (17)	17 (17)	8 (16)
	Rear End	1581 (9)	89 (16)	15 (25)	36 (17)	25 (14)	13 (13)	1 (2)
	Right Side	3555 (20)	128 (22)	20 (33)	55 (27)	36 (20)	13 (13)	10 (20)
	χ^2 - value/ p-value	**44.745**	**.000**		**χ^2 - value/ p-value**		**49.465**	**.000**
Posted Speed Limit	19 mph and lower	4163 (23)	172 (30)	22 (37)	65 (31)	60 (34)	33 (34)	4 (8)
	20-34 mph	5338 (30)	146 (26)	15 (25)	60 (29)	48 (27)	18 (18)	9 (18)
	35-45 mph	7843 (44)	228 (40)	21 (35)	73 (35)	66 (37)	44 (45)	32 (64)
	46 mph and higher	216 (1)	11 (2)	0 (0)	2 (1)	2 (1)	3 (3)	4 (8)
	Unknown	390 (2)	12 (2)	2 (3)	7 (3)	2 (1)	0 (0)	1 (2)
	χ^2 - value/ p-value	**18.832**	**.001**		**χ^2 - value/ p-value**		**42.318**	**.000**
Travel Lanes	Five or more Lanes	1361 (8)	44 (8)	6 (10)	15 (7)	10 (6)	8 (8)	6 (12)
	One/two Lanes	9943 (55)	298 (52)	35 (58)	112 (54)	87 (49)	53 (54)	20 (40)
	Other	2944 (16)	121 (21)	10 (17)	44 (21)	42 (24)	24 (24)	8 (16)
	Three/four Lanes	3702 (21)	106 (19)	9 (15)	36 (17)	39 (22)	13 (13)	16 (32)
	χ^2 - value/ p-value	**9.878**	**.020**		**χ^2 - value/ p-value**		**14.994**	**.242**
Driver Age Category	Others/Unknown	2364 (15)	50 (9)	6 (11)	19 (10)	16 (10)	8 (9)	3 (6)
	16-39 years	6603 (42)	165 (31)	14 (25)	64 (33)	55 (34)	23 (26)	17 (35)
	40-54 years	3221 (20)	186 (35)	24 (42)	71 (37)	53 (33)	28 (31)	15 (31)
	55 years and older	3589 (23)	128 (24)	13 (23)	39 (20)	38 (23)	31 (34)	14 (29)
	χ^2 - value/ p-value	**78.326**	**.000**		**χ^2 - value/ p-value**		**10.715**	**.554**
Driver Alcohol/ Drug	No or Unknown	17565 (98)	556 (98)	60 (100)	204 (99)	173 (97)	95 (97)	46 (92)
	Yes	385 (2)	13 (2)	0 (0)	3 (1)	5 (3)	3 (3)	4 (8)
	χ^2 - value/ p-value	**0.051**	**.821**		**χ^2 - value/ p-value**		**8.775**	**.067**
Driver Gender	Female	10060 (56)	122 (21)	11 (18)	45 (22)	45 (25)	20 (20)	6 (12)
	Male	7890 (44)	447 (79)	49 (82)	162 (78)	133 (75)	78 (80)	44 (88)
	χ^2 - value/ p-value	**266.803**	**.000**		**χ^2 - value/ p-value**		**4.625**	**.328**
Driver Race	Black	5386 (30)	164 (29)	14 (23)	68 (33)	58 (33)	15 (15)	15 (30)
	White	8158 (45)	312 (55)	32 (53)	106 (51)	89 (50)	69 (70)	30 (60)
	Other	4406 (25)	93 (16)	14 (23)	33 (16)	31 (17)	14 (14)	5 (10)
	χ^2 - value/ p-value	**26.148**	**.000**		**χ^2 - value/ p-value**		**18.207**	**.020**
Injury Class	No Injury	1879 (10)	60 (10)					
	Possible	7395 (39)	207 (35)					

Minor	6274 (33)	178 (30)
Serious	2637 (14)	98 (17)
Fatal	611 (3)	50 (8)
χ^2 - value/ p-value	**52.651**	**.000**

Figure 8 (a) depicts that commercial VRU crashes are considerably different in terms of fatality risk. The chances of getting fatally injured in commercial VRU crashes is almost three times that of non-commercial VRU crashes. We could also observe that VRUs involved in commercial crashes have more chances of sustaining serious injuries than non-commercial crashes. Figure 8 (b) is the hourly representation of commercial and non-commercial VRU crashes. The peaks for commercial and non-commercial crashes are distinct at 2 pm and 5 pm for commercial and non-commercial hits.

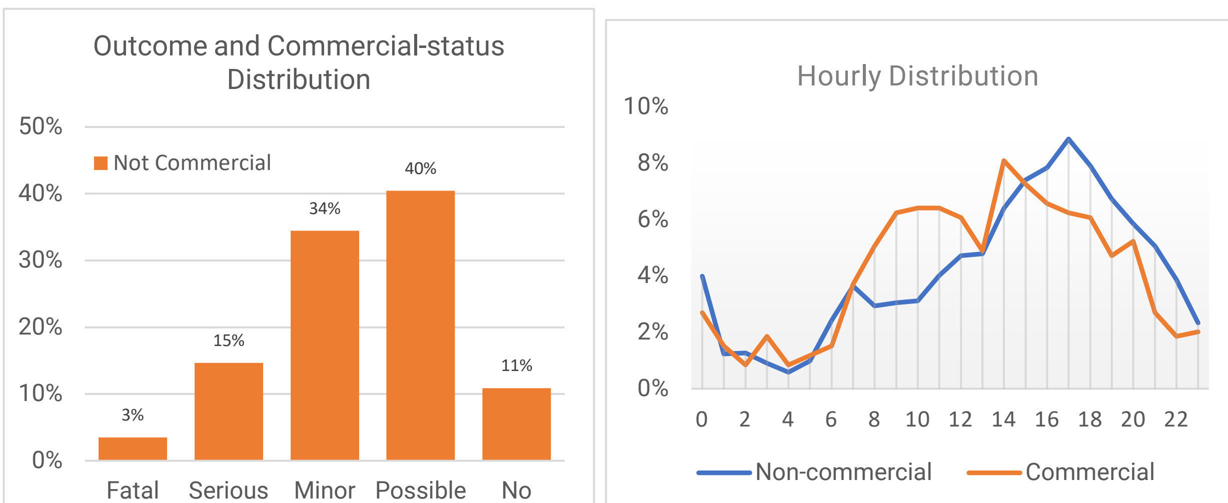

Figure 8: (a) Injury Distribution of Commercial and Non-commercial VRU Crashes, (b) Hourly Distribution of Commercial and Non-commercial VRU Crashes

Likewise, in figure 9 (a), we could see a rising trend in fatal and severe crashes as we increase the age of the VRUs. On the other hand, one could also observe the decreasing figures for crashes involving minor or no injuries. Figure 9 (b) illustrates the effect of speed on injury severity. For the given data, areas with a high posted speed limit (greater than 35 mph) tend to have a significant proportion of severe and fatal crashes.

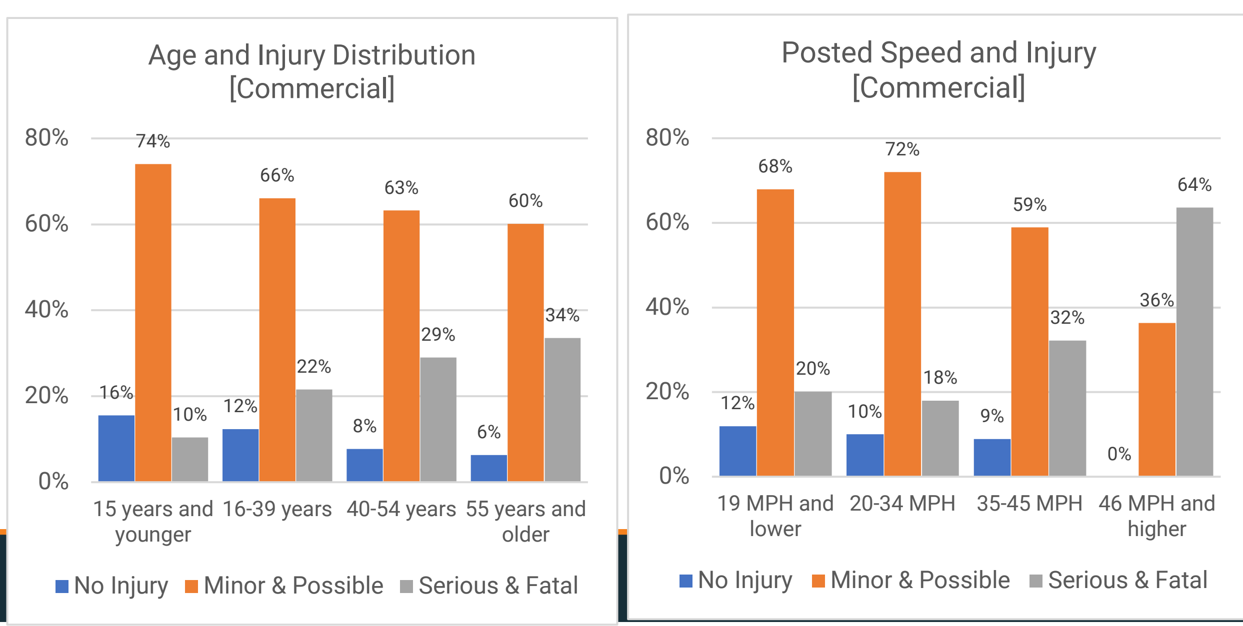

Figure 9: (a) Age and Injury Distribution of Commercial Crashes, (b) Posted Speed Limit and Injury Distribution of Commercial Crashes

Regression Results

Binomial Logit Model for Commercial Crashes

We fitted a binomial logistic model using nine significant variables from the crosstabs with the commercial indicator as a dependent variable. This model helped discriminate commercial crashes from non-commercial crashes while supporting our approach to categorize the commercial VRU crashes. The model has 19388 observations with the pseudo-r-squared value of 0.094, log-likelihood of -2402.09, and p-value of .000.

Table 5: Binomial logistic regression for commercial and non-commercial crashes

Particulars	Odds Ratio	Std. Err.	z	P>z
Age category (Base: 16 – 39 years)				
Below 15 years	0.90	0.12	-0.78	.433
40 - 54 years	1.25	0.14	2.03	.043
55 years and older	1.15	0.13	1.24	.214
Weekend	0.77	0.08	-2.36	.018
Time of Day (Base: 12:00 to 18:00)				
00:00 - 06:00	1.01	0.16	0.08	.937
06:00 - 12:00	1.50	0.16	3.83	.000
18:00 - 24:00	0.71	0.08	-3.06	.002
Private areas or Parking lot	1.35	0.14	2.84	.004
Weather (Base: Clear)				
Cloudy	1.11	0.17	0.67	.502
Other	0.48	0.18	-1.92	.055
Rainy	0.76	0.12	-1.73	.084
First Impact (Base: Front end)				
Left Side	1.12	0.16	0.78	.435
Rear End	1.98	0.28	4.82	.000
Right Side	1.62	0.19	4.20	.000
Other	2.25	0.32	5.63	.000
Driver Age (Base: 16 - 39 years)				
40 - 54 years	2.00	0.21	6.64	.000
55 years and older	1.18	0.14	1.46	.145
Others or unknown	1.34	0.23	1.65	.098
Male driver vs otherwise	4.79	0.52	14.38	.000
Injury Outcome (Base: No injury)				
Minor	0.85	0.13	-1.05	.293
Possible	0.89	0.14	-0.74	.458
Serious	1.19	0.21	1.01	.312
Fatal	2.65	0.56	4.63	.000

Constant	0.01	0.00	-25.60	.000

From the model, we can conclude that VRUs within the age group 40 to 54 years are significantly more susceptible to commercial crashes than other age groups. The variables weekdays versus weekends and time of the day conforms to the fact that the crashes involving commercial vehicles are less frequent during the weekends and night-time. There is less chance of getting into a commercial VRU crash on bad weather days such as rainy, snowy, windy, etc. A VRU is significantly more likely to get into commercial vehicle crashes in private areas and parking lots than non-commercial vehicle crashes. First impacts in commercial VRU crashes are more common on the rear end and right side. The odds for these impacts are considerably higher than the base value of the front end and left side first impacts. Primarily, commercial VRU crashes are characterized by male drivers in the age group 40-54 years. Finally, the fatal outcome variable is significant in predicting a commercial or non-commercial VRU crash with an odds ratio of 2.65:1 for fatal to no injury outcomes. Other outcomes, such as serious injury, minor injury, and possible injury, are not significant in differentiating between commercial and non-commercial VRU crashes.

Binomial Logit Model for Injury Severity

We also fitted a binomial logit model for injury severity. The model has injury outcome as the dependent variable, with a severe or fatal injury as its value and nine independent variables. As shown in Table 6, the log-likelihood for the model is -271.27, and the pseudo-r-squared value is 0.186 with a p-value .000 for a total of 593 pedestrians and bicyclists involved in the commercial crashes.

According to the model, the age of pedestrians and bicyclists is one of the critical factors for predicting injury severity. With the pedestrian's age from 16 years to 39 years as the base, age groups above it has significantly higher odds of being involved in fatal commercial crashes. The children's group did not yield significant results. Likewise, the gender and race of the VRUs were also not significant in determining the injury outcome. However, VRUs under the influence of drugs and alcohol have a very high chance of getting into a severe or fatal crash than non-intoxicated ones. The p-value further illustrates that alcohol and drug presence in VRUs is highly significant for predicting injury severity, although this was not the case with commercial vehicle drivers. Additionally, the model suggests that white drivers are much likely to get involved in fatal and severe injury commercial VRU crashes, almost 2.5 times when compared to the driver of other races.

The posted speed limit dictates the highest odds ratio for getting into a severe or fatal crash with highly significant p-values. For the areas with speed limits 46 mph and above, the odds of getting into a severe or fatal crash is 3.32 times that of the crashes at the base condition with a posted speed limit below 35 mph. Commercial vehicles moving in a speed limit area of 35 to 45 mph are twice as likely as the base condition for sustaining severe or fatal injuries. Likewise, with the datum at 12 pm to 6 pm, the odds of damage on the serious side of injury-spectrum for commercial VRU crashes is significantly high in the morning from 6 am to 12 pm. The odds of getting seriously or fatally injured are also high on rainy days with a considerable statistical significance.

Crashes occurring in intersections have a considerably lesser probability of yielding serious outcomes. First impacts are not much influential in determining the crash severity except for the impacts on the right and rear ends, which are relatively safer than the frontal impacts.

Finally, relatively heavier commercial vehicles such as trucks significantly influence the fatal/serious outcomes than lighter commercial vehicles such as vans. According to the model, composite trucks or tractor-trailer are the most lethal with 2.84 times, followed by single-unit trucks with more than twice the chance of delivering a severe or fatal injury to the pedestrians and bicyclists when compared to minivans or SUV-sized commercial vehicles. Large vans are also 85 percent more likely to cause these injuries.

Table 6: Binomial logistic regression for Injury Severity (Fatal/serious injury vs Otherwise)

Particulars	Odds Ratio	Std. Err.	z	P>z
Age category (Base: 16 - 39 years)				
Below 16 years	0.69	0.31	-0.84	.402
40 - 54 years	1.66	0.46	1.82	.069
55 years and older	2.08	0.58	2.63	.009
Alcohol or Drug Presence	5.84	2.72	3.79	.000
Time of Day (Base: 12:00 to 18:00)				
00:00 - 06:00	1.96	0.80	1.67	.096
06:00 - 12:00	1.72	0.46	2.01	.044
18:00 - 24:00	1.44	0.43	1.25	.213
Weather (Base: Clear)				
Cloudy	1.81	0.68	1.59	.111
Other	0.25	0.41	-0.86	.392
Rainy	2.06	0.77	1.93	.054
First Impact (Base: Front end)				
Left Side	0.62	0.23	-1.32	.186
Rear End	0.54	0.20	-1.67	.095
Right Side	0.45	0.14	-2.65	.008
Other	0.98	0.32	-0.07	.944
Posted Speed (Base: less than 35 mph)				
35 - 45 mph	2.05	0.47	3.14	.002
46 mph and above	3.28	2.36	1.65	.099
Intersection vs non-Intersection	0.38	0.08	-4.36	.000
White driver vs Otherwise	2.52	0.58	4.02	.000
Commercial Vehicle Type (Base: Minivan/Utility/pickups and other vehicles)				
Large Van	1.85	0.57	2.01	.045
Single Truck Unit	2.18	0.66	2.56	.010
Tractor-trailer	2.84	0.97	3.07	.002
Constant	0.07	0.03	-6.16	.000

Large Vans examples (e.g., Ford EC1)

Conclusion and Limitations

This paper examines non-interstate crashes between vulnerable road users (VRUs) and commercial vehicles that occur within census-defined urbanized areas in North Carolina and 14 counties in Tennessee. We define VRUs as pedestrians and bicyclists and commercial vehicles as large trucks and cargo vans. Our time series analysis indicated that over study period, there has been a statistically significant increase in these crashes in both North Carolina and Tennessee, highlighting the importance of looking at VRU-commercial vehicle crashes to improve traffic safety.

We analyze the data using descriptive statistics, mapping, and logistic regression. The mapping in North Carolina indicates little to no spatial association between VRU-commercial vehicle crashes and freight-producing jobs. We do see, however, some apparent association between population density and clustering of crashes. In Tennessee, we also see a higher number VRU-Commercial Vehicle crashes in major cities.

According to our severe model results, we find that the position of the VRU with respect to the street cross-section is an important determinant of the likelihood that the VRU will be severely injured or killed. The value of this variable that was most significant was “Travel Lane” in North Carolina Model. When compared to the base case of “sidewalk/path,” a crash in which the VRU was located within the travel lane is nearly five times more likely to produce a severe injury or death. In Tennessee model, the VRU-commercial vehicle crash was more likely to produce a severe injury or death in the roadside compared to the crash occurring at the intersection. The results might suggest that transportation planners and engineers could reduce the likelihood of severe crashes between VRUs and commercial vehicles by providing infrastructure that allows VRUs to travel without needing to occupy the vehicular travel lane.

The type of commercial vehicle involved in the crash was also an important predictor of the likelihood of severe and fatal crashes. Severe models in both North Carolina and Tennessee indicate that when compared to large commercial variables, light trucks and vans are less likely to produce severe and fatal crashes. This finding comports with previous knowledge about the relationship between vehicle size and crash severity, and we can conclude that the relationship is similar when extended to crashes between VRUs and commercial vehicles. The fact that vans are less likely to produce a severe crash with VRUs is heartening, as increased urban freight activity can lead to more conflicts between commercial vehicles and VRUs. If urban freight deliveries are made with smaller vehicles, as some recent studies have suggested is likely, we might see fewer severe crash outcomes, even as total crashes could increase.

We can reasonably expect the trend of increasing crashes between VRUs and commercial vehicles to continue. As freight patterns change and delivery vehicles move increasingly to more urban and residential areas, there will be more opportunities for conflicts between commercial vehicles and VRUs. However, if carriers continue their trend of using smaller vehicles for last mile delivery, there is evidence to suggest that crashes between VRUs and this type of delivery vehicle is less likely to be severe or fatal.

There are two important limitations of this study that should be stated for appropriate interpretation of our results. First, our sample of crashes for all non-van commercial vehicles spans from 2007-2018 in North Carolina and from 2008-2019 in Tennessee. For cargo vans, however, we were only able to include crashes between 2011 and 2018. Our understanding of the timeframe with which cargo vans have been utilized by carriers minimizes the potential effect of this discrepancy as this relatively new mode has only recently gained prominence in last-mile delivery. Second, the interpretation of our logistic regression models should be done with care. Our sample contains crashes between VRUs and commercial vehicles in urban areas North Carolina and Tennessee but is not a census of all road segments in those areas. For example, we cannot say that elements of a road segment are more likely to produce a crash, given our models, but rather that elements of a road segment are more likely to produce a severe or fatal crash, when compared to other road segments that also produced crashes. This paper looks at only at crash-level predictors of crash severity in incidents involving vulnerable road users and commercial vehicles. Further research should examine a broader spatial scale, incorporating elements of the built environment and transportation network to predict the likelihood of this type of crash happening. Being able to attribute crashes to specific land-use or transportation characteristics would further help planners and engineers in focusing their efforts to create safer environments for VRUs.

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Part II: Last Mile Strategies for Urban Freight Delivery

A Systematic Review

Introduction

Changing consumer preferences and technological advances have created greater demand for urban freight delivery. Freight volumes have increased in the past decade, and the spatial patterns have shifted toward urban areas that traditionally have not seen this type of traffic (Elbert et al., 2020). Increasing urban freight volumes create problems such as congestion, emissions, noise, and collisions (Crainic et al., 2004; McDonald, Yuan, & Baumann, 2019). Public discourse recognizes these challenges with large media outlets placing greater attention on the impacts of urban freight, particularly small package delivery (Haag & Hu, 2019; Callahan, 2019).

Transportation networks principally serve two main functions: facilitating the movement of people for access to daily activities and facilitating the movement of goods and services for commerce. The former has traditionally received the most scrutiny by transportation researchers, although the latter is similarly of critical importance, enabling regional economies. With changing patterns of the supply chain, person trips and freight trips are now competing for space within the urban environment. Last-mile freight delivery is especially salient in the context of this dynamic realm of urban transport. Last-mile delivery, a term used to describe the last stretch of the supply chain between a final distribution center and the desired destination point, is considered the most costly and inefficient portion of the supply chain. Researchers and private firms have recently sought ways to improve last-mile delivery so that it can be more efficient, cost effective, and less disruptive to passenger travel.

The push to identify ways to improve last-mile delivery has led to an explosion of research on the topic over the last decade. The emerging literature has been published by scholars in many fields throughout the social, environmental, and engineering sciences, all applying their fields' latest methods to innovate solutions for last-mile delivery. The rapid growth of knowledge coupled with the varied disciplines from which it is proliferating creates a need for a timely synthesis. To do this we conduct a systematic review to 1) catalogue last-mile delivery strategies, 2) quantify the frequency with which last-mile strategies have been studied, and 3) identify how researchers have quantified the impacts of these urban freight solutions.

We identify 21 unique last-mile strategies, placing them into four categories including innovative vehicles, urban goods consolidation, technological and routing advancements in city logistics, and emerging planning tools and policies. We find that these strategies are evaluated in a similarly diverse manner, with researchers focusing on operational, environmental, social, and economic impacts.

Methods

To identify last-mile delivery strategies and how they have been evaluated, we conducted a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) guidelines and procedures (Kitchenham, 2004; Liberati et al., 2009). We searched for peer-reviewed studies and reports that address last-mile delivery published from 2005 to 2019 in Web of Science, Scopus, Academic Search Premier, and Transportation Research Information Database. This selection of databases is a representative collection of social science and engineering research. We excluded Google Scholar as the opacity of its search algorithms and the surfeit of results returned would run contrary to the purpose of a systematic review (Boeker, Vach, & Motschall, 2013). We excluded articles from before 2005 as this is the year that Amazon Prime first emerged—an event that is considered a major milestone in the proliferation of e-commerce and home delivery (Harter et al., 2010). Our search terms for the title and abstract were ("urban logistics" OR "city logistics" OR "urban freight" OR "urban goods movement") AND ("last mile" OR "last-mile").

To be eligible for inclusion in the study, journal articles had to 1) be published in English, 2) be published between 2005 and 2019, 3) identify at least one last mile delivery option, 4) appear in a peer reviewed journal article or conference paper, and 5) have an accessible full-text article. Studies were excluded if the title/abstract screening determined that they did not meet these criteria. Screening was done by one analyst using the Covidence systematic review software package. For articles meeting the inclusion criteria, we reviewed full texts of our selected studies and abstracted 1) last-mile goods movement strategies and 2) the evaluation criteria for these strategies, e.g., emissions, congestion, safety, etc.

To identify last-mile strategies and evaluation criteria, we used template analysis—a form of thematic text analysis that applies an inductive approach to data analysis and coding protocol. Template analysis involves the searching of themes within a text that become apparent as critical to the description of a phenomenon (Fereday & Muir-Cochrane, 2006; King, 2004). Through this process we apply labels (codes) to sections of text to index the text as relating to a theme that we have identified. We developed themes and respective codes iteratively throughout the abstract and full-text reviews. As new themes were identified, previously-analyzed texts were re-considered for the presence of newly-identified themes. The resulting database was then analyzed to produce a comprehensive list and classification of last-mile urban freight delivery strategies.

The initial search of the research databases yielded 418 results of which 163 were removed as duplicates. From this set of 255 articles, 86 papers were removed because they did not fit the inclusion criteria. We reviewed full texts of the remaining 169 papers, from which an additional 54 studies were removed if the review indicated that they: 1) did not meet or inclusion criteria (n=22), or 2) if they were republications of other previously reviewed papers (n=7), or 3) if they were not available in full-text form (n=25). From this, we were left with 115 full-text articles to identify and define innovative last-mile delivery strategies and determine how these strategies were assessed. The PRISMA diagram below illustrates the selection process (Figure 10).

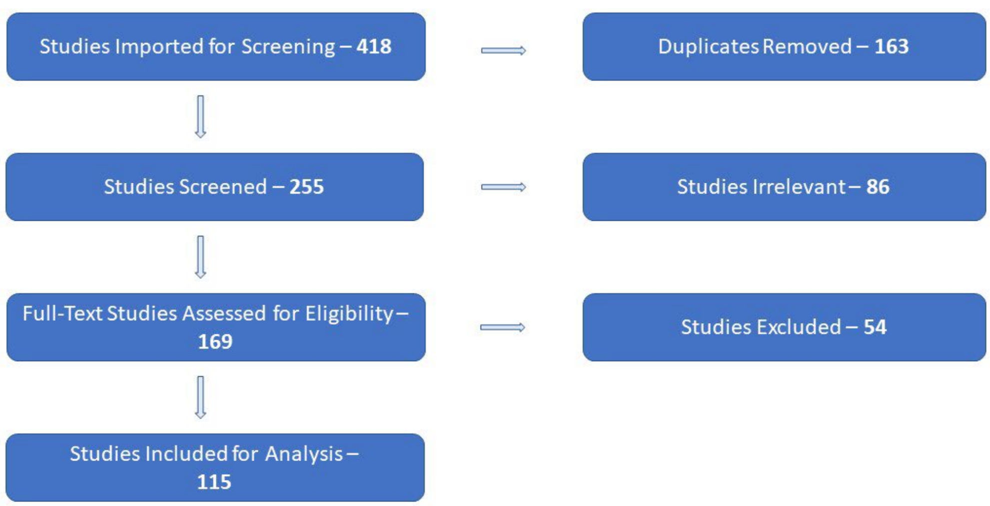

Figure 10: PRISMA Diagram

Last Mile Strategies

The systematic review identified 21 specific last mile delivery strategies which were grouped into four categories: 1) Innovative Vehicles, 2) Urban Goods Consolidation, 3) Technological and Routing Improvements in City Logistics, and 4) Emerging Planning Tools and Policies. Strategies are quite varied in their approach, ranging from solutions as simple as delivery vans to as complex as delivery robots and advanced algorithms for vehicle routing.

Innovative Vehicles

The most common type of last-mile delivery strategies discussed in the literature relates to innovative vehicles, accounting for more than one third of all referenced strategies in this review. Vehicles range in size, purpose, and propulsion technology, but they all share a common characteristic that they diverge from the typical large diesel-powered delivery truck. Table 7 identifies innovative vehicle strategies presented in the literature, lists common names for the strategies, and lists the authors who have published on these strategies.

From the thematic database, we determined which strategies were indeed unique, and which were essentially different expressions of the same strategy. We identified four broad categories of last-mile strategies and provide examples of included strategies as well as counts of the number of articles addressing each strategy. To quantify research interest in specific impacts of urban freight strategies, we analyzed full-texts using hierarchical coding, consistent with King (2004). Hierarchical coding involves the identification of higher-order and lower-order codes for indexing text that uses varying levels of specificity with respect to the research question. This analysis is done in parallel to the process of identifying last-mile strategies. Text that refers to ways that researchers have evaluated or propose to evaluate last-mile strategies are assigned codes that index this text. Articles can be assigned multiple codes for evaluation criteria if multiple criteria exist. From this, we identified four areas—operational, environmental, social, and economic criteria—that are the focus of research investigation. As a final step, we analyzed temporal trends based on the number of journal articles published that involved last mile urban freight strategies as well as a quantification of the journals publishing this work.

We see that the most commonly discussed vehicle innovation is freight cycles, being mentioned by 24 unique articles. Freight cycles can come in many forms and are typically differentiated by the number of wheels they have and how they are propelled. Some freight cycles are strictly human-powered and others are either entirely electric or assisted by electric motors. Freight cycles have been touted as promising alternative to traditional larger diesel-powered last-mile delivery vehicles for their nimbleness on small streets, ease of parking, and relatively low cost of operation. They are limited by their payload capacity and the distance that they can travel. Freight cycles are often mentioned in conjunction with mobile depots, a strategy that we will discuss later.

Another frequently mentioned innovative vehicle strategy is the use of alternatively-fueled freight vehicles. Electric freight vehicles are the most common, but alternatives can also include hybrid and fuel-celled freight vehicles. Authors discuss applying this technology to vehicles of many different sizes and configurations, but it is most often applied to smaller vehicles like light goods vehicles and vans. This strategy was identified by 16 unique articles.

Connected and autonomous vehicles have received a great deal of attention within the field of passenger transportation recently, and are also represented in the last-mile freight literature. Autonomous freight vehicles utilize emerging technology that allows them to traverse urban environments with reduced or zero human control. Again, the size of the vehicle depends on the study, and they can range from small single-package carrying vehicles to full-sized freight vehicles. This strategy was mentioned nine times in the studies we analyzed.

Modular freight vehicles are designs that allow for easy transfer of goods between different freight modes at transshipment facilities. This is often necessary when larger vehicles deposit goods at consolidation centers, from which they are carried the last mile to their final destinations. The modular design facilitates the transfer of goods between modes, often requiring shorter times and less space. This strategy was mentioned five times in the literature we analyzed.

Table 7: Innovative Vehicle Last-Mile Freight Delivery Strategies

Strategy	Includes	Authors	# of Articles
Freight Cycles	Tricycles, quadracycles, cycle logistics, cargo bikes, electric cycles	Bandiera et al., 2019; Choubassi et al., 2016; Clausen et al., 2016; Conway et al., 2012; Conway et al., 2017; de Oliveira et al., 2017; Fikar, Hirsch, & Gronalt, 2017; Fiori & Marzano, 2018; Guerrero & Díaz-Ramírez, 2017; He & Haasis, 2019; Heinrich, Shulz, & Geis, 2016; Martins-Turner & Nagel, 2019; Marujo et al., 2018; Navarro et al., 2016; Niels, Hof, & Bogenberger, 2018; Perboli & Rosano, 2019; Perboli et al., 2018; Perboli & Rosano, 2016; Saenz, Figliozzi, & Faulin, 2016; Schier et al., 2016; Slabinac, 2015; Staricco & Brovarone, 2016; Tipagornwong & Figliozzi, 2014; Weiss & Onnen-Weber, 2019	24
Alternative Fuel Freight Vehicles	Electric freight vehicles, hybrid-powered freight vehicles, electromobility	Amodeo et al., 2015; Bandiera et al., 2019; de Oliveira et al., 2017; Guerrero & Díaz-Ramírez, 2017; He & Haasis, 2019; Lebeau et al., 2013; Lebeau et al., 2015; Morganti & Browne, 2018; Morganti & Dablanc, 2014; Napoli et al., 2013; Perboli & Rosano, 2019; Ranieri et al., 2018; Shau et al., 2015; Taefi et al., 2015; Teoh, Kunze, & Teo, 2016	16
Autonomous Freight Vehicles	Robotic freight vehicles, shared autonomous vehicles, automated ground vehicles, self-driving parcels	Beirigo, Schulte, & Negenborn, 2018; Boysen, Schwerdfeger, & Weidinger, 2018; Digiesi et al., 2017; He & Haasis, 2019; Marsden et al., 2018; Mitrea & Kyamakya, 2017; Perboli & Rosano, 2019; Silvestri, Zoppi, & Molfino, 2019; Slabinac, 2015	9
Modular Freight Vehicles	Modular electric vehicles, transferable containers	Andaloro et al., 2015; Dell'Amico & Hadjidimitriou, 2012; He & Haasis, 2019; Rezgui et al., 2019; Slabinac, 2015	5
Delivery Drones	Drones	Guerrero & Díaz-Ramírez, 2017; He & Haasis, 2019; Perboli & Rosano, 2019; Slabinac, 2015	4
Light Commercial Vehicles	Delivery vans	Morganti & Dablanc, 2014	1
Underground Freight Pipline	Freight conveyors	Slabinac, 2015	1
Freight Trams	Gondolas	Staricco & Brovarone, 2016	1

Finally, delivery drones were identified in four studies in our sample. Delivery drones are unmanned electrically-powered areal devices meant for carrying smaller packages directly to customers' doors. Because they travel in the air, they are less affected by surface congestion and can also benefit from shorter travel distances. Delivery drones are still a relatively theoretical last mile strategy as the technology for facilitating freight transport with these areal devices has not quite made it to market and regulations for controlling their use is in initial stages.

A last-mile delivery strategy that has been regularly deployed but seldom mentioned in the academic literature is the use of delivery vans, also known as light goods vehicles. This last-mile strategy is not discussed often in the space of innovative strategies for urban freight delivery, but it has been somewhat of a linchpin in city logistics schemes as parcel carriers have been required to reach more dense urban locations. We saw traditional light goods vehicles mentioned only once among the papers we analyzed, while three other papers discussed applying emerging technologies like electrification and mobile depots to this mode (Morganti & Brown, 2018; Allen et al., 2018; Bandiera et al., 2019; de Oliveira et al., 2017).

Urban Goods Consolidation

Urban goods consolidation is the second most cited group of last-mile delivery strategies. Strategies in this category aim to optimize last-mile delivery, improving efficiency in the middle and end of the supply chain in part by reducing the number of last-mile delivery trips required to bring parcels to customers (Table 8). Urban Consolidation Centers (UCCs) is the most commonly cited urban goods consolidation strategy, and in fact, is the most cited of all last-mile delivery strategies that we identified in the literature. UCCs, also referred to as urban distribution centers, were discussed by 29 unique articles. UCCs are best defined as a facility for transshipment of goods headed for urban areas to consolidate deliveries and increase efficiency of last-mile delivery. Other similar strategies are known by different names and can be applied to different geographic scales, but they essentially provide the same function as UCCs. Conway et al. (2012) describe a close relative of urban consolidation centers known as urban micro-consolidation centers. These are warehouses or centers that act to consolidate freight, unloading from larger vehicles and loading smaller vehicles like freight-tricycles for last-mile delivery. They differ from traditional urban consolidation centers in their size, also emphasizing the use of smaller, often human-powered last-mile delivery options leaving the center.

Table 8: Urban Goods Consolidation Last-Mile Freight Delivery Strategies

Strategy	Includes	Authors	# of Articles
Urban Consolidation Centers	Urban distribution centers, micro consolidation centers, city logistics centers, logistics hotels, freight consolidation, consolidation centers	Aljohani & Thompson, 2018; Allen et al., 2018; Amodeo et al., 2015; Andaloro et al., 2015; Cherrett et al., 2012; Clausen et al., 2016; Conway et al., 2012; Dablanc et al., 2013; Digiesi et al., 2017; Finnegan et al., 2005; Gogas & Nathanail, 2016; Guerrero & Díaz-Ramírez, 2017; Handoko et al., 2016; Kin et al., 2018; Lagorio, Pinto, & Golini, 2016; Lebeau et al., 2013; Letnik et al., 2018; Lin, Chen, & Kawamura, 2016; Navarro et al., 2016; Ndhaief, Bistorin, & Rezg, 2017; Nguyen, Lau, & Kumar, 2015; Nsamzinshuti et al., 2016; Paddeu, 2017; Paddeu et al., 2018; Roca-Riu, Estrada, & Fernandez, 2016; Staricco & Brovarone, 2016; van Heeswijk, Mes, & Schutten, 2017; van Rooijen & Quak, 2010; Veličković et al., 2018	29
Parcel Lockers	Lockers, smart lockers, delivery lockers, dropboxes	Alves et al., 2019; Binetti et al., 2019; Carotenuto et al., 2018; Deutsch & Golany, 2018; Faugère & Montreuil, 2018; He & Haasis, 2019; Iwan, Kijeska, & Lemke, 2016; Lemke, Iwan, & Korczak, 2016; Moroz & Polkowski, 2016; Perboli & Rosano, 2019; Perboli et al., 2018; Pronello, Camusso, & Valentina, 2017; Zenezini et al., 2018	13
Pickup Points	Proximity stations, try-and-buy outlets, collection-and-delivery points	Allen et al., 2018; da Silva, de Magalhães, & Medrado, 2019; Digiesi et al., 2017; Guerrero & Díaz-Ramírez, 2017; Ranieri et al., 2018; Zenezini et al., 2018	6

Another frequently mentioned urban goods consolidation strategy is the use of parcel lockers. Parcel lockers are automated containers where pickups and deliveries are contained in a central location, managed either by a public or a private entity. They are usually enabled by technology that facilitates communication with smart phone devices and apps, allowing the authorized individual to access their goods. Parcel lockers can be located in places that are regularly visited in urban areas like convenience stores, gas stations, and transit stops. They are often used in conjunction with transit-based crowdshipping strategies, but we will discuss this strategy later in the paper. Pickup points are similar to parcel lockers, but they do not necessarily have the same automated quality. Pickup points can also be located at businesses and places where people have other daily needs. A distinguishing factor between pickup points and parcel lockers is that pickup points require a human attendant. Delivery drop off points can also be included in this strategy, eliminating the "first-mile" section of the supply chain for logistics firms.

Technological and Routing Advancements in City Logistics

The third category that emerged in the literature we call Technological and Routing Advancements in City Logistics. This group of strategies is vast, but they share a unifying factor of relating to improvements to logistics operations (Table 9). It can certainly be argued that any of the strategies among the four categories are related to logistics, but here we are specifically referring to the process of scheduling and routing packages and vehicles. Among this group, vehicle routing problem improvements were the most common.

Collaborative logistics was the strategy most discussed in this category, identified in 18 unique articles. Collaborative logistics entails the sharing of information between logistics firms to trade deliveries so that each firm is able to improve its efficiency. Collaborative logistics typically utilize advanced communications technologies and can also incorporate Geographic Information Systems (GIS) and app-based marketplaces to facilitate the transfer of delivery responsibilities between carriers. Giordani et al. (2018) put forward an exciting version of collaborative logistics in which auction-based online marketplaces are used by logistics firms to compete for the option to carry parcels to maximize efficiency.

Improvements to the vehicle routing problem is a solution that was also commonly cited among this group of strategies. The vehicle routing problem is an essential part of city logistics where transportation engineers apply simulations, decision-making algorithms, and other techniques to optimize the way that freight vehicles move from point to point on their supply chain. Improvements to the vehicle routing problem were quite varied among the studies that we analyzed, ranging from algorithms for reducing the amount of energy necessary for electric vehicles to perform last-mile freight delivery to the ordering of dispatches from a UCC. Contributions to the vehicle routing problem are extant within the past decade, but per the design of our study, we focused just on those articles that related specifically to last-mile freight delivery.

Crowdshipping is another strategy that is well covered in the last-mile delivery literature. Crowdshipping involves using advanced communication and real-time logistics optimization techniques to connect otherwise passenger-only trips to necessary last-mile delivery trips. The proliferation of smart phone technology has enabled individual travelers to participate in the last-mile delivery process voluntarily, often with compensation for carrying and delivering freight parcels. Crowdshippers are proposed to contribute to last-mile delivery using taxis, public transit, personal vehicles, and on foot.

Mobile depots are a strategy that uses multiple modes of freight delivery vehicles while also incorporating elements from the urban goods consolidation strategies. Mobile depots typically consist of heavy tractor-trailers that park in a central location in an urban area and act as last-mile dispatch centers. Smaller vehicles that have also been carried on the larger freight vehicle are then sent from the mobile depot to carry last-mile deliveries to their destinations. Most often, the smaller vehicle is a freight cycle. Mobile depots can also utilize smaller base vehicles such as light goods vehicles or vans. Additionally, mobile depots can dispatch all last-mile deliveries from a single temporary position, or they can make multiple stops throughout an urban area to further optimize last-mile delivery.

Another logistically-based last mile strategy that was discussed multiple times in the literature was the use of temporal changes to city logistics paradigms. Some authors suggest that changing the time of day that logistics firms make last-mile deliveries can provide improvements in the efficiency of delivery by avoiding the problems of congestion and failed deliveries due to customers not being at home. Other solutions to the unattended delivery problem included making last-mile deliveries to customers' workplaces or to their parked vehicles.

Table 9: Technological and Routing Improvements in City Logistics Strategies

Strategy	Includes	Authors	# of Articles
Collaborative Logistics	Logistics marketplaces, shared resources, joint distribution, last-mile pooling	Allen et al., 2017; Allen et al., 2018; Bates, Knowles, & Friday, 2017; Cherrett et al., 2012; Dallasega et al., 2018; de Souza et al., 2014; Digiesi et al., 2017; Durand, Mahjoub, & Senkel, 2013; Eidhammer & Anderson, 2014; Giordani et al., 2018; Giret, Julian, & Botti, 2019; Guerlain, Cortina, & Renault, 2016; Handoko & Lau, 2016; He et al., 2019; Kin et al., 2018; Munoz-Villamizar & Montoya-Torres, 2015; Paddeu et al., 2018; Ranieri et al., 2018	18
Vehicle Routing Problem Improvements	Optimization, approximate dynamic programming, distance minimization	Amodeo et al., 2015; Breunig et al., 2019; Digiesi et al., 2017; Ducret, Lemarie, Roset, 2015; Ehmke & Mattfield, 2012; Lebeau et al., 2015; Martins-Turner & Nagel, 2019; Munoz-Villamizar & Montoya-Torres, 2015; Orjuela-Castro, Orejuela-Cabrera, & Adarme-Jaimes, 2019; Perboli et al., 2018; Peroboli & Rosano, 2016; Ranieri et al., 2018; Rezgui et al., 2019; van Heeswijk, Mes, & Schutten, 2017; Zhou et al., 2018	15
Crowdshipping	Crowd logistics, crowdsourced delivery, crowd-tasking, transit logistics, taxi crowdshipping, neighbor relay	Akeb, Monsaf, and Durand, 2018; Allen et al., 2019; Chen & Pan, 2018; Devari, Nikolaev, & He, 2018; Gatta et al., 2018; Gatta et al., 2019; Gdowska, Viana, & Pedroso, 2019; Guo et al., 2015; He & Haasis, 2017; Kulinska & Kulinska, 2016; Serafini et al., 2019; Simoni et al., 2016; Slabinac, 2019; Wang et al., 2019	14
Mobile Depots	Micro depots, mobile city hubs	Allen et al., 2018; Arvidsson & Pazirandeh, 2017; He & Haasis, 2019; Marujo et al., 2018; Niels, Hof, & Bogenberger, 2018; Staricco & Brovarone, 2016; Verlinde, Macharis, & Milan, 2014; Weiss & Onnen-Weber, 2019	8
Temporal Changes	Workplace deliveries, off-hour deliveries, roaming delivery	Allen et al., 2018; Dablanc et al., 2013; Digiesi et al., 2017; Nsamzinshuti et al., 2016; Reyes, Savelsbergh, & Toriello, 2017	5
Enhanced Use of Existing Infrastructure	Spare capacity maximization, taxi logistics, urban waterway logistics, freight buses, freight subway,	Staricco & Brovarone, 2016; Horl et al., 2016; He & Haasis, 2019; Kin et al., 2018	4

Finally, other strategies for improving city logistics included utilizing existing infrastructure and transportation capacity for last-mile freight delivery. Authors suggested using taxis, buses, heavy-rail, and commuter-rail as a means to take advantage of transportation capacity that was under-utilized by passengers.

Emerging Planning Tools and Policies

The final category of last-mile delivery strategies that we identified included tools and policies used by public officials to affect the way that private logistics firms operate within cities. This category contained the fewest references in our sample, yet we identified four separate strategies for affecting last-mile deliveries in urban areas (Table 10). The most common policy for affecting last-mile delivery was urban access restrictions. Researchers propose a variety of mechanisms for restricting access, with spatial or temporal restrictions being the most frequently discussed. Letnik et al. (2018) suggest establishing loading bays within an urban area for parking and unloading freight vehicles. From this dedicated freight space drivers or other carriers then proceed with the goods on foot, by trolley, or by freight bikes. Additional tools included intelligent transportation systems that utilize real-time information to control the flow of freight vehicles depending on congestion and parking availability. Urban access restrictions were put forward in six articles that we analyzed.

Urban loading zones are another strategy proposed in the literature for affecting last-mile delivery. The devotion of public road space for parking and unloading of freight vehicles is a long-standing practice. However, recent innovations use the loading zone as a site to coordinate last-mile dispatch of smaller freight vehicles, cargo bikes, and on foot deliveries. Often this space is allocated by a government to facilitate improved urban freight outcomes, like limiting congestion and improper parking. Other strategies include sharing roadway space for both freight unloading and bus stop parking. These approaches were mentioned by six articles in our sample.

Table 10: Emerging Planning Tools and Policies for Last-Mile Delivery

Strategy	Includes	Authors	# of Articles
Urban Access Restrictions	Dynamic access, limited traffic zones, urban freight restrictions, intelligent transportation systems, congestion pricing	Allen et al., 2018; Chen, Wu, & Hsu, 2019; Dablanc et al., 2013; Finnegan et al., 2005; Navarro et al., 2016; Pronello, Camusso, & Valentina, 2017	6
Urban Loading Zones	Drop zones, shared drop zones, loading bays, shared loading zones	Allen et al., 2018; Cherrett et al., 2012; Letnik et al., 2018; Lopez et al., 2019; Pronello, Camusso, & Valentina, 2017; Ranieri et al., 2018	6
Parking Regulations	Freight parking management	Kolbay, Mrazovic, & Larriba-Pey, 2017; Dablanc et al., 2013	2
Certification Requirements	Consultation processes	Dablanc et al., 2013	1

Finally, cities also utilize parking regulations and certification schemes to facilitate improved urban freight outcomes. Freight parking is a large concern among transportation planners and engineers, and enforcement of existing regulations is often ineffective, as parcel carriers consider tickets simply as a price of doing business. Improved parking regulation can help cities and logistics firms to work together to reduce costs and improve on-street conditions for all road users. Certification requirements are another way that city officials can control flows of urban freight into and throughout their jurisdictions. With this strategy, officials require that logistics operators obtain a certification in order to travel within certain portions of an urban area. In exchange for this requirement, operators then gain access to restricted roadways and parking areas that see less competition for space. Parking regulations and certification requirements were not mentioned often in the literature, with only three articles proposing these strategies.

Evaluation of Strategies

The systematic review of last mile strategies identified four types of impacts of last-mile strategies that have received research attention –operational, environmental, social, and economic. The thematic analysis revealed specific metrics and concerns within each of these areas. We applied hierarchical coding to identify higher-order, or generalized criteria as well as lower-order, or more specific evaluation criteria. Below, Figure 11 depicts evaluation criteria by category.

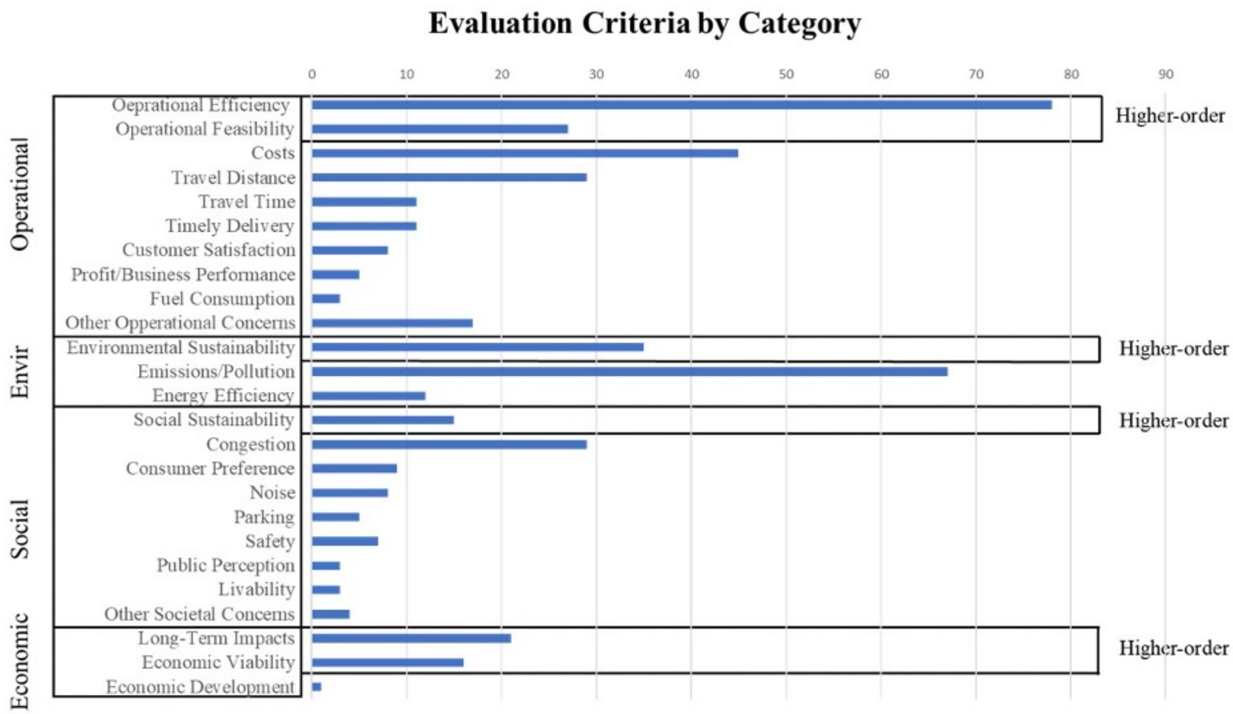

Figure 11: Selected Evaluation Criteria

Operational considerations were the most frequently cited type of impact among reviewed studies. Items identified in this category included higher-order considerations such as operational efficiency and operational feasibility, as well as lower-order considerations such as costs, travel distance, travel time, timely delivery, customer satisfaction, business performance, fuel consumption, and others. Figure 2 calls out higher-order criteria to delineate these from lower-order criteria. We highlight this distinction as it demonstrates the hierarchical coding method used in our template analysis.

The most common evaluation criteria, operational efficiency, was referenced in 78 unique articles. This is an example of a higher-order evaluation criteria. Text that refers to the ways a last-mile strategy broadly affects the efficiency of operations of a logistics firm or parcel carrier would be indexed using this code. However, if the text referred more specifically to something that directly affects operational efficiency, like cost or travel distance, it would be indexed using those lower-order codes. For example, Souza et al. (2014) discuss "optimizing commercial traffic" to benefit retailers and other urban-based businesses as well as congestion and air quality. Optimization was a common term found in the studies we analyzed; however, it is not often defined beyond that term itself. We can assume many things from this term, but instead of doing so, we simply indexed vague references to optimization as operational efficiency. Souza et al. (2014) go on to specifically mention congestion and air quality, both of which were recorded as lower-order evaluation criteria.

The studies that were most likely to describe operational considerations were those related to city logistics and vehicle routing problem improvements. In total, there were 234 references to operational criteria within the studies that we analyzed. The reason that this number is greater than the number of studies in our sample is that many studies include multiple evaluation criteria. This value of 234 is the largest of all the categories of evaluation criteria. This category also contained the most individual evaluation criteria, with two higher-order evaluation criteria and eight lower-order criteria.

Environmental impacts were the second most common evaluation criteria in the literature that we analyzed. Among these, emissions were most commonly cited, discussed in 62 articles. Other studies also frequently cited environmental sustainability, energy efficiency, and pollution as considerations for last-mile delivery strategies. Environmental sustainability is another relatively all-encompassing term that could also include individual criteria within the list of other environmental considerations, a good example of a higher-order evaluation criteria. Serafini et al. (2018) describe the development of a crowdshipping scheme in Rome, Italy. In this paper, they discuss alternative ways to implement crowdshipping, suggesting that doing so within the framework of the public transit system is the best alternative because it is the most “environmentally-friendly” alternative. Evaluating crowdshipping this way led us to index this text using the environmental sustainability code. In total, 114 studies mentioned environmental impacts of last-mile strategies. While frequently mentioned among the studies we analyzed, this category contained only three specific criteria. Emissions, a lower-order evaluation criteria within this category, was the second most cited impact of last-mile strategies.

Congestion was the most frequently mentioned among social evaluation criteria, being identified as an important means to evaluate last-mile delivery strategies by 29 different articles. Three other common criteria within this category were social sustainability, consumer preference, and noise. This category contained the second-most individual evaluation criteria of the four categories with one higher-order and eight lower-order criteria.

The impacts of last-mile delivery strategies on larger economic outcomes were considered in several studies. For example, Gatta et al. (2019) propose a transit-based crowdshipping last-mile strategy. In this paper, they model potential demand for the service based on many factors. Demand is measured in terms of number of orders, and this measure is put forward as a way to estimate economic viability of the service. Though economic viability is not a term used by the authors of the paper, it is a common construct observed in our template analysis, helping to unify different expressions of a common theme. Though similar, economic viability does not directly fit within operating considerations of individual firms, but rather is a way to consider the economic constraints of a last-mile strategies in the medium-term. Short-term costs to firms are thusly categorized as operational considerations whereas medium and long-term economic measures are categorized as economic considerations. Economic evaluation criteria were the least cited with only 38 criteria mentioned in the literature and only three individual criteria identified within this category.

Temporal Trends in Journals

Finally, we analyzed how the publication of articles related to last-mile delivery strategies has changed over time as well as which publications (academic journals) are publishing the most articles on the topic. Figures 12 and 13 highlight these trends.

Figure 12 shows a clear indication of increasing attention being given to last-mile delivery strategies in the past decade. While our selection criteria allowed for studies from 2005 on, the chart above starts in 2012. This is because there were only two studies in our sample published before 2012: One published in 2005 and another published in 2010. It was only in 2012 that multiple studies on the subject began to be published annually. Around 2015 the number of articles being published started to rise at a much faster rate, with a small respite to this trend in 2017. This review was conducted in 2019, and it would be reasonable to assume that more than the currently reported 21 articles will eventually be assigned to the 2019 calendar year. We will not speculate as to the future of this trend, but the rapid growth in publication on the topic indicates that last-mile delivery strategies is an increasingly important area in transportation planning and engineering.

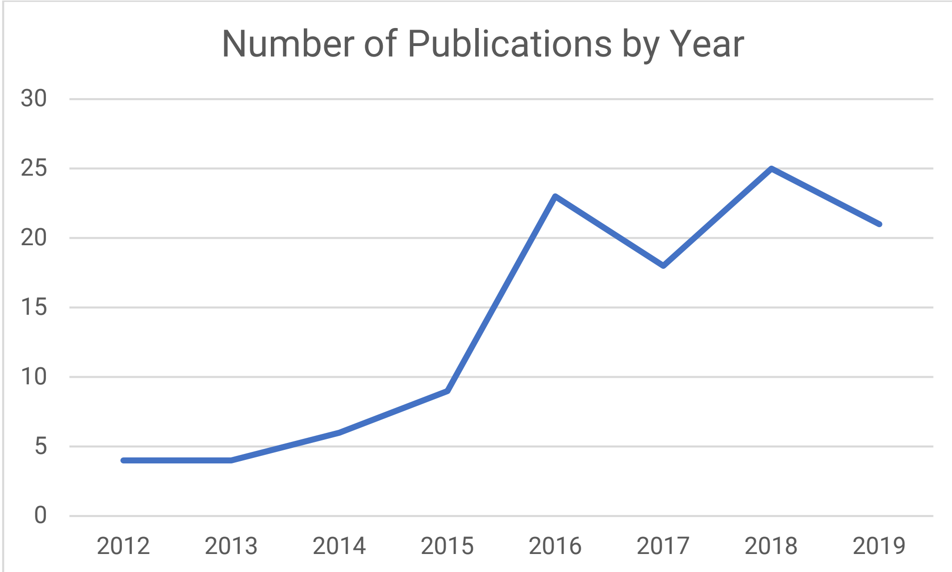

Figure 12: Temporal Trend in Last-Mile Strategy Publishing

Figure 13 displays the academic journals that are publishing the most on the topic of last-mile delivery strategies. We see that Transportation Research Procedia is the most prolific of the journals among our sample. This is to be expected, as this publication publishes peer-reviewed proceedings from multiple annual international transportation. The next most productive journal on the topic is Sustainability, followed by Transportation Research Record. The remaining journals have published four or fewer articles on the topic of last-mile delivery strategies.

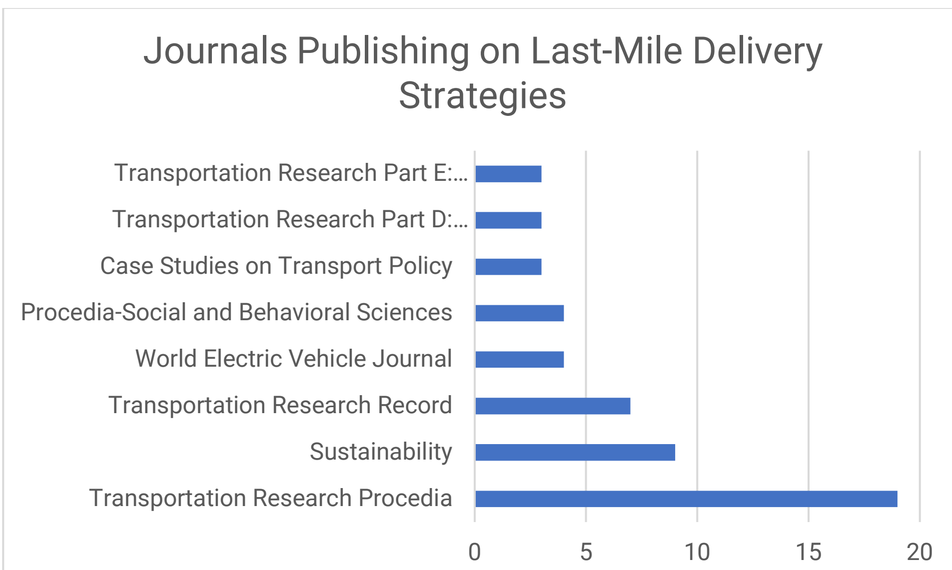

Figure 13: Academic Journals Publishing on Last-Mile Delivery Strategies

Discussion

In this study we conducted a systematic review to identify last-mile delivery strategies and to determine how those strategies have been evaluated in the literature. We found 21 unique last-mile delivery strategies, assigning them to 4 meaningful categories –innovative vehicles, urban goods consolidation, technological and routing advancements in city logistics, and emerging planning tools and policies. Our analysis found that researchers had analyzed the impact of urban logistics strategies around four impact areas: operational, environmental, social, and economic considerations. We found 25 distinct evaluation criteria among these categories, six of which were high-order, or generalized criteria, and 19 of which were lower-order, or more specific criteria.

Of the 21 unique last-mile delivery strategies, the most common were urban consolidation centers (UCCs) and freight bicycles. UCCs were identified by 29 articles in the sample that we analyzed. A UCC is a facility for the transshipment of goods headed for urban areas to consolidate deliveries and increase efficiency of last-mile delivery. UCCs take many forms and have many close analogues, and this diversity is likely a contributing factor to the strategy’s prominence in the literature. Another frequently cited strategy is freight bicycles. Freight bicycles can take many forms as well, being either human-powered or assisted with an electric motor. This strategy was mentioned 24 times in the literature that we analyzed. Another often-mentioned strategy was collaborative logistics. Collaborative logistics involves communication and planning between separate logistics firms to trade last-mile delivery tasks in a mutually beneficial agreement. This strategy utilizes emerging communication technology and algorithms to improve efficiency in last-mile delivery.

When we look at the number of strategies identified within each category, a clear picture appears. The two categories with the highest number of unique strategies are innovative vehicles and technological and routing advancements in city logistics with eight and six respectively. There were fewer urban goods consolidation strategies identified, however UCCs were the single most cited strategy in all the literature. Receiving much less attention, however, are emerging planning tools and policies. We identified only four strategies in this category, and even those that we identified were poorly represented among the studies in our sample. While logistics firms optimizing their routing techniques, transportation engineers configuring transshipment schemes, and mechanical engineers creating new urban freight vehicles have a great deal to contribute to the problem of last-mile delivery, so too might transportation planners and city officials. Policy and planning tools have the potential to greatly affect the problems associated with increasing urban freight and last-mile delivery, and this segment of the literature seems underdeveloped at this point.

The other part of our analysis examined how researchers evaluated last-mile delivery strategies. Here we found that the two most common evaluation criteria were operational efficiency and emissions. Again, we placed individual evaluation criteria into larger categories to better understand how researchers are considering the effects of last-mile strategies more broadly. Operational concerns contained the most individual criteria as well as the most total references in the literature, with 264 individual references to operational evaluation criteria identified in our analysis. Environmental concerns were much fewer in terms of the number of individual evaluation criteria, but the number of references to emissions make this category the second most cited among the four groups. Interestingly, economic criteria were the least well represented among the articles that we analyzed. While operational evaluation criteria contain many economic factors, these only affect the short-term economic outcomes of individual logistics firms, and do not necessarily pertain to longer-term economic impacts. Only three economic factors were identified as potential ways to evaluate last-mile delivery strategies. Another apparent omission from most studies of last-mile strategies was safety. Only seven studies from our sample of 115 mentioned safety as an outcome of interest when considering last-mile delivery strategies.

The relatively limited degree of consideration given to safety by researchers in the field of last-mile delivery comes as some surprise. As the safety impacts of increased urban freight activity gain increasing attention in the media and among city officials, we would expect this concern to permeate the academic literature. At this point, however, it has yet to happen. Researchers may be apprehensive to measure last-mile strategies in terms of safety as it could be difficult to attribute changes in aggregate safety metrics to specific last-mile strategies. The effects of increasing urban freight activity are almost certain to generate safety issues as larger freight vehicles enter urban and residential areas with more frequency. The safety effects of this trend require prompt and sincere attention from transportation researchers, representing a substantial contemporary research gap.

Finally, our analysis of the temporal trends in publishing on last-mile delivery shows that the topic has been growing in prominence in the past decade, with an increase in the rate of scholarly production since 2015.

This suggests that researchers will continue to discuss the strategies that we have detailed in this study and likely will produce even more innovative solutions to the problem of last-mile freight delivery in coming years. We should be cautious that the popularity of an idea in journal paper may not indicate that the idea has the same popularity in the industry. However, this paper can serve as a guide to researchers as they continue to advance knowledge on the topic by shedding light on what has been done as well as what areas have been neglected thus far.

Conclusion

We conducted a systematic review of the literature to identify last-mile delivery strategies and determine how those strategies have been evaluated. We find that there are four overarching categories of last-mile delivery strategies that help in synthesizing the large number of solutions. We suggest that strategies can be described as belonging to one of the following four categories: innovative vehicles, urban goods consolidation, technological and routing advancements in city logistics, and emerging planning tools and policies. We identify 21 unique last-mile strategies, of which urban consolidation centers (UCCs), freight bicycles, and collaborative logistics are the most commonly cited in the studies we analyzed. We suggest that there is a gap in the literature with respect to planning tools and policies for affecting urban freight delivery.

We also put forward four categories of evaluation criteria that researchers propose for determining success in urban freight solutions. These include operational, environmental, social, and economic criteria. We find that the most common evaluation criteria by far are those that fall within the operational category. Operational efficiency was cited as a potential evaluation criterion by 78 of the 115 studies that we analyzed. Emissions was the next most commonly cited criterion with 62 studies. We were surprised to see that safety was not of greater concern among researchers, with only seven studies including safety concerns. Considering the prominence of safety in other transportation arenas, we suggest that future research on the topic of last-mile delivery and urban freight should pay more attention to the effects of proposed strategies on safety outcomes.

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E-cargo Bikes to Address Urban Freight Problems

Introduction

Cities worldwide have been facing uneven but increasing urbanization growth over the recent decades (Sun et al., 2020). Changes follow urbanization growth in social and economic aspects of population and demographics, environment, and land use. With the changes affecting consumer behavior, urbanization has magnified the challenges of city logistics. In addition to traffic congestion, environmental effects, energy requirements, and emission, freight services face complex challenges mostly in urban areas between Vulnerable Road Users (VRUs) and commercial vehicles.

According to the annual Highway Statistics Series, published by U.S. Federal Highway Administration (FHWA), truck traffic share of vehicle-mile travel (VMT) on Urban roads and Urban interstates has been 5.57% and 11.35% in 2019, respectively (FHWA, 2020). With the expected increase in truck VMTs, cities would face magnified challenges related to safety, environment, and traffic congestion (Transportation Research Board National Academies of Sciences Engineering Medicine, 2013). Different strategies have been proposed by National Cooperative Freight Research Program (NCFRP) to address the urban freight problems and minimize the negative impacts of increased truck traffic share in urban areas. The strategies can be grouped into three main categories (Transportation Research Board National Academies of Sciences Engineering Medicine, 2013):

- Last-mile delivery strategies, focusing on reducing related traffic congestion,
- Environment strategies, focusing on reducing noise and emission, and
- Trade node strategies, focusing on problems related to metropolitan areas that serve as trade hubs and gateways.

Over the past decade, several innovative solutions have been introduced to reduce the negative environmental impacts of city logistics. One popular multipurpose solution is Light Electric Vehicles (LEVs) deployment which has become popular across the world (Dolati Neghabadi et al., 2019, Ploos van Amstel et al., 2018). Additionally, cycle logistics has also been considered as a sustainable alternative for last-mile deliveries. At the intersection of LEVs and cycle logistics, e-cargo bikes could be pioneers in urban core deliveries. The following section will provide a brief description of the characteristics of e-cargo bikes and review relevant literature about evaluating the efficiency of e-cargo bikes to address last-mile delivery problems.

Characteristics of E-Cargo Bikes

Similar to cargo bikes, e-cargo bikes benefit from several emergent advantages that increase their performance. These factors include:

- Being relatively small,
- Requiring less parking space and saving time by finding parking spaces faster than delivery vans,
- Producing less noise and emission relative to delivery vans,
- Being able to use bike infrastructure and maneuver through the city without being significantly affected by heavy traffic, especially in urban areas, and
- Having shorter distances from customers compared to delivery vans.

Additionally, by incorporating an electric assistant system, e-cargo bikes remove the barriers associated with human power, such as changes in grade, range, or low average speed. These factors make e-cargo bikes a suitable option for urban logistics (Arnold et al., 2018, Ploos van Amstel et al., 2018). This class of LEVs has been piloted in mostly large delivery companies such as UPS, DHL, and FedEx in Europe and the U.S. (Lia et al., 2014, Sheth et al., 2019).

Due to differences in the city logistics environment, many studies and projects related to (e-)cargo bikes have been conducted in European countries (Dolati Neghabadi et al., 2019). Since 2011, series of E.U. funded projects called CycleLogistics (2011-2014), CycleLogistics Ahead (2014-2017), and City Changer Cargo Bike (2018-2022) have been undergone in 18 countries to investigate the potentials of implementing (e-)cargo bikes in tackling some of the urban logistic challenges. Their analysis showed that about half of motorized trips for goods (including urban deliveries, have the potential to be shifted to the (e-)cargo cycles- about 33% of all urban deliveries (City Changer Cargo Bike, 2019, Wrighton and Reiter, 2016).

(E-)cargo bikes can be categorized into four groups: standard bicycle with panniers or shoulder bag, standard bicycle with a trailer, cargo bike, and cargo trike (Figure 14). Each group has its advantages and disadvantages related to commercial delivery. Table 5 provides a summary of EU Cyclelogistics findings on equipment types (Austrian Mobility Research, 2017). The same report has categorized the services offered by a cycle delivery into the following types: Mail, point to point, last mile, bike-train-bike services, first-mile, and advertising.

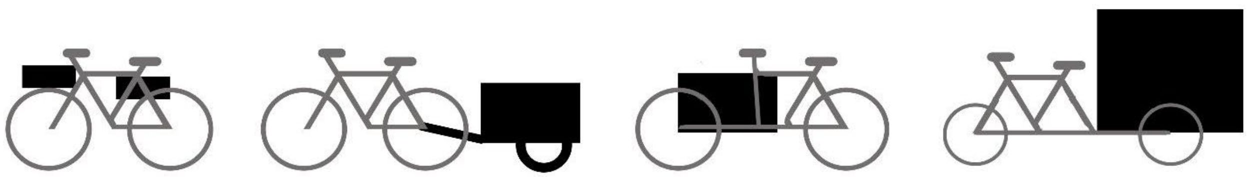

Figure 14: Four General Categories of Cargo Cycles from Left to Right: Standard Bicycle with Panniers or Shoulder Bag, Standard Bicycle with a Trailer, Cargo Bike, and Cargo Trik

One of the critical advantages of (e-)cargo cycles compared to traditional delivery vans is the ability to park on the sidewalk and closer to the customers without associated costs and time required for vehicle parking spaces. For instance, the inner-city last-mile speed in Charlotte, NC, and Nashville, TN, in 2017 was 12 mph and 16 mph, respectively, both among the top 25 most congested cities in the U.S. (Reed and Kidd, 2019). In urban core areas of the ten top largest cities of the U.S., it was found that parking limitations, restrictions, and associated costs have resulted in riders spending $72.7 billion cruising for a parking space (INRIX, 2017). That is equivalent to 6-15 minutes spent searching for on-street parking per trip in the U.S. largest cities.

Table 11: Characteristics of Different Bike Groups for Commercial Delivery

Category	Payload	Advantages	Disadvantages
Standard bicycle with panniers or shoulder bag	Up to 40 kg	• Fast in traffic • Ease of use • Ease of storage • Ease of parking • Use on and off-road paths • Lower costs (purchase and maintenance)	• Limited capacity • Lack of visibility • Security concerns
Standard bicycle with a trailer	Up to 80 kg	• Ability to carry larger loads • Potential advertising revenue • Lower costs (purchase and maintenance) • Use on and off-road paths	• Limited security • Weather concerns • Stability concerns • Push/pull effects while riding
Cargo bike	Up to 80 kg	• Ability to carry larger loads • Ease of use • Potential advertising revenue • Use on and off-road paths • Secure and weather protected	• Higher costs (purchase and maintenance) • Additional security required • Greater riding ability required
Cargo trike	Up to 250 kg	• Ability to carry larger loads • Ease of use • Potential advertising revenue • Secure and weather protected • Comparable with a small van	• Slower in traffic • Higher costs (purchase and maintenance) • May have road restrictions • Greater riding ability and strength required

Efficiency of E-Cargo Bikes to Address the Last-mile Delivery

Table 12 presents a summary of selected literature related to e-cargo bikes. Cargo cycles are most cost-effective if used in dense urban cores, especially for postal, parcel, or food deliveries (Ploos van Amstel et al., 2018, Rudolph and Gruber, 2017). Different studies evaluated the efficiency of the delivery system. They found that it will not change significantly if the providers replace up to about 10-48% of their van trips with cargo cycles (Melo and Baptista, 2017, Lenz and Riehle, 2013, Gruber et al., 2013). However, the competition between e-trikes and traditional vans is sensitive to the city urban policies, parking availability, and speed limits, in addition to the costs associated with the operation (e.g., drivers) (Tipagornwong and Figliozzi, 2014, Jaller and Pahwa, 2021). In general, studies agree on the importance of the location of distributing centers in a cost-saving that could result from implementing e-cargo cycles for delivery activities in dense urban cores (Sheth et al., 2019, Marujo et al., 2018, Tipagornwong and Figliozzi, 2014, Arnold et al., 2018, Lee et al., 2019, Jaller and Pahwa, 2021). Nevertheless, European cycle logistics projects have been economically successful, achieve high profits, and favorable to start-ups, while the bike model (e.g., trailer bike, cargo bike, tricycle, traditional bike) affects economic performance (Giglio et al., 2021).

From the environmental perspective, studies simulated and compared fuel costs and carbon emissions between e-trikes and vans. They found that the fuel costs effects were small on e-trikes competitiveness with vans while the carbon emission reduction is considerable and could range from 51% to 72% (Saenz et al., 2016, Tipagornwong and Figliozzi, 2014, Colson, 2019, Cairns and Sloman, 2019). Results from another study based on GPS data of cargo cycle operators in New York city also confirm positive environmental impacts of cargo cycles in congested areas (Conway et al., 2017). Researchers should further investigate the battery-related emissions of e-cargo cycles with life cycle analysis or similar methods.

In summary, the advantages of (e-)cargo cycles in city logistics are found to be lower vehicle and maintenance costs, lower parking costs, the potential of higher speed in traffic congestion, fewer driver training requirements, and lower negative environmental impacts. The challenges include security issues, limited capacity or range, seasonality, managing trailer locations, stability, route scheduling, and labor cost (Mayor of London, 2009, Behnke, 2019, Blazejewski et al., 2020).

Table 12: Main Findings from Selected Relevant Literature (Adapted from Cherry et al., 2019)

Author, year	**Location**	**Methods**	**Key findings**
Maes, J. and Vanelslander, T., 2012. (Maes and Vanelslander, 2012)	Europe	Market study and cost estimation	● Using bike messenger service can contribute to meeting CO2 emission requirements. ● Short-run employment possibilities are limited. ● Policy initiatives can help boost the bike courier market. ● Limitations in emission savings if the warehouse is not in the city.
Lenz, B. and Riehle, E., 2013. (Lenz and Riehle, 2013)	Europe	Interviews and survey	● Main services are courier, express, and parcel and delivery of basic products in catering. ● Parking prices are a motivation to shift from car to cargo bikes. ● The availability of city center hubs is an important spatial factor. ● Cargo freight has the potential to reduce emissions and noise pollution.
Gruber, J., Kihm, A. and Lenz, B., 2014. (Gruber et al., 2014)	Europe	Spatial analysis, cost estimations, and survey	● Electric cargo bikes lie between bikes and cars in terms of cost, payload, and range. ● Messengers' attributes such as demographics, attitude and values have significant impacts on their willingness to use e-cargo bikes. ● Important factors in the implementation of e-cargo bikes are their range, price, and publicly available information.
Tipagornwong, C. and Figliozzi, M., 2014. (Tipagornwong and Figliozzi, 2014)	USA	Cost analysis	● Cargo cycle competitiveness to diesel vans is sensitive to urban policies, road design variables (e.g., speed limit, parking availability), and drivers' cost, but not fuel cost. ● Cargo cycle services perform better in denser urban areas, with depots being located close to the customers.
Schliwa, G., et al., 2015. (Schliwa et al., 2015)	Europe	Thorough review and interview	● Local authorities play an essential role in providing conditions that help integrating cargo cycles in delivery services companies. ● These incentives can affect infrastructure (cycle lanes, speed limits), equipment, urban governance (zero-emission zones, parking enforcements).

Saenz, J., et al., 2016. (Saenz et al., 2016)	USA	Emission assessment	● Total greenhouse gas emissions are reduced between 51-72% if diesel vans are replaced by electric tricycles. ● E-cargo cycles' competitiveness and benefits maximized in dense and congested areas.
Nocerino, R., et al., 2016. (Nocerino et al., 2016)	Europe	Pilot project costs and environmental analysis	● Battery duration and reliability are among the main concerns of deploying e-scooters and e-bikes for logistics for logistic companies. ● Pilots demonstrated that capacity, battery, and reliability should be less concerned if enough and accurate cycles are chosen.
Koning, M. and Conway, A., 2016. (Koning and Conway, 2016)	Europe	Survey	● Most of the shifted volumes to cargo cycles were from motorized two-wheels and vans. ● The largest externality savings from implementing cargo cycles were in reduced pollutants and impacts on congestion, whereas the smallest savings were in reduced CO2 emissions and noise.
Conway, Aet al., 2017. (Conway et al., 2017)	USA	Case studies using GPS data	● Speed distributions vary on different road infrastructures. ● Service time with cargo cycle deliveries is shorter than truck deliveries. ● More space and emission savings can be observed in congested urban cores.
Melo, S. and Baptista, P., 2017. (Melo and Baptista, 2017)	Europe	Cost analysis	● Cargo cycles can replace up to 10% of vans without affecting the overall network efficiency in areas that distance is smaller than 2 km. ● About 25% of external cost reduction can be reached by introducing e-cargo cycles in urban logistic activities.
Figliozzi, M., et al., 2018. (Figliozzi et al., 2018)	USA	Lifecycle emissions minimization model	● Lifecycle emission rates per customer were at least six times lower when e-trikes were utilized than a diesel cargo van. ● Lifecycle CO_2e emission rates per customer were at least four times smaller when e-trikes are utilized than a diesel cargo van.

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Glossary of Terms

Crowdshipping: crowdsourced shipping

The method used to deliver packages to customers by leveraging non-professional and local courier services.

E-cargo bikes

Purpose-built electric cargo bikes.

E-commerce

The buying and selling of goods or services using the internet.

LEVs: light electric vehicles

Electric vehicles with one or more wheels powered by a battery, fuel cell, or hybrid-powered, and generally weighing less than 100 kilograms

Transshipment

The shipment of goods or containers to an intermediate destination, then to another destination.

UCCs: Urban Consolidation Centers

Facilities for transshipment of goods headed for urban areas to consolidate deliveries and increase efficiency of last-mile delivery.

VRU (vulnerable road users)

Both pedestrians and bicyclists.

Collaborative Sciences Center for
ROAD SAFETY

730 Martin Luther King Jr. Blvd.
Suite 300
Chapel Hill, NC 27599-3430
info@roadsafety.unc.edu

www.roadsafety.unc.edu