Who is Responsible for the Externalities Produced by Freight Carriers? Hint: The Answer is Not as Simple as it Seems…

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Abstract

This research sheds light into an important and overlooked aspect of urban freight management and planning: the impacts of the decisions made by shippers, receivers, transportation and land use agencies, the real estate sector and other agents—referred to as non-carrier agents, or NCAs—on the generation of freight externalities. The paper is based on the insight that, since freight carriers must meet the constraints set by these agents, NCAs' decisions could force the carriers to create externalities above and beyond those that the carriers would generate if they had complete control over their operations. As part of the research, the authors: identify a number of NCAs' decisions that could negatively affect the operational performance and the externalities produced by freight carriers; and compute the corresponding Shapley Values to allocate the responsibilities for the freight externalities among carriers and NCAs using numerical experiments based on real-life supply chains. The insights gained are used to identify policy implications related to electrification of the trucking sector.

Keywords: Urban Freight Management, Externalities, City Logistics, Shapley Value

1. Introduction and Background

The mitigation, or elimination, of the externalities produced by the various forms of transportation activity is one of the most important objectives of transportation planning and policy. Central to this quest's success is the correct identification of the root decisions that create externalities, as such an understanding provides crucial insight into how to address these effects. This is important because NCAs make decisions that directly influence carrier operations and could create externalities. The role played by NCAs in the generation of freight transportation externalities is frequently overlooked. At first glance, it seems logical to conclude that, since freight vehicles are the ones that physically produce the externalities, the carriers are solely responsible for the generation of the externalities. However logical this perception may be, it flies on the face of the complex web of decisions that influence supply chains and the resulting freight carrier activity.

To start, it is important to highlight that the agents involved in supply chains do not operate in isolation of each other, and freight operations do not take place in a vacuum. Freight carrier operations they are the result of the interactions between the economic agents that participate in the numerous production and consumption stages in supply chains. At each of these production-consumption links, an agent produces and/or sends supplies (the shipper) that are then consumed by a different agent (the receiver), after they are transported by the carrier. Because of these tight interconnections, no single agent can make unilateral changes without impacting in one way or another the other participants in the supply chain. As a result, in cases of conflicting preferences, the agent with more power tends to impose its will on the others. This cold logic of power explains why the carriers—frequently the weakest agent in supply chains (Holguín-Veras et al. 2015)—have to abide by the decisions and preferences of the more powerful NCAs. If the carriers do not follow the NCAs' instructions, they run the risk of being fired or fined.

Supply chains do not take place in a vacuum either. They are embedded in the fabric of rural/urban/suburban areas and have to abide by the regulations enacted by transportation, environmental, and land use agencies. These agencies typically control: (1) where manufacturers, distribution centers, truck terminals, retail stores, and other participants in supply chains are located; (2) the size and nature of the activities performed at these locations; (3) access to transportation networks by time of day and facility type, and to public spaces such as the curbsides and sidewalks; and (4) the environmental standards to be met by vehicles; among other impactful constraints. Complicating matters, with the advent of ecommerce, households became another active agent in supply chains. As a result, untold numbers of deliveries are made to buildings unprepared to receive supplies and parcels, forcing carriers to park on local streets aggravating urban congestion. Throughout the paper, the term "receivers" denotes both commercial establishments and households. The real estate sector establishes constraints—setting delivery time windows and building hours, determining whether or not the building design is conducive to efficient freight operations—that impact carrier operations. In addition, the markets in which the various segments of the freight industry operate determine the profitability of carriers' operations and, consequently, the ability of carriers to purchase environmentally friendly vehicles.

At first sight, in game theory terms, this situation seems to be similar to a multi-layer, multi-player Stackelberg game where the leading players make decisions that maximize their returns, while the follower agents are forced to make decisions under the constraints established by the leaders. However, close inspection reveals that these interactions are not a Stackelberg game, because the agents involved may have the option to cooperate with the others. In a separate publication, (Holguín Veras et al. 2023) defined the "Supply Chain Game" as one where the agents are interested in participating in the supply chain (if they are not, the supply chains would not exist). However, the conditions of their participation depends on the balance of power with the participating agents. For each interaction with another agent, they are only three possibilities: submit to the wish of a more powerful agent, cooperate with the agent if this outcome is the best for both agents, or impose its will on a weaker agent. (Holguín Veras et al. 2023) established that the Supply Chain Game leads to two outcomes: a state of natural cooperation, and the "Battle of the Sexes" game.

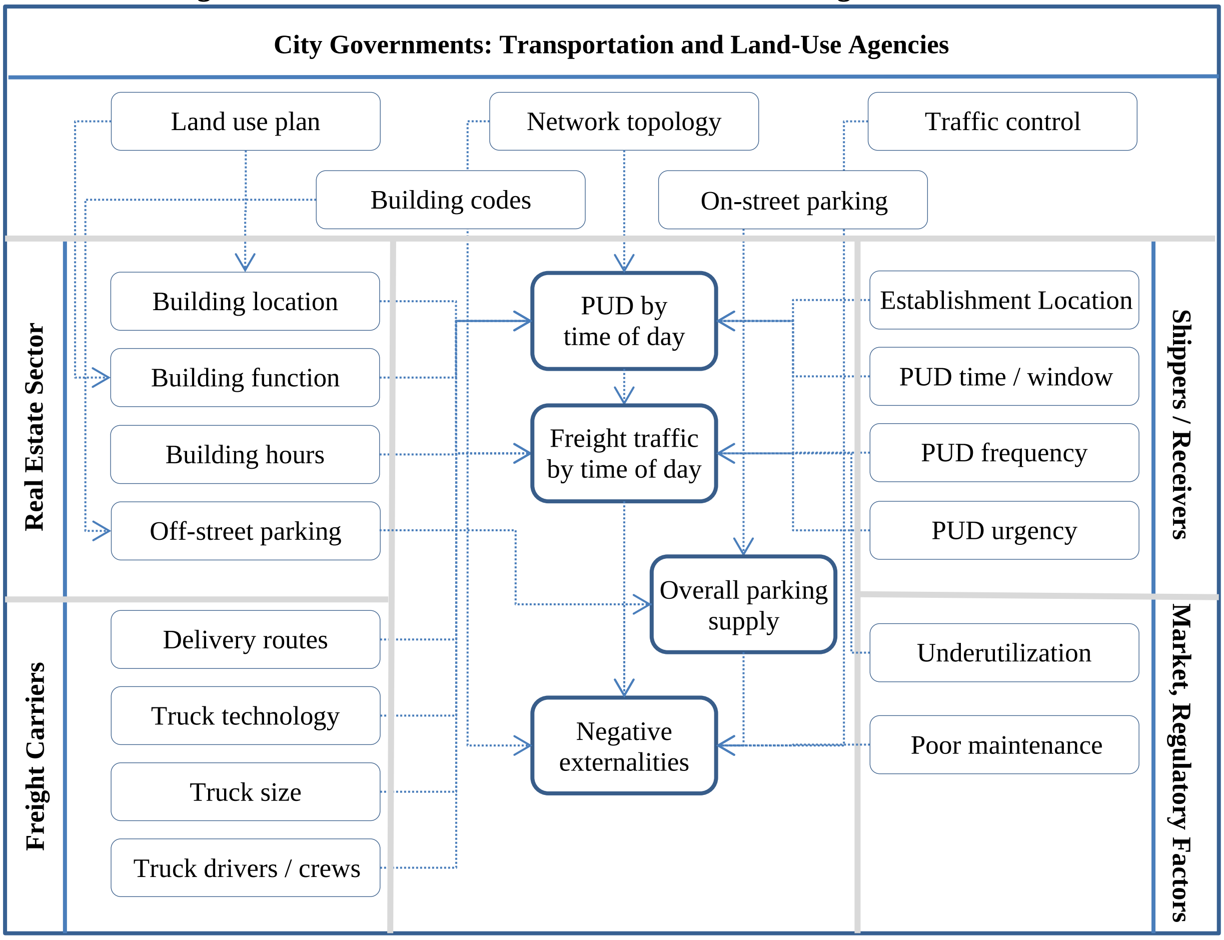
These insights have major implications. Most significantly, since the actions by NCAs to influence carrier operations could increase the externalities produced by the carrier—above and beyond the externalities that would be generated without the NCAs' interventions—NCAs would be responsible for the incremental externalities produced. To eliminate freight externalities, transportation planners must target all the agents—carriers and NCAs—involved in the decisions that contribute to the creation of the externalities. It is crucial to correctly identify which agents are responsible for the externalities in question, to be able to identify the public-sector initiatives needed to induce NCAs to modify the behaviors that create the externalities in question. These considerations take an existential importance in the era of climate change, where all policy weapons ought to be brought to bear to reduce global warming gases. Solely focusing on carriers is bound to be ineffective at best, and counterproductive at worst.

The main objective of this paper is to help fill an important gap in the research literature regarding the identification and quantification of the responsibilities of carriers and NCAs in the generation of urban freight externalities. In doing so, the paper significantly expands the literature on urban freight management and planning by considering the role played by NCAs, and develops a methodology to quantify the responsibilities of the NCAs for the externalities they help create. To this effect, the authors establish how NCAs influence carrier operations, discuss NCAs' roles in the generation of freight externalities; and conducts numerical experiments based on real-life supply chains to provide insight into the relative importance of the roles played by various agents. The paper concludes with a summary of the key insights developed during the research.

2. Contributors of Freight Externalities

This section seeks to illustrate the NCAs' decisions that influence carrier operations and externalities. As a result, the section does not comprehensively discuss the array of factors these agents consider when making other business decisions. Figure 1 shows some key ways in which the different agents influence freight activity and create urban freight externalities. As shown, five groups of influencing factors are considered. Hinting at the complexity of the processes that create freight externalities, only three of them—freight carriers, shippers, and receivers (both commercial and households)—are directly involved in the supply chain. The rest of the agents establish the geographic and economic environments where supply chains take place and, in doing so, have a direct effect on the externalities produced.

Figure 1: Contributors to Traffic Related Urban Freight Externalities



Note: FTG refers to "freight trip generation", and PUD to "pick-up and deliveries".

Moreover, to exemplify the impacts of NCAs' decisions, the authors analyzed the impacts of a number of decisions that have major impacts on freight externalities: (1) shipment size and frequency; (2) time of delivery; (3) allocation of curbside space for loading and unloading of deliveries (both off-street and on-street); and (4) location of logistical facilities. Strikingly, Table 1 makes clear that these decisions involve tradeoffs between the efficiency of freight activity and the benefits of some kind to the private-sector NCAs; and/or to influential stakeholders, such as passenger car drivers, in the case of public-sector NCAs. As hinted by Figure 1 and Table 1, using public policy levers to remove the most impactful constraints imposed on the carriers by the NCAs is bound to be effective in reducing freight externalities. As demonstrated by the Off-Hour-Deliveries (OHD) program, inducing receivers to accept deliveries during the 7PM to 6AM period led to emission reductions in the range of 50% to 67% (Holguín-Veras et al. 2018b). Inducing other NCAs to change their behaviors could be equally impactful.

Table 1: Summary of Impacts for Typical Decisions

Decision	Who Pays?	Who Benefits?
Shippers / receivers: Reduce shipment size, increase frequency of PUDs	**Carrier:** Increased costs / VKT/ parking	**Receiver:** Reduced inventory costs and the size of storage areas
	City: Increase infrastructure maintenance	
	Society: Increased congestion / health	
	Environment: Increased emissions	
Receivers: Require PUDs at the most congested times of day	**Carrier:** Increased costs / VKT / parking fines	**Receiver:** Continue following traditional practices, convenience
	City: Increase traffic control costs	
	Society: Increased congestion, health	
	Environment: Increased emissions	
Real Estate: Not to provide sufficient off-street loading docks for PUDs	**Carrier:** Increased operational costs / parking fines / VKT looking for parking	**Real Estate:** Increased amounts of space to commercialize
	City: Have to provide PUD on-street	
	Society: Increased congestion / health	
	Environment: Increased emissions	
City agencies: Not to provide sufficient on-street parking for PUDs	**Carrier:** Increased costs / parking fines / VKT looking for parking	**City:** Increased curbside space available for buses, passenger cars, and
	Society: Increased congestion, health	
	Environment: Increased in emissions	
Land use agencies: Not to provide space for urban/near-urban logistical facilities	**Carrier:** Increased costs / VKT	**City:** More land available for other uses
	City: Increase infrastructure maintenance	
	Society: Increased congestion, health	
	Environment: Increased emissions	

Note: "City" refers to "city agencies, "health impacts" refer to those associated with emissions; VKT denotes "vehicle-kilometers-traveled," and "PUD" refers to "pick-up and deliveries".

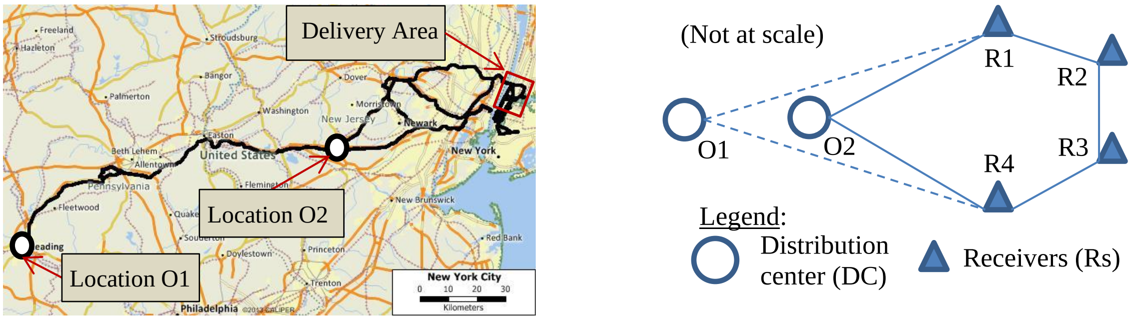
3. Quantification of Responsibilities and Experimental Setup

To quantify the responsibilities among carriers and NCAs, the authors used cooperative game theory to allocate the social costs of making deliveries. Cooperative game theory study the formation of coalitions to determine the payoffs that should be given to the partners to ensure the coalition is stable. Although conceived as a mechanism to optimally distribute earnings in profit making ventures, cooperative game theory is well-suited to allocate the responsibilities for freight externalities. Among the analytical formulations developed to compute these payoffs—*Stable Set* (Von Neumann and Morgenstern 1944), *Core of the Game* (Gillies 1959), *Aumann-Maschler Value* (Aumann and Maschler 1961), the *Kernel Value* (Davis and Maschler 1963), and others—the Shapley Value (Shapley 1952) stands out on account of its axioms that, once defined in terms of the economic value of externalities (instead of total profits) become: (1) the summation of the individual allocations equal to the total economic value of the externalities (efficiency principle); and (2) the individual allocations to each agent are proportional to their contributions to the creation of externalities (individual rationality principle). Mathematically speaking, the Shapley Value for agent *i*, φ_i, shown in equation (1), is the expected value of the value of the externalities, $v(S_i)$, produced by the potential coalitions where agent *i* is involved. See equation (1):

$$\varphi_i = \sum_{\{S \in N : i \in S\}} \frac{(S-1)!(n-S)!}{n!} \big(v(S) - v(S - \{i\})\big) \qquad (1)$$

The experiments focus on the impacts of three important decisions made by NCAs: (1) location of a distribution center (DC), typically made by shippers under the constraints set by the real estate sector and city agencies; (2) availability of parking at the receivers' locations, a decision of the real estate sector (off-street) and city agencies (on-street); and, (3) the time of delivery, a decision of the receivers. In this context, a shipper S operates a distribution center (DC) with two possible locations (O1,O2), a carrier C that makes deliveries to four receivers (R_1, R_2, R_3,R_4). There is a city government and real estate sector, CG-RE, that control the parking allocation to carriers. Thus, the game has four players (S,C,R,CG-RE). The carrier chooses the delivery route, under the operational constraints set by the NCAs. The shipper decides on the location of the DC, the CG-RE decides on the availability of parking, while the receivers (assumed to make the same decision) decide on time of the delivery. To ground the numerical experiments in reality, the authors selected a delivery route (conducted in both regular and off-hours) from the New York City Off-Hour Delivery project (Holguín-Veras et al. 2018a). The actual delivery route (pane a in Figure 2) was the base for the idealized delivery routes (pane b in Figure 2) used in the experiments. The parameters used in the numerical experiments come from the GPS data collected in New York City.

Figure 2: Idealized Delivery Routes Considered



Pane (a): Actual Delivery Route **Pane (b): Idealized Delivery Routes**

The marginal social costs—the sum of private and external costs—were estimated as the difference between the preferred scenarios for each of the NCAs and the carrier preferred scenario, (i.e., shortest travel distance to the delivery area, off-hour deliveries, and ready access to parking). More often than not, carriers and NCAs have different definitions of their preferred conditions. In equality of conditions: the shipper is interested in low land costs, frequently far from city centers; receivers tend to prefer regular hour deliveries; while city governments / real estate sector, for various reasons, do not provide the parking needed by carriers, and are not inclined to allow DCs close to urban cores.

The private costs account for the carrier's travel time, the distance travelled to make the delivery, and the expected value of parking fines. The external costs consider the costs of emission of various pollutants (CO_2, NO_x, PM2.5, PM10). See Tables 2 and 3. An important effect not considered is the increase in congestion and emissions produced by freight vehicles on the rest of the traffic stream and the blocking effects in urban streets. Thus, the marginal social costs created by receivers, and city governments / real estate sector are underestimated.

Table 2: Private Transportation Costs

	Time of Day	
Transportation costs	**Regular Hours**	**Off Hours**
Highway average travel speed (km/h)	53.24	57.75
City street average travel speed (km/h)	11.30	19.38
Cost per unit distance ($/km)	$0.61	$0.61
Cost per unit time ($/hour)	$45.13	$45.13
Average time between stops (min/stop)	66.83	49.00
Time cruising for parking (minutes/PUD)	5-10	0.00
Parking fine ($/PUD)	$68.91	0

Table 3: Emission Rates and Valuation of Pollutants

Pollutant	Emission rates		Economic Valuation of Pollutants		
	Regular Hours	Off Hours	Rate (original)	Rate (US$ in 2020)	Source
CO2 (g/km)	1548.16	694.45	$0.49/kg	$0.58/kg	Stern Review (UK, 2006)
NOX (g/km)	0.581	0.236	£6,199/ton	$5.61/kg	Ricardo Energy and Environment (2017)
PM10 (g/km)	0.086346	0.029762	£105,836/ton	$95.79/kg	Ricardo Energy and Environment (2017)
PM25 (g/km)	0.083	0.028	$12.85/kg	$22.16/kg	Small and Kazimi (1995)

4. Discussion of Results and Conclusions

Table 4 shows the breakdown of the social cost for the carrier preferred scenario—i.e., DC close to the delivery area, off-hour deliveries, and parking available—and the Shapley Values quantifying the increases in social costs of making deliveries attributed to NCAs' decisions. The contributions of shippers and carriers are reported together because their contributions are interwoven (Friesz and Morlok 1980, Friesz et al. 1986). A similar situation is that of city governments / real estate sector that jointly determine freight parking availability. The experiments consider two scenarios of cruising times for parking. See Table 4.

Table 4: Social Costs and Shapley Values

A) Carrier Preferred Scenario						
Agent:	**Social Costs**		**Private Costs**		**Externalities**	
Shipper-Carrier	**$426.42**		**$367.61**		**$58.81**	
B) Shapley Values (Expected Values of the Increases in Social Costs)						
	Case 1: Cruising for Parking = 5 min					
Agent:	**Social Costs**		**Private Costs**		**Externalities**	
Shipper-Carrier	$309.37	54.32%	$212.26	62.13%	$97.11	42.62%
Receivers	$201.45	35.37%	$90.98	26.63%	$110.47	48.48%
City Gov. /Real Estate Sector	$58.70	10.31%	$38.41	11.24%	$20.29	8.90%
Total	**$569.51**	**100%**	**$341.65**	**100%**	**$227.86**	**100%**
Increase = B/A	**133.56%**		**92.94%**		**387.46%**	
	Case 2: Cruising for Parking = 10 min					
Agent:	**Social Costs**		**Private Costs**		**Externalities**	
Shipper-Carrier	$309.37	49.83%	$212.26	57.06%	$97.11	39.02%
Receivers	$200.71	32.33%	$89.54	24.07%	$111.16	44.67%
City Gov. /Real Estate Sector	$110.77	17.84%	$70.19	18.87%	$40.58	16.31%
Total	**$620.84**	**100%**	**$371.99**	**100%**	**$248.84**	**100%**
Increase = B/A	**145.59%**		**101.19%**		**423.13%**	

These results compellingly demonstrate the significant effects of NCAs' decisions, found to increase emission externalities by 387%-423%, while increasing private costs by 92%-101%. As shown, the majority of the freight externalities, 57-61% of the total, are the result of the decisions made by receivers (45-48%), and city governments / real estate sector (9-16%). The duplet shipper-carrier contribute the rest (39-43%). It should be noted that the contribution of the city governments / real estate sector to the freight externalities is underestimated as these estimates do not include the increase in emissions from the traffic stream resulting from the trucks traveling in congested networks, cruising for parking in narrow streets, and double-parked trucks.

These results, based on real-life data, have major implications on urban freight management on account to the practical impossibility of rapidly electrification of trucking (at best a medium-term possibility). In the short- and medium-terms, freight demand management—fostering off-hour deliveries, staggered deliveries, and the like—remain the best short-term option. Fostering freight-efficient land-uses (Holguin-Veras et al. 2021) is bound to play a key role in the medium and long-terms complementing electrification. Without doubt, using all these tools provide the best chance of mitigating the worst effects of climate change.

5. References

Aumann, R. J. and M. Maschler (1961). The Bargaining Set for Cooperative Games. Research Memorandum No. 34. Princeton, NJ, Princeton University Press**:** 1-35.

Davis, M. and M. Maschler (1963). "Existence of Stable Payoff Configurations for Cooperative Games: Abstract." Bull. Amer. Math. Soc. **69**: 106–108.

Friesz, T. L., J. A. Gottfried and E. K. Morlok (1986). "A Sequential Shipper-Carrier Network Model for Predicting Freight Flows." Transportation Science **20**(2): 80-91.

Friesz, T. L. and E. K. Morlok (1980). Recent Advances in Network Modeling and their Implications for Freight Systems Planning. Proceedings of Transportation Research Forum 21.

Gillies, D. B. (1959). Solutions to General Non-Zero Sum Games. Contributions to the Theory of Games (AM-40). A. M. Tucker and R. D. Luce. Cambridge, MA, Princeton University Press. **4:** 47-86.

Holguín-Veras, J., F. Aros-Vera and M. Browne (2015). "Agent Interactions and the Response of Supply Chains to Pricing and Incentives." Economics of Transportation.

Holguín-Veras, J., T. Encarnación, C. A. González-Calderón, J. Winebrake, S. Kyle, N. Herazo-Padilla, L. Kalahasthi, W. Adarme, V. Cantillo, H. Yoshizaki and R. A. Garrido (2018a). "Direct Impacts of Off-Hour Deliveries on Urban Freight Emissions." Transportation Research Part D: Transport and Environment **61**(1): 84-103.

Holguín-Veras, J., S. Hodge, J. Wojtowicz, C. Singh, M. Jaller, F. Aros-Vera, K. Ozbay, A. Weeks, M. Repogle, C. Ukegbu, J. Ban, M. Brom, S. Campbell, I. Sanchez-Díaz, C. González-Calderón, A. Kornhauser, M. Simon, S. McSherry, A. Rahman, T. Encarnación, X. Yang, D. Ramírez-Ríos, L. Kalahasthi, J. Amaya, M. Silas, B. Allen and B. Cruz (2018b). "The New York City Off-Hour Delivery Program: A Business and Community-Friendly Sustainability Program." INFORMS Journal on Applied Analytics **48**(1): 70-86.

Holguin-Veras, J., D. Ramirez-Rios, J. Ng, J. Wojtowicz, D. Haake, C. T. Lawson, O. Calderón, B. Caron and C. Wang (2021). "Freight-Efficient Land Uses: Methodology, Strategies, and Tools." Sustainability **13**(6).

Holguín Veras, J., T. E. Encarnación-Rivera and D. Ramírez-Rios (2023). "Urban Freight Externalities: Contributing Factors and Agent Responsibilities " (in review).

Shapley, L. S. (1952). "A Value for n-Person Games." **295**: 1-13.

Von Neumann, J. and O. Morgenstern (1944). Theory of Games and Economic Behavior. Princeton, NJ, Princeton University Press.