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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

List of Acronyms

PUDO	pickup/drop-off
TNC	transportation network company

Executive Summary

The emergence of various new forms of urban mobility services in recent years has led to new pressures on curbside space. Municipalities, the entities frequently responsible for managing the curbside, are in many instances handling these growing pressures by reallocating portions of the curbside away from traditional uses (such as metered and residential parking) in favor of uses such as ride-hailing and scooter and bike-share corrals. As yet, however, such actions are being undertaken on an ad hoc basis due to the rapidly growing complexity of the curbside and the lack of standard analytical approaches. This lack of analytical capability is due to the traditional focus of transportation network modeling predominantly on the interaction of supply and demand on links and nodes, with limited focus on link edges (the curbside). In this report, we address this research need by proposing an approach for modeling intermodal competition for curbside space, inspired by the classical bid-rent model of urban land use, intended to support curb managers to move toward maximizing the aspects of economic welfare that relate to curb access. In the bi-level model, choices made by the curbside manager impact travelers' mode choices, and vice versa. We then present a numerical case study to demonstrate the properties of the proposed model, showing its tractability, flexibility, and intuitive sensitivity to systematic variation in inputs. The model demonstrates the type of adaptive and evolving approach needed to maximize benefits from increasingly dynamic curb management strategies.

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1 Introduction

The curbside serves a critical role in the mobility system as the main interface between the road network and adjacent urban land uses. In recent years, traditional curbside uses (e.g., bus stops and lanes, commercial loading, curbside through lanes, bicycle lanes, taxi stands, metered and unmetered parking) have been joined by demand for pickup/drop-off (PUDO) of newly emerging mobility services such as micromobility (e.g., shared scooters and e-bikes), ride-hailing, and freight service/delivery vehicles (e.g., Klein, Moore, and Reja 1997; Nelson\Nygaard Consulting Associates 2014; Klein 2015; Barth 2019; Gregg and Hess 2019; Henao and Marshall 2019; Butrina et al. 2020; Miklas-Kalczynska and Kalczynski 2020).

Efficiencies in curbside management offer the possibility to minimize negative impacts (e.g., searching for parking, idling, double parking, queuing, safety, energy consumption) while encouraging and supporting outcomes such as economic development, sustainability, and social equity (Lee, Agdas, and Baker 2017; Seattle Department of Transportation 2019). Thus, the competing pressures of these "legacy" and new activities on the curbside are encouraging transportation planners to place greater emphasis on managing curb space.

Curb space—the edges of the vehicular portion of a street right of way—is a critical component of transportation management (e.g., interrelationship with travel demand, traffic control, traffic calming), particularly for high-density urban neighborhoods (extended discussion can be found in Zalewski, Buckley, and Weinberger 2012; Lefebvre-Ropars, Morency, and Negron-Poblete 2021). Cities are increasingly aware of the potential to manage curbside space more efficiently than simply for automobile parking. While this is frequently the dominant curbside use (de Cerreño 2004; Shoup 2017; Millard-Ball et al. 2019), a number of large municipalities (see City of Fort Lauderdale 2018; Perez et al. 2020; Akers 2021) have implemented programs during major special events (e.g., professional sports or concerts) and/or in neighborhoods with nightlife activity to create formal PUDO zones for use by ride-hailing passengers. There has also been consideration of charging fees that explicitly monetize PUDO activity, with the possibility of using dynamic price signals to shape demand (City of Toronto 2019); this would be a departure from general current practice. An ecosystem of entities both new (Coord 2012; SharedStreets 2022; AllVision 2022) and established (Inrix 2022; Institute of Transportation Engineers 2018; International Transport Forum 2018) within the transportation sector have directed focus on the opportunities and challenges of curbside management in its contemporary context. The growth of ride-hailing activity at airports, which have traditionally charged for parking at closer to open-market rates than municipalities do for on-street parking, has in certain instances been associated with unanticipated decreases in airport parking revenues (Wadud 2020; Tirachini 2019; Henao et al. 2018). However, no standard framework exists for system planners to evaluate the potential and subsequent impacts for the curbside space allocation under various modes of transport.

The remainder of this paper is organized as follows: In Section 2, we review the relevant literature on curbside space management and application of bid-rent theory. Section 3 introduces the proposed approach for quantitatively modeling the curbside, and Section 4 presents the model formulation. Section 5 presents a numerical case study that includes various sensitivity analyses, and Section 6 summarizes and concludes the report with a brief discussion of future research needs.

2 Literature Review

2.1 Curbside Space Management

Recent efforts to quantify curbside activity include Lu (2019) and Smith et al. (2019). Both efforts focus on the productivity of curbside space, as measured by the number of passenger loading/unloading activities per unit length of curb space per unit time. Both studies contain empirical case studies that document large differences in curbside “productivity” (characterized by the aforementioned productivity metric) by various modes of transport (e.g., bus, private car parking, ride-hailing). However, both studies employ strictly descriptive statistical approaches of empirical case studies with field data. There is thus a gap in the lack of a general approach to enable maximizing the overall economic value (welfare) of the curbside.

The body of prior literature analyzing the curbside includes studies of optimizing the occupancy rates of on-street parking (Box 2004; Pierce and Shoup 2013; Arnott 2014; Millard-Ball, Weinberger, and Hampshire 2014), as well as the effects of on-street parking on road segment capacity and/or safety (Yousif and Purnawan 1999; Marshall, Garrick, and Hansen 2008). Arnott, Inci, and Rowse (2015); Inci and Lindsey (2015); and Cao, Menendez, and Waraich (2019) each investigate the optimal supply of on-street parking in the presence of competitive off-street garage parking. The prospect of shared automated vehicles is of growing interest (Eluru and Choudhury 2019; Vosooghi et al. 2019; Fagnant and Kockelman 2018), and Yang et al. (2020) and Chai et al. (2020) investigate the trade-offs between traffic from private automated vehicles searching for parking versus traffic from shared automated vehicles that use the curbside for pickup/drop-off and must travel empty to their next passenger’s location. Xu, Yin, and Zha (2017) investigate the potential for dedicating curbside space for dwelled transportation network company (TNC) vehicles that are awaiting ride requests (to reduce cruising). Yang et al. (2020) develop a microscopic simulation model based on a taxi first-in-first-out lane at a railway station. Shoup (2021) examines how parking duration, number of automobile occupants, walking speed, and value of saving time spent walking determine parking choices when prices increase as drivers approach their destinations. Designing policies to optimize curbside urban freight activity has also attracted much interest (e.g., Jaller, Holguin-Veras, and Darville Hodge 2013; Yang and Regan 2013; Marcucci, Gatta, and Scaccia 2015; Amer and Chow 2017; Zhang et al. 2020).

2.2 Application of Bid-Rent Theory

The bid-rent theory of land use (see Ricardo 1817; von Thunen 1826; Launhardt 1885; Isard 1956) was originally developed in the context of agricultural land uses in the hinterlands of an urban area, and later was applied to develop concentric-ring models of urban land use (Burgess 1925).

Alonso (1960, 1964) formalized the application of bid-rent theory in the context of urban land for a monocentric city. Various urban land uses (e.g., residential, commercial, and industrial of varying densities) compete for real estate, with all uses desiring proximity to a single central point (e.g., the city center in the case of a monocentric city), but each land use type characterized by a unique function (a bid-rent curve) that relates its willingness to pay for space in proximity to the central point. Each parcel of real estate is occupied by the use that values it more highly than the values that all other competing uses place on the parcel. Notable applications within the bid-rent framework include the bidirectional relations between activity location and transportation among households (e.g., Lerman and Kern 1983; Blackley 1985; Chang 2007; Ng and Lo 2015) and investigation of polycentric urban structures (e.g., Fujita and Ogawa 1982; Debrezion, Pels, and Rietveld 2007; Yang et al. 2020).

In Section 3, bid-rent theory is mapped onto the curbside surface through the mechanism of the different curbside uses competing for proximity to activity locations.

3 Overview of the Proposed Model

The proposed model simulates competition for the curb space among different uses, allowing the allocation of space to be formally optimized. Each linear segment of curbside space is allocated to the use that is optimal for it.

The proposed approach for modeling curbside activity extends from classical bid-rent theory in the following ways:

1. In bid-rent theory, the arena of competition is the two-dimensional plane of urban land; however, in the context of curbside modeling, the focus is instead on the collection of one-dimensional spaces along the line segments that represent the edges (i.e., curbsides) of the road network (or two dimensions if the width of right of way required for the curbside activity is explicitly considered).
2. Curbside uses (e.g., parking, passenger loading, freight loading) are distinctive types of activities and qualitatively different from the types of land uses (e.g., residential, commercial, industrial) employed in classical applications of bid-rent theory.
3. Bid-rent theory attempts to describe patterns of urban land use that are market-driven; however, curbside space allocation is a centrally controlled decision made by the street network operator. The objective is similar (optimal allocation of space), but the decision-making mechanism is different.
4. Bid-rent theory was initially developed considering a monocentric city form, and later extended to address polycentric urban form, with multiple nodes around which activities are centered. Harris and Ullman (1945), for instance, in their discussion of polycentric urban form, present an archetype of four major nodes (central business district, wholesale/light manufacturing district, heavy industrial district, and residential district) found in "most large American cities." In the context of the curbside, however, each curbside activity (e.g., a traveler who parks a car at a parking meter) is generated by a nearby land use (e.g., the building that is the ultimate destination of the traveler that has parked). Thus, the number of nodes around which curbside uses are organized is related to the number of distinct activity locations in the urban area (perhaps approximated by the number of buildings), and hence orders of magnitude larger than the low-single-digit number of central nodes in a typical polycentric bid-rent application.

Formally, for each linear element (e.g., a linear foot or a linear meter) of curbside i, we denote a value of economic welfare V_{ij} that accrues from allocating that curbside to candidate use j, which is the sum of welfare (characterized in principle via willingness to pay) accruing to all users (indexed $1 \ldots . x$) who perform use j at curbside portion i:

$$V_{ij} = \sum_{k=1}^{x} V_{ij}^{k} \quad (1)$$

Note that treating Equation 1 as the full calculation of welfare neglects the possibility of externalities (welfare impacts on other road users and/or non-users); we do not address this issue here and leave it as an item for further research.

There are in general two categories of curbside uses: uses that involve "through travel," which do not have a local origin or destination, and uses that involve loading/unloading or parking for which the traveler (or freight parcel, in the case of commercial loading) connects to their ultimate origin or destination on foot. Examples of the former include bicycle lanes or lanes for general motor traffic where stopping at the curbside is not permitted. For these users, the value of allocating curbside to the "through travel" use of their mode of travel is related to the value they place on accessibility to reach their not-proximate destination. (In the numerical analysis in the next section, this is specified via the value-of-time concept.) For the second category (travelers that would use the curbside for some form of loading/unloading or parking), the welfare that accrues to user k of use j if curbside portion i is allocated to use j is some decreasing function (i.e., distance decay) of the distance $l_{i \leftrightarrow m_k}$ between the traveler k's ultimate origin or destination m_k that will be accessed on foot and the location of curbside portion i:

$$V_{ij}^{k} = f\left(l_{i \leftrightarrow m_k}\right) \quad (2)$$

Beyond this general dependence of V_{ij}^{k} on spatial proximity, V_{ij}^{k} will also depend on other factors, such as factors idiosyncratic to each different curbside use in a given empirical application; the form of these relationships would be determined for the specific uses considered in an empirical application of this model.

For any given allocation of curbside space along the edges of a road network, aggregate welfare V is the summation of welfare accruing at all curbside portions, given the use j that is allocated at each curbside location i:

$$V = \sum_{i=1}^{n} V_{ij} \quad (3)$$

Equations 1–3 are descriptive; they link between a curbside space allocation policy (i.e., governance rules set by municipal curbside management staff), users' willingness to pay for their individual curbside usage episodes, and calculation of aggregate welfare accrual.

Beyond characterizing welfare accrual for a given curbside space allocation, the entity or individual responsible for setting curbside space allocation can identify the optimal allocation by maximizing V subject to a set of constraints. First, each portion of curbside space must be allocated to exactly one use at any one time. (Note: the proposed model is amenable to extension to incorporate uses that change by time of day/day of week, or dynamically in response to stochasticity in demand, but the initial numerical analysis case study presented in the next section treats uses as mutually exclusive and time-invariant.) Second, the physical aspect of the design problem imposes constraints such as minimum dimensions or unit dimensions for specific uses. For instance, it would not be possible to allocate a portion of curbside to a metered parking space where the allocated length is less than the length of a parked car (plus the distance required to maneuver into/out of the parking space).

4 Formulation With Representative Curbside Uses

This section presents an implementation of the proposed model with a set of representative curbside uses. Section 5 then presents the set of scenarios analyzed in this report's case study, designed to expose the properties of the approach.

We define five types of curbside activities, one of which relates to through travel, one to commercial vehicle loading/unloading, and the remaining three to passenger journeys having a local destination. Other curbside uses (e.g., micromobility corrals, bus stops, bicycle lanes) can be readily incorporated in future applications. In the interest of simplicity for this case study, we include:

- **Curbside lane for through travel:** This would involve the allocation of curbside space to a "no stopping" lane carrying moving traffic.
- **Bus stop:** This is a zone of fixed size (50 feet in length) included in all scenarios.
- **Commercial loading:** This is a curbside zone for commercial vehicle loading/unloading.
- **Ride-hailing PUDO:** This is a curbside zone where passengers board and alight from ride-hailing vehicles.
- **On-street parking:** This is a zone of on-street parking spaces for locally destined/originating motorists.

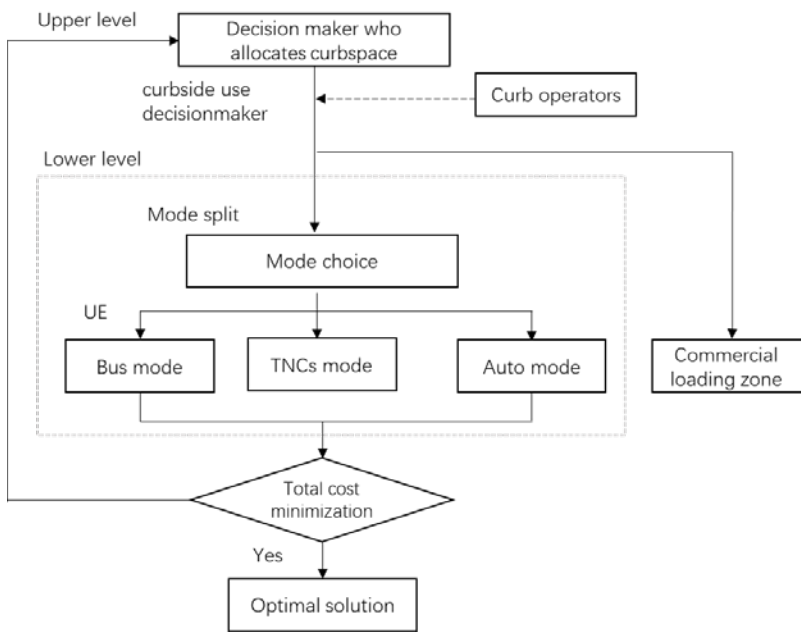

Figure 1. Overview of bi-level model

The system simulates two levels of interacting decision-making (see Figure 1). In the upper level, the curbside manager, the entity responsible for allocating curb space to the competing uses, compares all feasible allocations of curb space and selects the allocation that optimizes social welfare. The lower level of decision-making is individual travelers choosing which mode of travel to use.

Table 1 summarizes the notation employed in the case study.

Table 1. Summary of Notation

Term	Description
V_j	Welfare accruing to users of transport mode j, indexed: bus (B), ride-hailing (D), and automobile users (A)
$T_{T,B}$	Travel time from origin to bus stop
$T_{z,j}$	Walking time from zone z of activity j to journey's destination
f	Bus fare
N_j	Number of travelers for activity j
α_D, α_A	Alternative-specific constant for ride-hailing and automobile users, respectively
l_T^D	Travel cost from the journey origin to the PUDO zone
$T_{d,D}$	Delay time (from congestion) in the PUDO zone
l_T^A	Travel cost for automobile mode
$T_{d,A}$	Parking search time
p_v	Parking fee
C_j	Costs incurred by users of activity j
W	Value of time for commuters
v_j	Arrival rate of travelers for activity j per unit time
$t_{j,0}$	Uncongested (free-flow) processing time for curbside activity j
n_j	Number of increments assigned to activity j
s_j	Sequence of curbside activity j ordering from the intersection
W'	Value of time for commercial truck driver

The lower-level model simulates each traveler's mode choice using a standard multinomial logit form.

For bus travel, the utility function consists of four parts: travel time from origin to bus stop ($T_{T,B}$), walking time from the bus stop to the journey's destination ($T_{z,B}$), fare (f), and discomfort ($G(N_B)$, where N_B is the number of travelers choosing bus), via the following specification:

$$V_B = \beta_T \left(T_{z,B}\right) + \beta_T \left(T_{z,B}\right) + \beta_f * f + \beta_g \, G(N_B) \tag{4}$$

The discomfort function $G(N_B)$ is specified in keeping with Ersoy, Hasker, and Inci (2016) as a simple convex function with respect to N_B to reflect the discomfort associated with increased crowding:

$$G(N_B) = t_T^T(0.05 \cdot N_B^2 + 0.25 \cdot N_B) \tag{5}$$

For the ride-hailing mode, the utility function consists of four terms: an alternative-specific constant (α_D), the travel cost from the journey origin to the PUDO zone (l_T^D), the walking time from the PUDO zone to the final destination ($T_{z,D}$), and any delays associated with congestion in the PUDO zone ($T_{d,D}$):

$$V_D = \alpha_D + \beta_f \cdot l_T^D + \beta_T \cdot T_{z,D} + \beta_T \cdot T_{d,D} \tag{6}$$

Finally, the automobile mode's utility function comprises an alternative-specific constant (α_A), the travel cost (l_T^A), a term to represent parking search time ($T_{d,A}$, see Equation 17), walking time from parking location $T_{z,A}$, and parking fee p_v:

$$V_A = \alpha_A + \beta_f \cdot l_T^A + \beta_T \cdot T_{d,A} + \beta_T \cdot T_{z,A} + \beta_f \cdot p_v \tag{7}$$

In the upper-level model, we express welfare as the negative of the costs incurred by users. Thus, the objective function is specified to be cost minimization, considering the sum of costs incurred by users of all five of the curbside activities:

$$Minimize\ N_T \cdot C_T + N_B \cdot C_B + N_D \cdot C_D + N_C \cdot C_C + N_A \cdot C_A \tag{8}$$

where C_T, C_B, C_D, C_C, and C_A represent costs incurred by through travel users, bus users, PUDO users, commercial trucks, and parking users, respectively. We now present the respective cost functions, which all use straightforward relationships; more refined relationships can be introduced, such as treatments that allow queuing of one curbside use to cause delays to users of other forms of travel.

For through travel in the curbside lane, we specify the cost functions as follows:

$$C_T = W \cdot v_T \cdot t_{T,0} \cdot\ 0.15 \cdot (\frac{v_T}{n_T})^4 \tag{9}$$

W represents value of time, v_j represents volume of travelers for activity j, $t_{j,0}$ represents uncongested (free-flow) processing time for curbside activity j (through travel in Equation 9), and n_j represents the number of increments of curbside space allocated to activity j. n_t, n_D, and n_C are three decision variables in the model. Thus, Equation 9 is an application of the classical Bureau of Public Roads (BPR) function that results in costs for through travel decreasing as the number of increments of curbside space for through travel are increased (and vice versa).

For congested costs associated with ride-hailing PUDO, we employ the traditional $M/M/n$ queuing model (see Larson and Odoni 1981), as shown in Equations 10–14:

$$\rho_D = \frac{v_D}{n_D \cdot \mu_D} < 1 \tag{10}$$

$$P_x = \frac{1}{\sum_{s=0}^{n_D-1} \frac{1}{s!}(\frac{v_D}{\mu_D})^s + \frac{1}{n_D!} \cdot \frac{1}{1-\rho_D} \cdot (\frac{v_D}{\mu_D})^{n_D}} \tag{11}$$

$$L_q = \frac{(n_D \rho_D)^{n_D}}{n_D!(1-\rho_D)^2} P_x \quad (12)$$

$$T_{d,D} = \frac{L_q}{v_D} \quad (13)$$

$$C_{d,PD} = W * T_{d,D} \quad (14)$$

In Equation 10, ρ is the volume-to-capacity ratio of the PUDO zone (which in a static model cannot exceed 1.0 while maintaining a finite queue; a microsimulation approach would be more appropriate in such an instance), v_D is the arrival rate (in units of vehicles per hour), n_D is the number of 50-ft increments of curbside space allocated to PUDO, and μ_D is the inverse of dwell time in the PUDO zone (units of hours). In Equation 11, P_x is the probability that exactly x vehicles are queued at the PUDO zone. In Equation 12, L_q is the queue length (number of vehicles) at the PUDO zone. In Equation 13, $T_{d,D}$ is the expected delay time at the PUDO zone, and this is monetized in Equation 14 into cost $C_{d,D}$. Equation 10 relates the arrival rate at the PUDO zone with its service capacity, and Equation 11 calculates the probability that a given PUDO increment of curbside space is occupied. Equation 12 then calculates the expected queue length at entry to the PUDO zone, Equation 13 converts this into time spent queuing, and Equation 14 monetizes this into an equivalent monetary cost using value of time.

There is a second component of cost associated with the PUDO zone, due to the time value of walking to and from the intersection. This is expressed in Equations 15 and 16:

$$\text{x}= \begin{cases} 1 & s_j \le s_D \\ 0 & s_j > s_D \end{cases} \quad (15a)$$

$$T_{z,D} = \frac{\sum x \cdot n_j \cdot l}{v\prime} \quad (15b)$$

$$C_{z,D} = T_{z,D} \cdot W \quad (16)$$

where $T_{z,D}$ is walking time to and from the destination and $C_{z,D}$ is the cost due to walking. Finally, overall cost associated with the PUDO zone is the sum of costs from queuing in vehicle in the PUDO zone and walking time to the destination:

$$C_D = C_{d,D} + C_{z,D} \quad (17)$$

For commercial vehicles, we specify the *M/M/n* model to analyze the cost related to the queuing process in commercial loading zone, as shown in Equations 18–23:

$$\mu_C = \frac{1}{T_C} \quad (18)$$

$$\rho_C = \frac{v_C}{n_C \cdot \mu_C} < 1 \quad (19)$$

$$P_C = \frac{1}{\sum_{s=0}^{n_C-1} \frac{1}{s!} (\frac{v_C}{\mu_C})^s + \frac{1}{n_C!} \cdot \frac{1}{1-\rho_C} \cdot (\frac{v_C}{\mu_C})^{n_C}} \quad (20)$$

$$L_{qC} = \frac{(n_C \rho_C)^{n_C}}{n_C!(1-\rho_C)^2} P_C \quad (21)$$

$$T_C = \frac{L_{qC}}{v_C} \quad (22)$$

$$C_C = T_C \cdot W' \quad (23)$$

For on-street parking, we calculate costs ($C_{d,A}$) from in-vehicle delays due to congestion ($T_{d,A}$, in units of time) via the modified BPR curve and empirical parameter values proposed by Lam et al. (1999) for the context of on-street parking, representing the parking search process:

$$C_{d,A} = v_P \cdot W \cdot T_{d,\mathrm{A}} = v_P \cdot W \cdot t_{A,0} \cdot 0.31 \cdot (\frac{v_A}{n_A})^{4.03} \quad (24)$$

Equation 25 expresses the costs associated with walking from an on-street parking space to the destination, and Equation 26 shows overall costs associated with on-street parking to be the sum of the monetized in-vehicle delays and walking time:

$$C_{z,A} = T_{z,A} \cdot W \quad (25)$$

$$C_A = C_{d,A} + C_{z,A} \quad (26)$$

Hence, the social optimum is the set (n_T,n_B,n_D,n_C,n_A,s_B,s_D,s_C,s_A) that minimizes the negative of the costs incurred by users of all five of the curbside activities. The optimization problem is written in full in Equations 27a–27e:

$$\min_{n_T,n_B,n_D,n_C,n_A,s_B,s_D,s_C,s_A} N_T \cdot C_T + N_B \cdot C_B + N_D \cdot C_D + N_C \cdot C_C + N_A \cdot C_A \quad (27a)$$

Subject to:

$$(n_T + 2 \cdot n_B + 2 \cdot n_D + 2 \cdot n_C + n_A) \cdot l \leq L \quad (27b)$$

$$N_B + N_D + N_A = N \quad (27c)$$

$$1 \leq s_j \leq 4 \quad (27d)$$

$$n_j, s_j \in integer \quad (27e)$$

This optimization problem is a mixed-integer nonlinear programming problem, which in general is NP-hard (Nondeterministic Polynomial) (Floudas 1995). However, because the approach is a block-based model, the curb space management problem is a small-scale optimization. The numerical case study presented in Section 5 has a total of 39,169 candidate solutions from which the optimal solution is to be identified. A brute-force approach resulted in successfully obtaining the globally optimal solution with a runtime of approximately 4–5 hours per scenario. All experiments were run in MATLAB software on a PC with 3.20 GHz of Intel Core i7-8700 CPU and 16 GB of RAM under a Windows environment.

5 Numerical Case Study

The spatial context of the case study (depicted in Figure 2) is a set of numbered zones representing outlying geographic zones and lettered zones representing a downtown district centered on an intersection. The orange arrows show demand patterns of representative journeys that are "through travel" with respect to the downtown district (trips between Zones 1 and 3 are shown), while green arrows show demand patterns to and from the downtown district (trips between Zones 1 and B are shown).

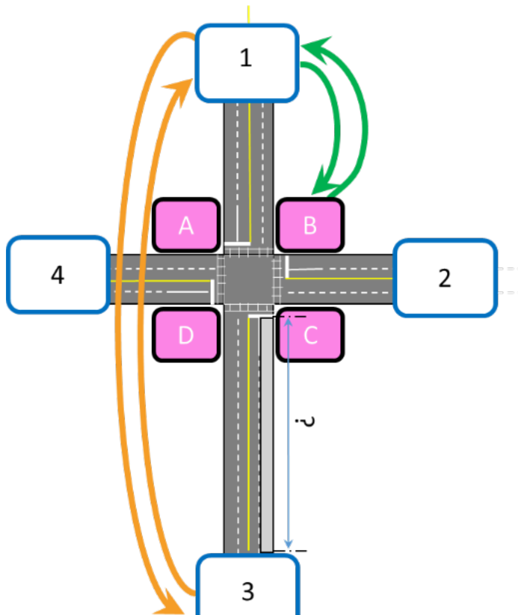

Figure 2. Schematic spatial layout of case study (not to scale)

We focus the allocation problem on the 1,000 linear feet of the curbside between Zones C and 3 (highlighted in light gray) beginning at the central intersection and extending south. This road segment is specified to have a cross-section wide enough for two lanes in the northbound direction. Thus, one lane (the lane adjacent to the centerline) is expressly allocated to traffic movements, and the optimization problem is which uses to allocate to which portions of the second (curbside) lane.

In order to investigate sensitivity of results to changes in inputs, we first developed a baseline scenario, which is followed by a set of numbered scenarios in which inputs are systematically varied. The input values (summarized in Table 2) were selected to be broadly reasonable and suitable to demonstrate whether the model exhibits the desired sensitivity.

The analysis period is 1 hour, free-flow travel speed on the road segment is set as 35 mph (25 mph on the curbside segment), and walking speed is set as 3.1 mph (5 kph). Entry of private cars to park in the on-street parking spaces is expressed in units of vehicles per hour, and is specified to follow a Poisson distribution. Dwell time in the on-street parking spaces is specified to follow an exponential distribution. We specify that space is allocated in integer increments of 25 feet in length for through travel and on-street parking, and increments of 50 feet in length for PUDO and commercial loading. The greater length of PUDO increments is intended to conceptually represent that PUDO is a high-turnover activity and thus is allocated additional space to facilitate rapid entry and exit of the PUDO zone without requiring vehicles to perform reversing maneuvers (as with parallel parking). We analyze three groups of travelers to represent heterogeneity in modal preferences (manifested as different values of alternative-specific constants).

The case study's specification of values for parameters and attributes in the lower-level mode-choice model are summarized in Table 2.

Table 2. Summary Description of Numerical Parameter and Attribute Values in Case Study's Lower-Level Mode-Choice Model

Term	Value	Description
β_T	−0.1	Sensitivity to travel time (together with β_f, implied value of time is $20/h)
$t_{T,0}$	2.4 minutes	Travel time for through travel (assumed 1-mi travel distance at 25 mph)
f	$2.00	Bus fare
β_f	−0.3	Generic (non-mode-specific) sensitivity to out-of-pocket cost (together with β_T, implied value of time is $20/h)
β_g	−0.1	Bus users' sensitivity to discomfort from on-bus crowding
l_T^D	$1.76	Travel cost for assumed 1-mi travel distance in TNC vehicle, calculated as fuel consumption cost per mile (10 liters per 100 km at $1/liter fuel cost) plus twice the value of time divided by speed (to represent time spent by both ride-hailing driver and passenger)
l_T^A	$0.96	Travel cost for assumed 1-mi travel distance in private automobile, calculated as fuel consumption cost per mile (10 liters per 100 km at $1/liter fuel cost) plus the value of time divided by speed
p_v	$4/h	Parking fee, specified to be $4/h
α_D		2.5 in Group 1; −2.5 in Group 2; −1 in Group 3
α_A		−1 in Group 1; −1 in Group 2; −5 in Group 3

Table 3. Description of Scenarios

Scenario #	Description	Total Demand (persons/h)	PUDO Service Rate (veh/h)	Value of Time ($/h)	Parking Duration (h)	Travel Through Demand (veh/h)	Walking Speed (mph)	Parking Fees ($/h)	Commercial Loading Demand (veh/h)	Loading Duration (h)
Baseline	--	75	24	20	3	250	3.1	4	5	0.25
1	Suboptimal curb space allocation [a]									
2	Increase in PUDO service rate	75	48	20	3	250	3.1	4	5	0.25
3	Increase in value of time	75	24	40	3	250	3.1	4	5	0.25
4	Decrease in parking dwell time	75	24	20	1.5	250	3.1	4	5	0.25
5	Increase in loading duration	75	24	20	3	250	3.1	4	5	0.50
6	Increase in through travel demand	75	24	20	3	500	3.1	4	5	0.25
7	Decrease in parking charges	75	24	20	3	250	3.1	2	5	0.25
8	Increase in loading demand	75	24	20	3	250	3.1	4	10	0.25
9	Increase in total demand	300	24	20	3	250	3.1	4	5	0.25
10	Decrease in values of Alternative-Specific Constants [a]									
11	Decrease in TNC charges [a]									

[a] See Section 5 for details of scenario specification.

Tables 4 and 5 present results of the case study's scenarios, with Table 4 presenting the main set of results. For the baseline scenario, it can be seen that the optimal solution of space allocation is the first 100 ft allocated to a lane for travel through the intersection, followed in sequence by 50 ft allocated to a bus stop, 100 ft to commercial loading zone, 200 ft to PUDO zone, and the remaining 650 ft to parking. Table 5 shows that the optimal curbside activities in the baseline are (beginning from intersection and moving away) PUDO zone, bus stop, loading zone, and parking zone.

In Scenario #1, the inputs are the same, but the layout (amount of space allocated to each curbside use) is not the optimal layout from the baseline scenario, but rather an alternate layout with reduced through travel space and PUDO zone space. The result is higher costs imposed on through travel and ride-hailing users, with lower costs imposed on bus, commercial trucks, and parking users. The net effect is an increase in total costs, as would be expected from a suboptimal allocation of space.

Table 4. Results From Case Study Sensitivity Analyses

Scenario #	Optimal Length (ft) of Through Travel Lane	Optimal Length (ft) of Bus Stop	Optimal Length (ft) of Commercial Loading Sone	Optimal Length (ft) of PUDO Zone	Optimal Length (ft) of On-Street Parking	C_t ($)	C_B ($)	C_C ($)	C_D ($)	C_A ($)	C_{total} ($)	N_B	N_D	N_A
Baseline	100	50	100	200	650	3.23	81.70	8.57	2.45	25.20	121.14	25.15	26.81	23.04
1	75	50	150	100	675	10.20	77.99	4.98	21.37	24.30	138.84	25.17	26.79	23.04
2	100	50	100	100	700	3.23	80.17	7.34	4.20	23.44	118.39	25.16	26.81	23.04
3	100	50	100	200	650	6.45	204.03	17.13	10.44	48.08	286.13	27.61	25.02	22.37
4	125	50	100	200	625	1.32	30.39	6.12	2.02	33.37	73.23	16.71	24.06	34.22
5	100	50	150	200	600	3.23	81.71	9.97	2.45	27.22	124.59	25.16	26.81	23.03
6	225	50	100	200	525	4.03	88.57	6.12	2.45	31.02	132.20	25.15	26.82	23.03
7	100	50	100	200	650	3.23	29.95	6.12	2.02	51.08	92.40	16.73	24.07	34.20
8	100	50	150	200	600	3.23	81.71	9.97	2.45	27.22	124.59	25.16	26.81	23.03
9	75	50	100	200	675	10.20	423.49	7.95	20.99	103.45	566.08	45.59	55.68	48.72
10	100	50	150	200	600	3.23	204.28	6.82	7.51	6.19	228.03	35.31	32.25	7.44
11	100	50	100	200	650	3.23	88.14	8.57	2.27	25.85	128.05	25.87	25.73	23.40

Table 5. Optimal Sequencing of Curbside Uses From Case Study Scenarios. (Location #1 is closest to intersection; #4 is farthest.)

Scenario #	Sequence of Bus Stop	Sequence of PUDO Zone	Sequence of Loading Zone	Sequence of Parking Zone
Baseline	2	1	3	4
1	1	2	3	4
2	2	1	3	4
3	1	2	3	4
4	3	1	2	4
5	2	1	3	4
6	3	1	2	4
7	3	1	2	4
8	2	1	3	4
9	1	2	3	4
10	1	2	3	4
11	2	1	3	4

Scenario #2 is characterized by an increase in the service rate (i.e., decrease in dwell time) within the PUDO zone. This increase in efficiency within the PUDO zone leads to less congestion in the PUDO zone, and hence a reallocation of curbside space away from PUDO in favor of on-street parking.

Scenario #3 represents an increase in the value of time. This parameter appears in the cost functions for all four curbside activities, as well for through travelers and commercial truck drivers. The net result in this instance is that overall cost increases, but the optimal allocation of space remains unchanged, while the order of curbside activities changes from "PUDO/Bus/Loading/Parking" to "Bus/PUDO/Loading/Parking." This result depends on the increased demand of bus users and the specific cost functions used for each activity.

In Scenario #4, there is a decrease in parking dwell time, which means that driving and parking becomes relatively more attractive. The result is a shift of demand from bus and ride-hailing toward parking, and an increase in space allocation for through travel in the optimal layout (from 100 ft to 125 ft) with the order of bus stop shift with the order of commercial loading zone. This is because the reduced parking dwell time leads to the reduced cost for each commuter, and hence the total cost is decreased.

Scenario #5 analyzes an increase in loading duration for commercial trucks, which means that the commercial loading/unloading service rate decreases, and the optimal length for commercial loading zone increases to 150 ft (50 ft from the parking zone is reassigned to the loading zone).

Scenario #6 is an increase in through travel demand, which leads to more of the curbside adjacent to the intersection being allocated to the curbside lane for through travel (i.e., the bus stop and other curbside uses begin farther from the intersection), and the parking slots decrease.

The gain from more spaces assigned to through travel overwhelms the cost increasing from less parking.

Scenario #7 has a decrease in parking fees, which results in an increase of commuter demand from bus mode and TNC mode to parking. The optimal curb space allocation remains the same, but the order of bus stop turns to the third, as the shifted demand from bus is more than that from ride-railing, so allocating the more beneficial location to the PUDO zone rather than to the bus stop is the optimal solution.

Scenario #8 simulates a situation in which there is more demand for commercial loading. The effect on the optimal layout is to shift the 50 ft that was allocated to the parking zone in the baseline scenario to instead be dedicated to commercial loading zone.

Scenario #9 shows the impact of increasing total demand to access the central downtown district (while holding through travel demand constant). The optimal layout has, as would be expected, an increase in space allocated to the parking zone, accommodated by a shift of space away from the curbside lane for through travel.

In Scenario #10, the utility functions of the mode-choice model are modified, and the alternative-specific constants (α_D, α_A) are reduced by half. This implies that the ceteris paribus propensity to use any of the modes of travel is reduced, thus increasing the relative importance of journey times and costs. The alternative-specific constants for the private automobile mode are negative for all three groups of users; therefore, reducing the absolute value of these alternative-specific constants results in an increase in bus and TNC use and an increase in space allocated to the commercial loading zone. Bus mode attracts more demand than TNC use, so the optimal location of the bus stop becomes closer to the intersection.

Finally, Scenario #11 simulates the effect of varying TNC charges, with the per-mile cost of the ride-hailing mode doubled. A small amount of ride-hailing demand shifts to private car and bus, and the optimal curbside layout remains the same. This result depends on the minor changed demand of TNC users and the specific utility functions used for each activity; there is no assurance that the optimal layout will in all cases not depend on the TNC charges.

6 Conclusions

Motivated by the rapid growth in new types of mobility-related activities seeking to use curbside space in cities, this report proposes a model for competing demands to use the curbside. We extend classical bid-rent theory of urban land use into the novel context of the curbside, the interface between the transportation network and adjacent urban land uses.

The model is intended to allow curbside space to be optimally allocated in a transparent way, in contrast to the current practice of ad hoc heuristic decision-making about curbside regulation. In the bi-level model, a curb space manager and individual travelers both make mutually interdependent choices.

In a set of numerical analyses of a small-scale case study network, we demonstrate that the proposed model is tractable, flexible to simulating various types of curbside uses with different properties, and capable of exhibiting intuitive sensitivity to systematic variation in inputs.

We close by discussing a set of future research needs that would be helpful to extend this line of inquiry. First, it will be useful to allow other types of outcomes to enter into the objective functions used for optimization purposes, such as environmental considerations (e.g., externalities due to emissions) or social equity considerations. Completely different objective functions could also be employed, such as minimizing energy consumption or allowing determination of whether welfare-optimizing layouts are identical to or systematically different from energy-minimizing layouts. Second, it will be important to demonstrate the spatial scalability of the model (e.g., to larger-scale urban grids) and to extend the approach to allow the optimal curbside space allocations to vary temporally with travel/activity demand, as well as the ability to simulate behavioral response to charging fees for curbside PUDO activities. Third, incorporating microsimulation techniques would be useful to explicitly simulate operations within the various curbside uses in higher fidelity, as well as the interaction with traffic control at nearby intersections.

It is hoped that this proposed approach for making decisions about curbside space allocation will be useful to future researchers, road network managers, and policymakers.

References

Akers, M. 2021. “Downtown going digital to help manage traffic congestion.” *Las Vegas Review-Journal*, March 4, 2021. https://www.reviewjournal.com/local/traffic/downtown-going-digital-to-help-manage-traffic-congestion-2294328/.

AllVision. 2022. “AllVision.” Accessed Feb. 1, 2022. www.allvision.io.

Alonso, W. 1960. “A Model of the Urban Land Market: Location and Densities of Dwellings and Businesses.” Doctoral dissertation, University of Pennsylvania, Economics Department. https://www.proquest.com/openview/e2d436480b34868b85b7e78ac9c0e755/1?pq-origsite=gscholar&cbl=18750&diss=y

Alonso, W. 1964. “Location and Land Use. Toward a General Theory of Land Rent.” *Location and Land Use. Toward a General Theory of Land Rent*. https://www.hup.harvard.edu/catalog.php?isbn=9780674730854

Amer, A., and J.Y.J. Chow. 2017. “A downtown on-street parking model with urban truck delivery behavior.” *Transportation Research Part A: Policy and Practice* 102: 51–67. https://www.sciencedirect.com/science/article/abs/pii/S0965856415301154

Arnott, R. 2014. “On the optimal target curbside parking occupancy rate.” *Economics of Transportation* 3 (2): 133–144. https://www.sciencedirect.com/science/article/abs/pii/S2212012214000380

Arnott, R., E. Inci, and J. Rowse. 2015. “Downtown curbside parking capacity.” *Journal of Urban Economics* 86: 83–97. https://www.sciencedirect.com/science/article/abs/pii/S0094119014001089

Barth, B. 2019. “Curb Control.” *Planning*, June 2019. https://www.planning.org/planning/2019/jun/curbcontrol/.

Blackley, P. R. 1985. “The demand for industrial sites in a metropolitan area: theory, empirical evidence, and policy implications.” *Journal of Urban Economics* 17 (2): 247–261. https://www.sciencedirect.com/science/article/abs/pii/009411908590049X

Box, P.C. 2004. “Curb-Parking Problems: Overview.” *Journal of Transportation Engineering* 130 (1): 1–5. https://ascelibrary.org/doi/abs/10.1061/%28ASCE%290733-947X%282004%29130%3A1%281%29

Burgess, E.W. 1925. “The Growth of the City: An Introduction to a Research Project.” In *The City*. Edited by R.E. Park and E.W. Burgess. Chicago, IL: University of Chicago Press. http://urpa3301.weebly.com/uploads/4/0/9/2/4092174/burgess.pdf

Butrina, P., S. Le Vine, A. Henao, J. Sperling, and S. E. Young. 2020. “Municipal adaptation to changing curbside demands: Exploratory findings from semi-structured interviews with ten US cities.” *Transport Policy* 92: 1–7. https://www.sciencedirect.com/science/article/abs/pii/S0967070X19308923

Cao, J., M. Menendez, and R. Waraich. 2019. "Impacts of the urban parking system on cruising traffic and policy development: the case of Zurich downtown area, Switzerland." *Transportation* 46: 883–908. https://link.springer.com/article/10.1007/s11116-017-9832-9

Chai, H., C. Rodier, J. Song, M. Zhang, and M. Jaller. 2020. *The Impacts of Automated Vehicles on Center City Parking Demand*. Davis, CA: UC Davis, National Center for Sustainable Transportation. http://dx.doi.org/10.7922/G2X928J1.

Chang, J.S. 2007. "Multiclass Bid-Rent Network Equilibrium Model." *Transportation Research Record* 2003: 112–119. https://journals.sagepub.com/doi/abs/10.3141/2003-14?journalCode=trra

City of Fort Lauderdale. 2018. "City of Fort Lauderdale Launches Designated Rideshare Pickup and Drop-off Zones on E. Las Olas Boulevard." Press release, Jan. 8, 2018. https://www.fortlauderdale.gov/Home/Components/News/News/1790/16.

City of Toronto. 2019. *Automated Vehicles Tactical Plan, Chapter 7: Transportation System Efficiency*. Toronto, Canada: City of Toronto. https://www.toronto.ca/wp-content/uploads/2019/05/982d-TS_Transportation-System-Efficiency.pdf.

Coord. 2022. "Coord." Accessed Feb. 1, 2022. www.coord.com.

de Cerreño, A. L. 2004. "Dynamics of on-street parking in large central cities." *Transportation Research Record* 1898 (1): 130–137. https://journals.sagepub.com/doi/abs/10.3141/1898-16?journalCode=trra

Debrezion, G., E. Pels, and P. Rietveld. 2007. "The Effects of Railway Investments in a Polycentric City: A Comparison of Competitive and Segmented Land Markets." *Environment and Planning A: Economy and Space* 39 (9): 2048–2067. https://journals.sagepub.com/doi/abs/10.1068/a39180?journalCode=epna

Eluru, N., and C. Choudhury. 2019. "Impact of shared and autonomous vehicles on travel behavior." *Transportation* 46: 1971–1974. https://link.springer.com/article/10.1007/s11116-019-10063-1

Ersoy, F.Y., K. Hasker, and E. Inci. 2016. "Parking as a loss leader at shopping malls." *Transportation Research Part B: Methodological* 91: 98–112. https://www.sciencedirect.com/science/article/abs/pii/S0191261515300072

Fagnant, D., and K. Kockelman. 2018. "Dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas." *Transportation* 45: 143–158. https://link.springer.com/article/10.1007/s11116-016-9729-z

Floudas, C. A. 1995. *Nonlinear and mixed-integer optimization: fundamentals and applications*. Oxford, UK: Oxford University Press.

Fujita, M., and H. Ogawa. 1982. "Multiple equilibria and structural transition of non-monocentric urban configurations." *Regional Science and Urban Economics* 12 (2): 161–196. https://www.sciencedirect.com/science/article/abs/pii/016604628290031X

Gregg, K., and P. Hess. 2019. "Complete streets at the municipal level: A review of American Municipal Complete Street Policy." *International Journal of Sustainable Transportation* 13 (6): 407–418. https://www.tandfonline.com/doi/abs/10.1080/15568318.2018.1476995

Harris, C. D., and Ullman, E. L. 1945. "The nature of cities." *The annals of the American academy of political and social science* 242(1), 7-17. https://journals.sagepub.com/doi/abs/10.1177/000271624524200103?journalCode=anna

Henao, A., and W. E. Marshall. 2019. "The impact of ride hailing on parking (and vice versa)." *Journal of Transport and Land Use* 12 (1): 127–147. https://www.jstor.org/stable/26911261

Henao, A., J. Sperling, S. Young, V. Garikapati, and Y. Hou, Y. 2018. "Airport Analyses Informing New Mobility Shifts: Opportunities to Adapt Energy-Efficient Mobility Services and Infrastructure." Presented at the Intelligent Transportation Society of America 2018 Annual Meeting, Detroit, MI, 4–7 June 2018. https://www.nrel.gov/docs/fy18osti/71036.pdf.

Inci, E., and R. Lindsey. 2015. "Garage and curbside parking competition with search congestion." *Regional Science and Urban Economics* 54: 49–59. https://www.sciencedirect.com/science/article/abs/pii/S0166046215000629

Inrix. 2022. "Inrix Road Rules." Accessed Feb. 1, 2022. http://inrix.com/products/road-rules/.

Institute of Transportation Engineers. 2018. *Curbside Management Practitioners Guide*. Washington, D.C.: Institute of Transportation Engineers. https://www.ite.org/pub/?id=C75A6B8B-E210-5EB3-F4A6-A2FDDA8AE4AA.

International Transport Forum. 2018. *The Shared-Use City: Managing the Curb*. Paris, France: International Transport Forum. https://www.itf-oecd.org/sites/default/files/docs/shared-use-city-managing-curb_3.pdf.

Isard, W. 1956. *Location and Space Economy*. New York, NY: John Wiley and Sons. http://www.economia.unam.mx/cedrus/descargas/locationspaceeco00isar%20(1).pdf

Jaller, M., J. Holguin-Veras, and S. Darville Hodge. 2013. "Parking in the City: Challenges for Freight Traffic." *Transportation Research Record* 2379: 46–56. https://journals.sagepub.com/doi/abs/10.3141/2379-06?journalCode=trra

Klein, D. B., A. T. Moore, and B. Reja. 1997. "Curb rights: Eliciting competition and entrepreneurship in urban transit." *The Independent Review* 2 (1): 29–54. https://www.jstor.org/stable/24560837

Klein, N. J. 2015. "Get on the (curbside) bus: The new intercity bus." *Journal of Transport and Land Use* 8 (1): 155–169. https://www.jstor.org/stable/26202707

Lam, W. H., Tam, M. L., Yang, H., and Wong, S. C. 1999. "Balance of demand and supply of parking spaces. " In 14th International Symposium on Transportation and Traffic Theory, Transportation Research Institute. https://trid.trb.org/view/656780

Larson, R.C., and A.R. Odoni. 1981. *Urban Operations Research*. https://trid.trb.org/view/205030

Launhardt, W. 1885. *Mathematische Begrundung der Volkswirtschaftslehre*. Leipzig: B. G. Teubner.

Lee, J., D. Agdas, and D. Baker, D. 2017. "Cruising for parking: New empirical evidence and influential factors on cruising time." *Journal of Transport and Land Use* 10 (1): 931–943. https://www.jstor.org/stable/26211763

Lefebvre-Ropars, G., C. Morency, and P. Negron-Poblete. 2021. "A needs-gap analysis of street space allocation." *Journal of Transport and Land Use* 14 (1): 151–170. https://www.jstor.org/stable/48646181

Lerman, S. R., and C. R. Kern. 1983. "Hedonic theory, bid rents, and willingness-to-pay: some extensions of Ellickson's results." *Journal of Urban Economics* 13 (3): 358–363. https://www.sciencedirect.com/science/article/abs/pii/0094119083900396

Lu, R. 2019. "Pushed from the Curb: Optimizing Curb Space for use by Ride-Sourcing Vehicles." Presented at the 98th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2019. https://www.proquest.com/openview/20ff1b673cf4267cc1d4e8c4e66ee279/1?pq-origsite=gscholar&cbl=18750

Marcucci, E., V. Gatta, and L. Scaccia. 2015. "Urban freight, parking and pricing policies: An evaluation from a transport providers' perspective." *Transportation Research Part A: Policy and Practice* 74: 239–249. https://www.sciencedirect.com/science/article/abs/pii/S0965856415000282

Marshall, W. E., N. W. Garrick, and G. Hansen. 2008. "Reassessing on-street parking." *Transportation Research Record* 2046 (1): 45–52. https://journals.sagepub.com/doi/abs/10.3141/2046-06?journalCode=trra

Miklas-Kalczynska, M., and P. Kalczynski. 2020. "Self-organized carpools with meeting points." *International Journal of Sustainable Transportation* 15 (2): 140–151. https://www.tandfonline.com/doi/abs/10.1080/15568318.2019.1711468

Millard-Ball, A. 2019. "The autonomous vehicle parking problem." *Transport Policy* 75: 99–108. https://www.sciencedirect.com/science/article/abs/pii/S0967070X18305924

Millard-Ball, A., R. Weinberger, and R.C. Hampshire. 2014. "On the optimal target curbside parking occupancy rate." *Transportation Research Part A: Policy and Practice* 63: 76–92. https://www.sciencedirect.com/science/article/abs/pii/S2212012214000380

Nelson\Nygaard Consulting Associates. 2014. *Curbside Management Study*. Washington, D.C.: District Department of Transportation. https://dcgov.box.com/v/curbside-management-study-2014.

Ng, K. F., and H. K. Lo. 2015. "Optimal housing supply in a bid-rent equilibrium framework." *Transportation Research Part B: Methodological* 74: 62–78. https://www.sciencedirect.com/science/article/abs/pii/S0191261515000065

Perez, B., D. Lipscomb, B. Eskin, and E. Gwerengwe. 2020. "Curbside Reimagined: Repurposing the District's Curbside Dynamically in the Networked Mobility Age." In: 99th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 2020.

Pierce, G., and D. Shoup. 2013. "SFPark: Pricing Parking by Demand." *Access* 43: 20–28. https://escholarship.org/content/qt0j41t7rz/qt0j41t7rz.pdf

Ricardo D. 1817. *On the Principles of Political Economy and Taxation*. London, UK: John Murray, Albemarle-Street.

Seattle Department of Transportation. 2019. *Emerging Technology and Mobility Options Operating in City Right-of-Way: Response to Statement of Legislative Intent 35-3-A-1-2019*. Seattle, WA: Seattle Department of Transportation. http://seattle.legistar.com/View.ashx?M=F&ID=7279835&GUID=BAC05CD4-76C4-4309-A77A-D329B1AB7243.

SharedStreets. 2022. "Pilot project: Taxi and TNC activity." Accessed Feb. 1, 2022. https://sharedstreets.io/taxi-tnc-activity/.

Shoup, D. 2017. *The high cost of free parking, Updated edition*. New York, NY: Routledge. https://www.taylorfrancis.com/books/mono/10.4324/9781351179539/high-cost-free-parking-donald-shoup

Shoup, D. 2021. "Pricing curb parking." *Transportation Research Part A: Policy and Practice*. https://www.sciencedirect.com/science/article/pii/S0965856421001105

Smith, A., A. Wylie, A. Salzberg, E. Womeldorff, G. Rubendall, and I. Ballus-Armet. 2019. "A Data Driven Approach to Understanding and Planning for Curb Space Utility." Presented at the 98th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2019. https://trid.trb.org/view/1572510

Tirachini, A. 2019. "Ride-hailing, travel behaviour, and sustainable mobility: an international review." *Transportation*. https://link.springer.com/article/10.1007/s11116-019-10070-2

von Thunen, J. 1826. *Der isolierte Staat in Beziehung auf Landwirtschaft und Nationalekonomie*.

Vosooghi, R., J. Kamel, J. Puchinger, V. Leblond, and M. Jankovic. 2019. "Robo-Taxi service fleet sizing: assessing the impact of user trust and willingness-to-use." *Transportation* 46: 1997–2015. https://link.springer.com/article/10.1007/s11116-019-10013-x

Wadud, Z. 2020 "An examination of the effects of ride-hailing services on airport parking demand." *Journal of Air Transport Management* 84: 101783. https://www.sciencedirect.com/science/article/abs/pii/S0969699719302108

Xu, Z., Y. Yin, and L. Zha. 2017. "Optimal parking provision for ride-sourcing services." *Transportation Research Part B: Methodological* 105: 559–578. https://www.sciencedirect.com/science/article/abs/pii/S0191261517308962

Yang, C.H., and A. Regan. 2013. "A multi-criteria decision support methodology for implementing truck operation strategies." *Transportation* 40: 713–728. https://link.springer.com/article/10.1007/s11116-012-9432-7

Yang, F., W. Gu, M. J. Cassidy, X. Li, and T. Li. 2020. "Achieving higher taxi outflows from a drop-off lane: A simulation-based study." *Transportation Research Part C: Emerging Technologies* 115: 102623. https://www.sciencedirect.com/science/article/abs/pii/S0968090X19313865

Yousif, S., and P. Purnawan. 1999. "On-Street Parking: Effects on Traffic Congestion." *Traffic Engineering and Control*. https://www.researchgate.net/profile/Purnawan-Phd/publication/46212892_On-street_parking_Effects_on_traffic_congestion/links/56f17d7508aed354e56fbafe/On-street-parking-Effects-on-traffic-congestion.pdf

Zalewski, A., S. Buckley, and R. Weinberger. 2012. "Regulating Curb Space: Developing a Framework to Understand and Improve Curbside Management." Presented at the 2012 TRB Annual Meeting. http://libraryarchives.metro.net/DPGTL/studies/2011-regulating-curb-space.pdf

Zhang, Y., Q. Chen, A. Conway, and C. Tejada. 2020. "Before/After Freight Impact Analysis of the New York City Clear Curbs Initiative Phase 2: Area-wide Parking Violation Analysis." In: 99th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2020.