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Impact of On-Street Parking Characteristics on Urban Street Level of Service: A Comparison of Two-Way and One-Way Movement Systems

Using the Highway Capacity Manual 7th Edition

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A B S T R A C T

On-street parking reduces the capacity and speed of urban streets through lane occupancy, parking maneuvers, and side friction, but the size of the effect depends on how parking is configured and used and on whether the street operates two-way or one-way. This paper quantifies and compares these effects for a 1.0 km signalized urban street segment using the urban street segment methodology of the Highway Capacity Manual, 7th Edition (HCM 7). Four geometries are analyzed: two-way streets with two and three through lanes per direction, and the corresponding one-way streets with four and six lanes formed by merging both directions. For each geometry, six demand levels (volume sets A–F) are combined with six parking rates (0–100 %) under three modeling families: a no-parking base; a parking-only model in which parked vehicles occupy through lanes; and an all-assumptions model that adds pedestrian, bus, U-turn, and access-point friction and places parking either in a separate lane (Case 1) or in the existing travel lanes (Case 2). We independently recomputed and reproduced all 456 spreadsheet records. Lane occupancy dominates the results: parking rates of no more than 32.5 % were sufficient to push volume sets C–E beyond capacity (LOS F) in every geometry, whereas a separate parking lane changed LOS by at most one level within the model. The one-way configurations tolerated larger parking rates than their two-way counterparts (critical rate 31.1 % versus 20.0 % for set C with four versus two lanes) because their base volume-to-capacity ratio was about 6 % lower, but they incurred larger modeled friction delay on wide cross-sections. Parking-maneuver delay and field calibration are outside the model, so the findings are screening-level.

Keywords—on-street parking, level of service, Highway Capacity Manual, urban street segments, one-way streets, side friction, lane occupancy.

1. INTRODUCTION

Signalized urban street segments are the basic building blocks of arterial corridors. In the Highway Capacity Manual, 7th Edition (HCM 7), their quality of service is evaluated from the average travel speed of through vehicles relative to the base free-flow speed (BFFS), subject to a volume-to-capacity (*v/c*) check on the through

movement at the downstream boundary intersection [1], [2]. Many such streets also provide on-street parking. Parking narrows the effective carriageway width, and vehicles entering and leaving parking spaces disrupt the adjacent traffic stream and cause additional delay [3], [4].

Recent field and simulation studies consistently report that parking degrades street performance, although the magnitude depends on the parking regime and the method. Legal on-street parking reduced the capacity of a main highway in Debre Markos, Ethiopia, by 24.1 % and illegal double parking by a further 25.89 % [5], and very high side friction that included parking cut capacity by about 49 % and speed by about 47 % in Al-Najaf, Iraq [6]. A VISSIM model of Baghdad's central business district found that removing on-street parking raised network flow by 46.6 % and cut vehicle delay by 69 % [3], and a calibrated Leicester model found travel-time reductions of 27–30 % when parking was replaced by lanes or public space [7]. Reviews and field studies of stream speed and roadside friction continue to document the problem [8], [9].

Whether the street operates one-way or two-way further changes the picture; one-way streets were designed to move vehicles through simplified, efficient intersections, yet they can lengthen trips, and two-way networks without left turns can be the most efficient configuration in simulation [10], [11]. At the segment level, a simulation of stopped delivery vehicles that block a lane found lower delays on one-way than on two-way streets [12]. The debate over converting one-way streets continues in recent simulation and planning studies [13], [14]. Those studies address network configuration, however, rather than the interaction of parking with directionality at the segment level. No segment-level comparison of parking characteristics across two-way and one-way systems under the HCM 7 methodology was found.

This paper therefore applies the HCM 7 urban street segment methodology to (i) quantify the effect of parking rate on level of service (LOS) under three modeling assumptions, (ii) compare two-way streets with two and three through lanes per direction against one-way streets with four and six lanes, (iii) separate the effect of lane occupancy from that of mid-segment friction, and (iv) derive a screening measure, the *critical parking rate*, at which through demand first exceeds capacity. The remainder of the paper reviews the literature (Section 2), describes the methodology (Section 3), presents results for the 2-lane/4-lane pair (Section 4) and the 3-lane/6-lane pair (Section 5), and closes with conclusions and recommendations (Section 6).

2. LITERATURE REVIEW

This section reviews previous works in seven groups: the HCM treatment of parking, field studies, simulation and analytical studies, curb management and parking search, evidence from Iraq and Egypt, one-way versus two-way operation, and a synthesis that states the research gap. Table 1 summarizes the studies with the clearest quantitative or comparative findings.

2.1 Treatment of parking in the HCM

In the HCM 7 urban street segment procedure, the base free-flow speed includes an adjustment for on-street parking equal to −3.0 mi/h multiplied by the proportion of link length with parking on the right-hand side, and an access-point adjustment of $-0.078\ D_a/N_{th}$ mi/h, where D_a is the access-point density, and N_{th} is the number of through lanes [2]. Segment running time also contains a term, d_{other}, that the manual describes as available for mid-segment delay from parking maneuvers, pedestrian crosswalk activity, or bicycle activity not otherwise represented [2]. LOS is assigned from travel speed against thresholds tabulated by BFFS and is F whenever the downstream through-movement v/c exceeds 1.0 [2]. At the signalized intersection, parking enters through a maneuver-based saturation-flow adjustment factor (Eq. 19-11 of HCM 7) [2]. None of these mechanisms (free-flow speed friction, maneuver delay, saturation-flow reduction) represents a parked vehicle occupying a travel lane over a stretch of the street; in the present study, that condition is represented by reducing the effective number of through lanes.

Recent work has also examined how to apply the HCM 7 urban street method. One study used vehicle trajectory data as an alternative to the extensive volume and geometry collection that the method otherwise requires, and offered recommendations for further development of the HCM [15]. Such data could support field validation of HCM-based parking effects, which the present study does not attempt.

2.2 Field studies of parking and roadside friction

Parking and capacity. Field studies that isolate parking report large losses. In Al-Najaf, Iraq, on-street parking, pedestrian activity, entry–exit maneuvers, and temporary parking together cut speed by about 47% and capacity by about 49% at very high side-friction levels [6]. In Debre Markos, Ethiopia, legal parking reduced capacity by 24.1% and illegal double parking by a further 25.89%, and removing parking was estimated to raise capacity by 49.9% and cut travel time by 36% [5]. A field study of stream speed reported speeds of 39.28–51.47 km/h on sections without parking and reductions of 39.09–81.30% on sections with parking [9]. Other studies examine the consequences of on-street parking in Chittagong [16], the relation between parking and travel time [17], the effect of parking on traffic capacity [18], and the characteristics of on-street parking on a commercial street in Baghdad [19].

Roadside friction more broadly. A review of 90 studies linked capacity loss to reductions in effective carriageway width, reporting a 3.37% capacity loss for a 2.95% width reduction and 26.08% for 21.81% [8]. Field studies of undivided streets [20], of arterials in selected towns [21], and of roads with several concurrent roadside frictions [22] examine how side-friction parameters affect capacity and speed. Researchers have studied roadside impedance on urban streets in Baghdad [23] and street vendors on an urban arterial [24].

Specific friction sources. Curbside bus stops have been analyzed for capacity reduction factors [25] and for capacity drops on multilane divided roads [26]; non-motorized vehicles for their effect on speed and capacity [27]; and pedestrian crossings for warrants based on vehicular delay [28]. Traffic impact analysis of on-street parking near signalized intersections has also been reported [29]. Buses and pedestrians are among the friction sources included in the model used later in this paper, although its inputs are engineering-judgment values rather than values taken from these studies.

2.3 Simulation and analytical studies

Simulation studies agree on direction. A VISSIM model of Baghdad's central business district found that removing on-street parking raised network flow by 46.6%, cut travel time by 38%, and cut vehicle delay by 69% [3], and another VISSIM study examined how roadside parking maneuvers alter flow characteristics [4]. In a calibrated Leicester network model, replacing on-street parking with driving lanes, cycle lanes, or public space reduced travel time by 27–30 % and delay by 43–47 % relative to the other tested measures, whereas pick-up/drop-off bays were less effective because of added stop-and-go events [7].

Researchers have studied double parking and short stops that block a lane directly. A New York City study compared double parking by commercial and passenger vehicles [30]. A VISSIM study of delivery stops that block a lane found lower delays on one-way than on two-way streets because, in two-way operation, vehicles overtake in the oncoming lane; stops longer than 10 min degraded LOS and speeds, and the results agreed with field observations [12]. That study evaluated LOS using the HCM 7 speed-based measure, making it the closest antecedent to the present work. It varied stop duration, stop position, volume, speed limit, vehicle type, and directionality, but not the share of the curb lane occupied by parked vehicles.

Analytical work includes a theoretical estimate of the influence width and shy-away distance of parallel curb parking on undivided roads [31] and regression of travel time on parking activity [17].

2.4 Curb management, parking search, and automated-vehicle scenarios

Curb-management studies treat parking as one of several competing curb uses. A simulation study quantified how allocations among bus stops, paid parking, passenger pick-up/drop-off zones, and commercial loading zones change curb productivity, accessibility, and CO_2 emissions across traffic volumes, parking demand, dwell times, and design speeds [32]. Related work developed a curb space allocation tool [33], examined the causes and consequences of curb parking management [34], and reviewed competition among parking, ride-hailing, and freight users [35]. A London report on kerbside management calls for reclaiming the curb for other uses such as bike lanes and pedestrian zones, as summarized in [7], [36].

Parking search adds traffic that segment volumes do not capture. Recent work examines the nature of on-street parking search [37] and what drives drivers to start cruising [38], and reports that providing curb availability

information to delivery drivers reduces parking cruising [39]. Automated-vehicle scenarios further change the parking question: studies examine relocating shared automated vehicles under on-street parking constraints [40], the parking futures of European cities [41], and the effect of a multi-story parking facility on intersection performance in Baghdad [42]. Together, these studies frame parking as reallocatable space, which the lane-occupancy scenarios in this paper quantify as a trade-off.

2.5 Evidence from Iraq and Egypt

Iraq supplies several recent studies: on-street parking characteristics on a commercial street in Baghdad [19], a VISSIM analysis of parking in the Baghdad central business district [3], roadside impedance in Baghdad [23], side-friction effects in Al-Najaf [6], and the effect of a multi-story parking facility near Baghdad intersections [42]. For Greater Cairo, a study based on adult road-user opinions investigated the causes of congestion and possible resolution policies [43]. No study isolates on-street parking within the HCM 7 segment framework for Egyptian arterials, so evidence from Iraq and other comparable contexts is used here for orientation only.

2.6 One-way versus two-way operation

One-way streets were originally designed to accelerate vehicles through simplified, efficient intersections, yet in a network the shortest path between two points is often shorter when all streets are bidirectional [10]. Boeing and Riggs simulated conversion in San Francisco and reported that trips on the current network are about 1.7 % longer than on an all-two-way network [10]. A simulation study of three street configurations found that a two-way network without left turns was the most efficient with and without link disruptions [11]. Case-specific work includes a simulation of one-way circulation around the historic center of Košice [13] and a framework for one-way reconfiguration tested on the Sioux Falls and Isfahan networks [14]. At the segment level, the delivery-stop simulation described above found lower delays on one-way than on two-way streets when a lane was blocked [12].

2.7 Synthesis and research gap

Table 1. Key studies reviewed; findings as reported by the cited sources; years in parentheses.

Ref.	Approach and setting	Reported finding or focus
[6]	Field speed–flow data, Al-Najaf (2023)	About 47 % lower speed and 49 % lower capacity at very high side friction
[5]	Field data and model, Debre Markos (2024)	Legal parking −24.1 % capacity; double parking a further −25.89 %; removing parking +49.9 % capacity, −36 % travel time
[8]	Literature review, 90 studies (2023)	Capacity −3.37 % for −2.95 % effective width; −26.08 % for −21.81 %
[9]	Field stream speeds, ideal versus parking sections (2024)	Ideal-section speeds of 39.28–51.47 km/h; reductions of 39.09–81.30 % at parking sections
[19]	Field characteristics, Al-Rowad Street, Baghdad (2021)	Characteristics of on-street parking on a commercial street, surveyed over five evening hours
[3]	VISSIM, Baghdad CBD (2023)	Removing parking: flow +46.6 %, travel time −38 %, delay −69 %
[7]	Aimsun, Leicester network (2024)	Parking replaced by lanes or public space: travel time −27–30 %, delay −43–47 %
[12]	VISSIM, blocked lane by stopped vehicle, HCM 7 LOS (2025)	Lower delay on one-way than two-way streets; stops over 10 min degrade LOS and speed
[32]	Curb simulation (2023)	Curb-use allocations compared on productivity, accessibility, and CO_2
[15]	HCM 7 with vehicle trajectory data (2024)	Trajectory data used to implement and assess the HCM 7 urban street method

Ref.	Approach and setting	Reported finding or focus
[43]	Road-user opinion study, Greater Cairo (2023)	Causes of congestion and resolution policies
[11]	Network simulation under link disruptions (2023)	Two-way network without left turns is most efficient with and without disruptions.
[10]	Conversion simulation, San Francisco (2022)	Trips on the current network about 1.7 % longer than on an all-two-way network
[13]	OmniTRANS model, Košice inner circuit (2021)	Compares traffic intensities and capacities before and after one-way conversion
[14]	Optimization framework, Sioux Falls and Isfahan (2022)	Framework for selecting one-way reconfiguration, tested on two networks

Three observations follow. First, recent field and simulation studies agree that parking and roadside friction reduce capacity and speed, and that the reductions can be large where parking is unregulated, but the studies are site-specific and mostly report capacity or speed rather than HCM segment LOS. Second, curb-management and automated-vehicle studies treat parking as reallocatable space, but at the curb or network scale. Third, directionality studies compare network configurations or, in the delivery-stop case, a single stop; none varies the share of parking occupancy across lane counts and demand levels under a single methodology.

This study addresses the gap with a like-for-like, segment-level comparison, under the HCM 7 methodology, of how parking rate and parking configuration change LOS on two-way and one-way streets of comparable width.

3. RESEARCH METHODOLOGY

3.1 Study design

The study follows the flow chart in Fig. 1. Twelve spreadsheet workbooks, three for each of four geometries, implement the HCM 7 segment calculation for the base, parking-only, and all-assumptions families. This paper analyzes those results and independently verifies them; it introduces no coefficients beyond those in the workbooks.

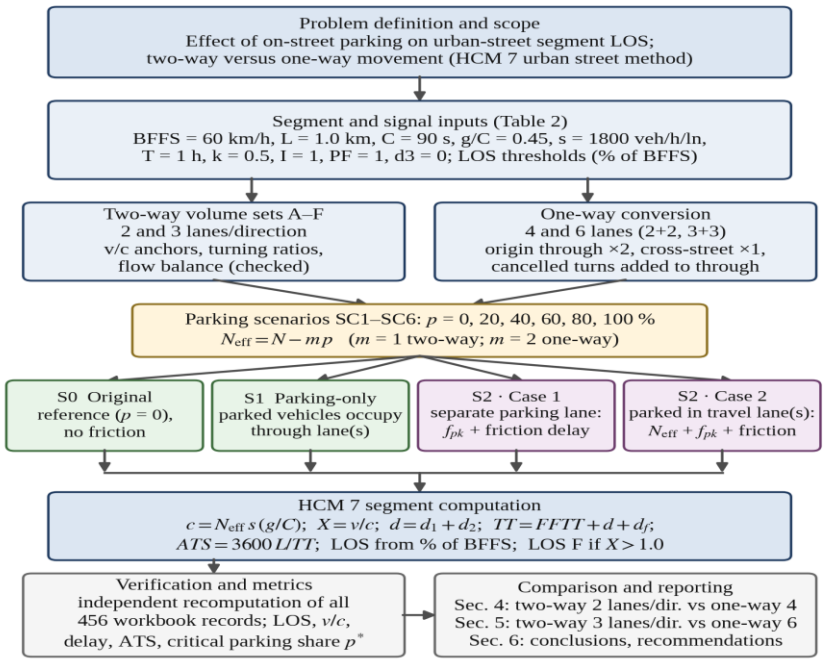


Figure 1. Study flow chart. S0 = original no-parking base; S1 = parking-only model; S2 = all-assumptions model (Cases 1 and 2); N_{eff} = effective through lanes; m = number of edge lanes exposed to parking.

3.2 Study segment, signal timing, and demand

The study segment is a 1.0 km stretch between two isolated pretimed signals with a common cycle and effective green ratio (Table 2). Volume sets A–F are defined for each two-way geometry by fixing the downstream through *v/c* at 0.15, 0.60, 0.90, 1.00, 1.035, and 1.08 (2 lanes) and at 0.15, 0.65, 0.95, 1.00, 1.04, and 1.08 (3 lanes), and by back-calculating origin volumes and turning movements so that flow is conserved between the two intersections. Each set is named for the LOS it produces in the no-parking two-way base model. Sets E and F carry *v/c* above 1.0 and are therefore LOS F under HCM 7; set E is LOS E by speed alone.

Table 2. Common inputs and friction assumptions.

Parameter	Value	Note
Segment length, L	1.0 km	Between two signalized intersections
Base free-flow speed, BFFS	60 km/h	Given
Cycle length, C; green ratio, g/C	90 s; 0.45	Assumed for the through phase
Saturation flow, s	1800 veh/h/ln	HCM ideal value
Analysis period T; factors k, I	1 h; 0.5; 1.0	Pretimed, isolated; PF = 1, $d_3 = 0$
Arterial turning ratios	L 20 %, R 15 %	Of arterial through volume
Minor-street volumes	T 40 %; L 20 %, R 15 %	T of arterial through; L, R of minor through
LOS thresholds (% of BFFS)	A >80; B >67; C >50; D >40; E >30	F if ≤30 or $v/c > 1.0$
U-turns (S2)	100 own + 100 opposing veh/h	Blockage 4 s per maneuver (assumed)
Pedestrians (S2)	100 ped/h, group size 1	Blockage = N_{th}·3.5 m/1.34 m/s + 2 s (assumed)
Buses (S2)	10 bus/h	Curb stop; 30 s blockage (assumed)
Access points (S2)	10 per side; 100 in + 100 out veh/h	Blockage 3 s per maneuver (assumed)

For the one-way geometries, the origin-through volume is doubled, cross-street volumes are unchanged, and the cross-street turns that would enter the opposing direction (north-approach right and south-approach left) are canceled and added to the cross-street through movement. Downstream through demand on the one-way street is therefore 1.877 times the two-way directional value (for example 456.2 versus 243.0 veh/h for set A on the four-lane street) while capacity doubles, so every one-way set has a *v/c* about 6.2 % lower than the corresponding two-way set. The sets are thus matched by scenario label rather than by identical *v/c*. Fig. 2 shows the four geometries.

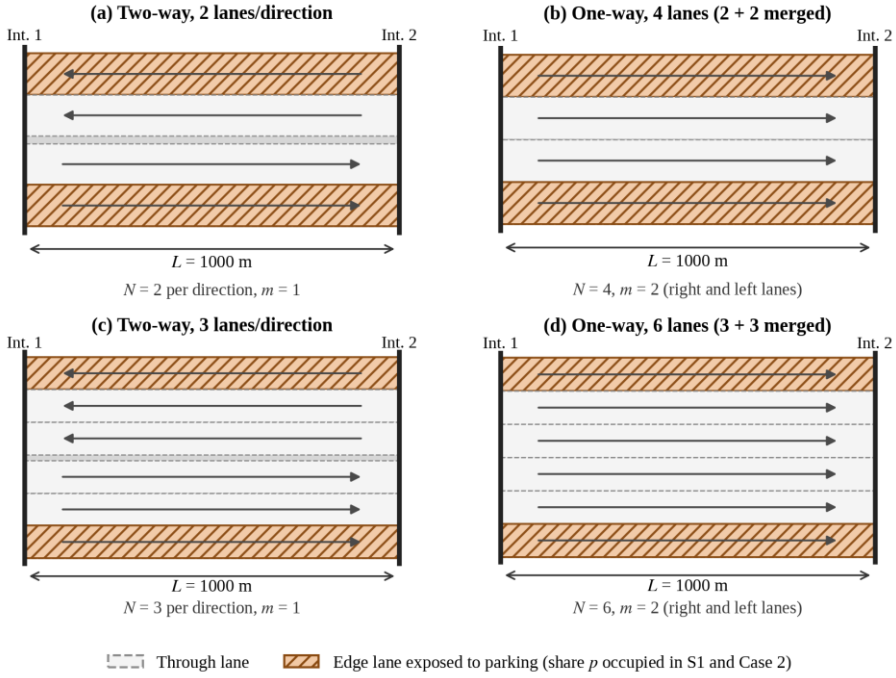


Figure 2. Studied geometries (plan view). Hatched edge lanes are exposed to parking; N is the number of through lanes (per direction for two-way streets) and m the number of edge lanes exposed to parking.

3.3 HCM 7 segment computation

Through-movement capacity and v/c at the downstream intersection are

$$c = N_{\text{eff}} \cdot s \cdot \frac{g}{C} \tag{1}$$

$$X = \frac{V}{c} \tag{2}$$

where N_{eff} is the number of available through lanes, and uniform and incremental signal delay follow the HCM signalized-intersection formulation [1], with PF = 1 and $d_3 = 0$:

$$d_1 = \frac{0.5\,C(1-g/C)^2}{1-\min(1,X)\,g/C} \tag{3}$$

$$d_2 = 900\,T\left[(X-1)+\sqrt{(X-1)^2+\frac{8\,k\,I\,X}{c\,T}}\right] \tag{4}$$

Segment travel time and average travel speed (ATS) are

$$\text{FFTT} = \frac{3600\,L}{S_f} \tag{5}$$

$$TT = \text{FFTT} + d_1 + d_2 + d_f \tag{6}$$

$$\text{ATS} = \frac{3600\,L}{TT} \tag{7}$$

where S_f is the free-flow speed (km/h), and d_f is the mid-segment friction delay (zero in S0 and S1). The start-up lost-time and proximity terms and the signal-spacing factor of HCM 7 Eqs. 18-4 to 18-7 are not applied, so running time reduces to 3600 L/S_f [2].

LOS is assigned from ATS as a percentage of BFFS and set to F whenever $X > 1.0$ [2]. HCM 7 tabulates absolute speed thresholds by BFFS; for a 40 mi/h BFFS these are 32, 27, 20, 16, and 12 mi/h, or 80, 67.5, 50, 40, and 30 % of BFFS [2]. The workbooks use the percentage form. Because 60 km/h (37.3 mi/h) lies between tabulated columns, LOS near a threshold should be treated as indicative.

3.4 Parking scenarios and friction

Parking rates p of 0, 20, 40, 60, 80, and 100 % define scenarios SC1–SC6. In the parking-only family (S1), parked vehicles occupy through lanes, so

$$N_{\text{eff}} = N - mp \tag{8}$$

with m = 1 for two-way streets (the right lane of each direction) and m = 2 for one-way streets (right and left lanes), and the free-flow speed stays at BFFS. Table 3 lists the resulting lane counts and capacities.

Table 3. Geometries, capacities, and effective through lanes N_{eff} by parking rate p (S1 and Case 2).

Geometry	***N***	***c* (veh/h)**	***m***	***N*eff at *p* (%)**						***f*A (km/h)**
				0	**20**	**40**	**60**	**80**	**100**	
Two-way, 2 lanes/direction	2	1620	1	2.0	1.8	1.6	1.4	1.2	1.0	−2.02
Two-way, 3 lanes/direction	3	2430	1	3.0	2.8	2.6	2.4	2.2	2.0	−1.35
One-way, 4 lanes	4	3240	2	4.0	3.6	3.2	2.8	2.4	2.0	−1.01
One-way, 6 lanes	6	4860	2	6.0	5.6	5.2	4.8	4.4	4.0	−0.67

In the all-assumptions family (S2), the free-flow speed is adjusted and a mid-segment friction delay is added:

$$S_f = \text{BFFS} + f_A + f_{pk}, \quad f_{pk} = -3.0p, \quad f_A = -0.078\frac{D_a}{N_{th}} \tag{9}$$

with f_{pk} and f_A converted to km/h (1 mi = 1.6093 km) and D_a computed from the 20 access points on the 1.0 km segment [2]. Parking therefore lowers S_f by up to 4.83 km/h at p = 100 %. Friction delay is the sum over the four sources in Table 2 of

$$d_i = \frac{k_i E_i \tau_i^2}{7200} \cdot \frac{1}{1 - q/S} \tag{10}$$

where E_i is events per hour, τ_i blockage time (s), k_i the share of directional flow in the blocked lane(s) (1 for pedestrians, who stop all lanes; 1/N for buses, U-turns, and access points), q the mid-segment directional flow, and S the saturation flow of the lanes available, with q/S capped at 0.95. This delay stands in for the d_{ap} and d_{other} terms of HCM 7 Eq. 18-7 [2]; the blockage times, group size, and lane shares are engineering-judgment inputs documented in the workbooks, not HCM defaults. Case 1 places parking in a separate lane: through lanes, capacity, and v/c are unchanged, and parking acts only through f_{pk}. Case 2 places parked vehicles in the existing lanes: N_{eff} from Eq. (8) sets capacity and v/c; f_A, the lane share, and the flow inflation use N_{eff}, and f_{pk} is also applied to the remaining lanes on one side only, since HCM defines it for right-side parking.

3.5 Verification and derived metric

All 456 records (4 geometries × [6 base + 36 S1 + 36 Case 1 + 36 Case 2]) were recomputed with Eqs. (1)–(10) in an independent script. Recomputed capacity, v/c, delay, travel time, ATS, and free-flow speed agreed with the

workbook values to within 10^{-15} relative difference; all LOS classes were reproduced, and the workbooks' summary sheets matched their calculation sheets. Setting $X' = 1$ in Eqs. (1), (2), and (8) gives the critical parking rate

$$p^* = \frac{N - V/(s\,g/C)}{m} = N_d(1 - X_0) \tag{11}$$

where V is the downstream through volume, $N_d = N/m$ is the number of lanes per direction of the corresponding two-way street, and X_0 is the no-parking v/c. A value of $p^* \geq 1$ means the demand is served even with the edge lanes fully occupied. Eq. (11) is derived from the workbook model and was checked against the LOS-F flags for all four geometries; it is a screening measure of capacity, not speed-based LOS. As a worked check, set C on the two-way 2-lane street has $V = 1458$ veh/h, so $X_0 = 0.900$ and $p^* = 2 \times (1 - 0.900) = 20.0$ %, matching the workbook (LOS D with $X' = 1.00$ at $p = 20$ %, LOS F from 40 %). The one-way 4-lane street has $V = 2737$ veh/h, $X_0 = 0.845$, and $p^* = 31.1$ %.

4. IMPACT OF PARKING CHARACTERISTICS ON TWO-WAY (2 LANES/DIRECTION) AND ONE-WAY (4 LANES) MOVEMENT SYSTEMS

4.1 Base conditions (no parking, no friction)

Table 4 gives the no-parking base results. Because the one-way street carries 1.877 times the directional through demand of the two-way street on twice as many lanes, its downstream v/c is 6.2% lower for every volume set (set D: 1.000 versus 0.939; set F: 1.080 versus 1.014). The effect on delay is small at low demand and large near capacity: control delay for set C falls from 32.4 s to 25.0 s, for set D from 69.5 s to 31.5 s, and for set E from 111.6 s to 38.9 s. HCM 7 LOS improves for set C (C to B, 1 level), set D (D to C, 1 level), and set E (F to C, 3 levels). Set F remains LOS F on both streets because the one-way v/c of 1.014 still exceeds 1.0. These gains follow from the modeled demand-capacity relationship and should not be read as a general advantage of one-way operation.

Table 4. Base results (S0) for 2-lane two-way and 4-lane one-way streets. LOS is the HCM 7 LOS; speed-based LOS is shown in parentheses where $v/c > 1.0$ forces F.

Set	Two-way, 2 lanes/direction					One-way, 4 lanes				
	V (veh/h)	v/c	d (s)	ATS (km/h)	LOS	V (veh/h)	v/c	d (s)	ATS (km/h)	LOS
A	243	0.150	14.8	48.1	A	456	0.141	14.6	48.2	A
B	972	0.600	20.3	44.8	B	1825	0.563	18.9	45.6	B
C	1458	0.900	32.4	39.0	C	2737	0.845	25.0	42.4	B
D	1620	1.000	69.5	27.8	D	3041	0.939	31.5	39.3	C
E	1677	1.035	111.6	21.0	**F (E)**	3147	0.971	38.9	36.4	C
F	1750	1.080	182.4	14.8	**F**	3284	1.014	71.2	27.4	**F (D)**

4.2 Parking-only model (S1): lane occupancy

Fig. 3 (upper panels) plots the downstream v/c against parking rate, and Table 5 lists the resulting LOS. With parked vehicles occupying through lanes, capacity falls to $(N - m\,p)\cdot s\cdot g/C$, so v/c rises hyperbolically with p. The critical parking rates from Eq. (11) for sets B, C, D, and E are 80.0 %, 20.0 %, 0.0 %, 0.0 % on the two-way street and 87.4 %, 31.1 %, 12.3 %, 5.7 % on the one-way street; a rate of 0 % means the set has no capacity margin (on the two-way street set D sits at $v/c = 1.000$ and set E already exceeds capacity). Set A never exceeds capacity: its

LOS drops from A to B at p = 40% on the two-way street and at 60% on the one-way street. The number of LOS F cells (of 36) is 22 on the two-way street and 21 on the one-way street.

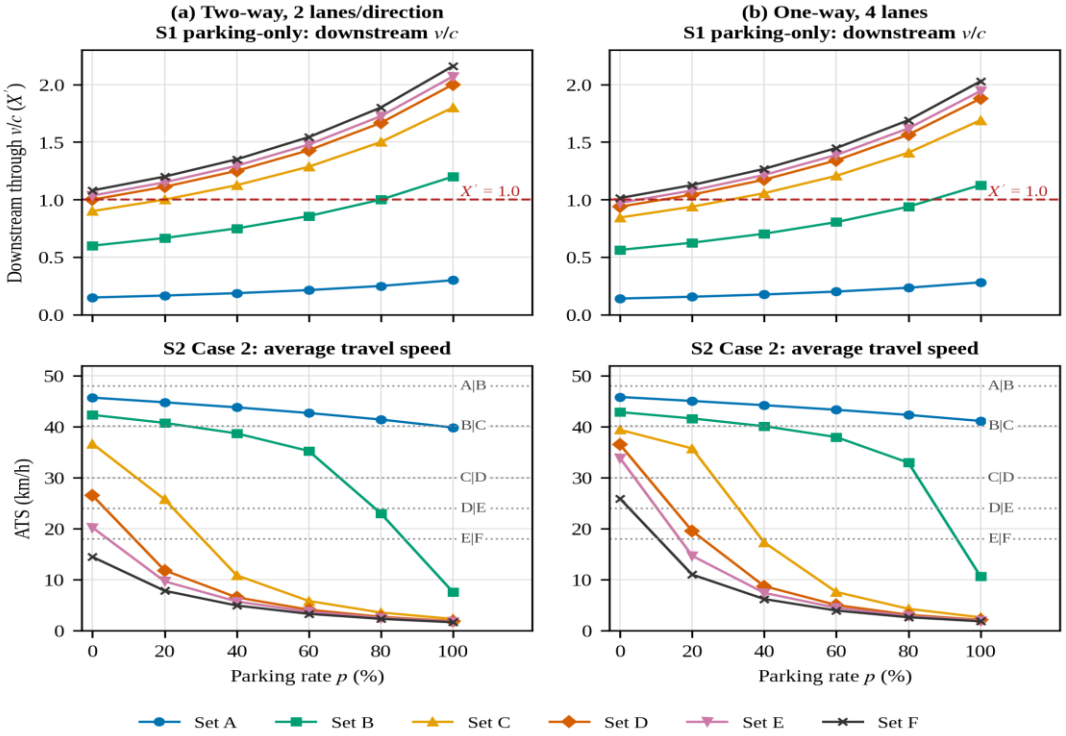


Figure 3. Two-way 2 lanes/direction versus one-way 4 lanes: (upper) downstream through v/c under S1 versus parking rate; (lower) ATS under S2 Case 2 versus parking rate, with the LOS thresholds (dotted). Values where $v/c > 1.0$ are theoretical (no initial-queue delay, $d_3 = 0$); LOS is F there regardless of speed.

Table 5. HCM 7 LOS under S1 (parked vehicles occupy through lanes) by parking rate (%).

Set	Two-way, 2 lanes/direction						One-way, 4 lanes					
	0	**20**	**40**	**60**	**80**	**100**	**0**	**20**	**40**	**60**	**80**	**100**
A	A	A	B	B	B	B	A	A	A	B	B	B
B	B	B	B	C	D	**F**	B	B	B	B	C	**F**
C	C	D	**F**	**F**	**F**	**F**	B	C	**F**	**F**	**F**	**F**
D	D	**F**	**F**	**F**	**F**	**F**	C	**F**	**F**	**F**	**F**	**F**
E	**F**	**F**	**F**	**F**	**F**	**F**	C	**F**	**F**	**F**	**F**	**F**
F	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**

4.3 All-assumptions model (S2): friction and parking configuration

Case 1 (separate parking lane). Friction alone (p = 0) lowers LOS relative to the base for set A (A to B) on the two-way street and for set A (A to B) and set C (B to C) on the one-way street (Table 6, first block). Across the full 0–100 % range, LOS changes by at most one level: set B (B to C at 100 %) on the two-way street and no set changes on the one-way street. Parking acts here only through f_{pk}, which reaches −4.83 km/h at p = 100 %. The resulting ATS decline over 0–100 % ranges from 3.06 km/h (set A) to 0.32 km/h (set F) on the two-way street and from 2.97 to 0.97 km/h on the one-way street.

Case 2 (parked vehicles in the travel lanes). When parked vehicles occupy the existing lanes (Table 6, second block), the LOS pattern follows S1 closely because lane loss dominates. Case 2 is never better than S1; it is worse in 5 of 36 cells on the two-way street (sets A, B) and in 6 of 36 on the one-way street (sets A, B, C), where friction lowers speed while *v/c* remains at or below 1.0. The number of LOS F cells is 22 and 21, respectively, compared with 12 and 6 under Case 1. Set B illustrates the difference between the two systems: LOS runs B, B, C, C, E, F for p = 0–100 % on the two-way street but B, B, C, C, C, F on the one-way street; ATS at p = 80 % is 23.0 versus 32.9 km/h, and at 100 % it is 7.5 versus 10.6 km/h (LOS F in both, since $X' > 1.0$).

Table 6. HCM 7 LOS under S2 by parking rate (%): Case 1 (separate parking lane) and Case 2 (parked vehicles in the existing lanes).

Set	Two-way, 2 lanes/direction						One-way, 4 lanes					
	0	**20**	**40**	**60**	**80**	**100**	**0**	**20**	**40**	**60**	**80**	**100**
Case 1: separate parking lane												
A	B	B	B	B	B	B	B	B	B	B	B	B
B	B	B	B	B	B	C	B	B	B	B	B	B
C	C	C	C	C	C	C	C	C	C	C	C	C
D	D	D	D	D	D	D	C	C	C	C	C	C
E	**F**	**F**	**F**	**F**	**F**	**F**	C	C	C	C	C	C
F	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**
Case 2: parked vehicles occupy through lane(s)												
A	B	B	B	B	B	C	B	B	B	B	B	B
B	B	B	C	C	E	**F**	B	B	C	C	C	**F**
C	C	D	**F**	**F**	**F**	**F**	C	C	**F**	**F**	**F**	**F**
D	D	**F**	**F**	**F**	**F**	**F**	C	**F**	**F**	**F**	**F**	**F**
E	**F**	**F**	**F**	**F**	**F**	**F**	C	**F**	**F**	**F**	**F**	**F**
F	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**

Table 7 separates the speed loss due to friction from that due to parking. Before adding parking, friction alone lowers the ATS of set A by 2.4 km/h on the two-way street and 2.4 km/h on the one-way street, and of set C by 2.3 and 3.0 km/h. At p = 100 %, the parked-lane condition (Case 2) is far more damaging than the separate lane (Case 1) wherever *v/c* passes 1.0.

Table 7. ATS (km/h) and LOS (in parentheses) for selected sets: base, friction only, and 100 % parking under Cases 1 and 2.

Set	Two-way, 2 lanes/direction				One-way, 4 lanes			
	S0 base	**Friction only (p = 0)**	**Case 1, p = 100 %**	**Case 2, p = 100 %**	**S0 base**	**Friction only (p = 0)**	**Case 1, p = 100 %**	**Case 2, p = 100 %**
A	48.1 (A)	45.7 (B)	42.7 (B)	39.8 (C)	48.2 (A)	45.8 (B)	42.9 (B)	41.1 (B)

Set	Two-way, 2 lanes/direction				One-way, 4 lanes			
	S0 base	Friction only (p = 0)	Case 1, p = 100 %	Case 2, p = 100 %	S0 base	Friction only (p = 0)	Case 1, p = 100 %	Case 2, p = 100 %
B	44.8 (B)	42.3 (B)	39.7 (C)	7.5 (F)	45.6 (B)	42.9 (B)	40.3 (B)	10.6 (F)
C	39.0 (C)	36.7 (C)	34.7 (C)	2.3 (F)	42.4 (B)	39.4 (C)	37.2 (C)	2.6 (F)
D	27.8 (D)	26.5 (D)	25.4 (D)	1.8 (F)	39.3 (C)	36.5 (C)	34.6 (C)	2.1 (F)

4.4 Comparison of the two movement systems

Two points stand out. First, the fraction of capacity lost to parking at a given p is identical in the two systems ($m\,p/N = p/2$), because the one-way street loses two of 4 lanes where the two-way street loses one of 2; the different outcomes come from the base v/c and, under S2, from friction. Second, friction is heavier on the one-way street: total friction delay for set A at $p = 0$ is 1.87 s on the two-way street versus 2.88 s on the one-way street, mainly from the pedestrian term (0.80 s versus 2.35 s), which grows with the crossing distance built into the friction model (Table 2). That growth is a property of the model, not an empirical finding.

5. IMPACT OF PARKING CHARACTERISTICS ON TWO-WAY (3 LANES/DIRECTION) AND ONE-WAY (6 LANES) MOVEMENT SYSTEMS

5.1 Base conditions (no parking, no friction)

Table 8 gives the no-parking base results. Because the one-way street carries 1.877 times the directional through demand of the two-way street on twice as many lanes, its downstream v/c is 6.2% lower for every volume set (set D: 1.000 versus 0.939; set F: 1.080 versus 1.014). The effect on delay is small at low demand and large near capacity: control delay for set C falls from 36.2 s to 25.7 s, for set D from 61.3 s to 29.0 s, and for set E from 112.5 s to 36.1 s. HCM 7 LOS improves for set C (C to B, 1 level), set D (D to B, 2 levels), and set E (F to C, 3 levels). Set F remains LOS F on both streets because the one-way v/c of 1.014 still exceeds 1.0. These gains follow from the modeled demand-capacity relationship and should not be read as a general advantage of one-way operation.

Table 8. Base results (S0) for 3-lane two-way and 6-lane one-way streets. LOS is the HCM 7 LOS; speed-based LOS is shown in parentheses where $v/c > 1.0$ forces F.

Set	Two-way, 3 lanes/direction					One-way, 6 lanes				
	V (veh/h)	v/c	d (s)	ATS (km/h)	LOS	V (veh/h)	v/c	d (s)	ATS (km/h)	LOS
A	365	0.150	14.7	48.2	A	684	0.141	14.6	48.3	A
B	1580	0.650	20.6	44.7	B	2965	0.610	19.3	45.4	B
C	2309	0.950	36.2	37.4	C	4334	0.892	25.7	42.0	B
D	2430	1.000	61.3	29.7	D	4562	0.939	29.0	40.5	B
E	2527	1.040	112.5	20.9	**F (E)**	4744	0.976	36.1	37.4	C
F	2624	1.080	178.1	15.1	**F**	4927	1.014	65.8	28.6	**F (D)**

5.2 Parking-only model (S1): lane occupancy

Fig. 4 (upper panels) plots the downstream *v/c* against parking rate, and Table 9 lists the resulting LOS. With parked vehicles occupying through lanes, capacity falls to $(N - m\,p)\cdot s\cdot g/C$, so *v/c* rises hyperbolically with *p*. The critical parking rates from Eq. (11) for sets B, C, D, and E are ≥100 %, 15.0 %, 0.0 %, 0.0 % on the two-way street and ≥100 %, 32.5 %, 18.4 %, 7.2 % on the one-way street; a rate of 0 % means the set has no capacity margin (on the two-way street set D sits at *v/c* = 1.000 and set E already exceeds capacity). Set A never exceeds capacity: its LOS drops from A to B at *p* = 60% on the two-way street and at 80% on the one-way street. The number of LOS F cells (of 36) is 22 on the two-way street and 20 on the one-way street.

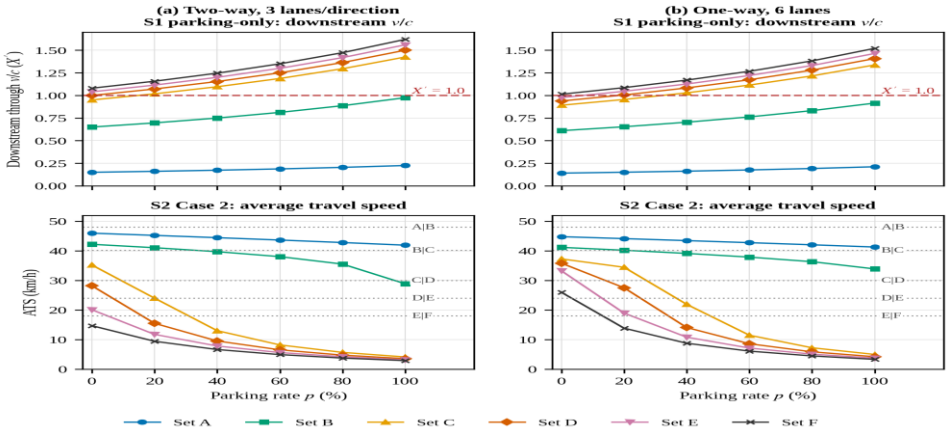


Figure 4. Two-way 3 lanes/direction versus one-way 6 lanes: (upper) downstream through *v/c* under S1 versus parking rate; (lower) ATS under S2 Case 2 versus parking rate, with the LOS thresholds (dotted). Values where *v/c* > 1.0 are theoretical (no initial-queue delay, $d_3 = 0$); LOS is F there regardless of speed.

Table 9. HCM 7 LOS under S1 (parked vehicles occupy through lanes) by parking rate (%).

Set	Two-way, 3 lanes/direction						One-way, 6 lanes					
	0	**20**	**40**	**60**	**80**	**100**	**0**	**20**	**40**	**60**	**80**	**100**
A	A	A	A	B	B	B	A	A	A	A	B	B
B	B	B	B	B	C	C	B	B	B	B	B	B
C	C	**F**	**F**	**F**	**F**	**F**	B	C	**F**	**F**	**F**	**F**
D	D	**F**	**F**	**F**	**F**	**F**	B	**F**	**F**	**F**	**F**	**F**
E	**F**	**F**	**F**	**F**	**F**	**F**	C	**F**	**F**	**F**	**F**	**F**
F	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**

5.3 All-assumptions model (S2): friction and parking configuration

Case 1 (separate parking lane). Friction alone (*p* = 0) lowers LOS relative to the base for set A (A to B) on the two-way street and for set A (A to B), set C (B to C) and set D (B to C) on the one-way street (Table 10, first block). Across the full 0–100 % range, LOS changes by at most one level: set B (B to C at 80 %) on the two-way street and set B (B to C at 60 %) on the one-way street. Parking acts here only through f_{pk}, which reaches −4.83 km/h at *p* = 100 %. The resulting ATS decline over 0–100 % ranges from 3.02 km/h (set A) to 0.32 km/h (set F) on the two-way street and from 2.81 to 0.97 km/h on the one-way street.

Case 2 (parked vehicles in the travel lanes). When parked vehicles occupy the existing lanes (Table 10, second block), the LOS pattern follows S1 closely because lane loss dominates. Case 2 is never better than S1; it is worse

in 6 of 36 cells on the two-way street (sets A, B) and in 10 of 36 on the one-way street (sets A, B, C, D), where friction lowers speed while *v/c* remains at or below 1.0. The number of LOS F cells is 22 and 20, respectively, compared with 12 and 6 under Case 1. Set B is the clearest contrast: it never exceeds capacity in either geometry (X' = 0.97 versus 0.92 at 100 %), but under Case 2 its LOS runs B, B, C, C, C, D on the three-lane street and B, B, C, C, C, C on the six-lane one-way street, with ATS at 100 % of 28.9 versus 33.9 km/h. Under S1, the six-lane one-way street holds LOS B at every parking rate, whereas the three-lane two-way street falls to LOS C at 80–100%.

Table 10. HCM 7 LOS under S2 by parking rate (%): Case 1 (separate parking lane) and Case 2 (parked vehicles in the existing lanes).

Set	Two-way, 3 lanes/direction						One-way, 6 lanes					
	0	**20**	**40**	**60**	**80**	**100**	**0**	**20**	**40**	**60**	**80**	**100**
Case 1: separate parking lane												
A	B	B	B	B	B	B	B	B	B	B	B	B
B	B	B	B	B	C	C	B	B	B	C	C	C
C	C	C	C	C	C	C	C	C	C	C	C	C
D	D	D	D	D	D	D	C	C	C	C	C	C
E	**F**	**F**	**F**	**F**	**F**	**F**	C	C	C	C	C	C
F	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**
Case 2: parked vehicles occupy through lane(s)												
A	B	B	B	B	B	B	B	B	B	B	B	B
B	B	B	C	C	C	D	B	B	C	C	C	C
C	C	**F**	**F**	**F**	**F**	**F**	C	C	**F**	**F**	**F**	**F**
D	D	**F**	**F**	**F**	**F**	**F**	C	**F**	**F**	**F**	**F**	**F**
E	**F**	**F**	**F**	**F**	**F**	**F**	C	**F**	**F**	**F**	**F**	**F**
F	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**	**F**

Table 11 separates the speed loss due to friction from that due to parking. Before adding parking, friction alone lowers the ATS of set A by 2.2 km/h on the two-way street and 3.5 km/h on the one-way street, and of set C by 2.2 and 4.7 km/h. At p = 100 %, the parked-lane condition (Case 2) is far more damaging than the separate lane (Case 1) wherever *v/c* passes 1.0.

Table 11. ATS (km/h) and LOS (in parentheses) for selected sets: base, friction only, and 100 % parking under Cases 1 and 2.

Set	Two-way, 3 lanes/direction				One-way, 6 lanes			
	S0 base	**Friction only (p = 0)**	**Case 1, p = 100 %**	**Case 2, p = 100 %**	**S0 base**	**Friction only (p = 0)**	**Case 1, p = 100 %**	**Case 2, p = 100 %**
A	48.2 (A)	46.0 (B)	43.0 (B)	41.9 (B)	48.3 (A)	44.8 (B)	42.0 (B)	41.3 (B)

Set	Two-way, 3 lanes/direction				One-way, 6 lanes			
	S0 base	Friction only (p = 0)	Case 1, p = 100 %	Case 2, p = 100 %	S0 base	Friction only (p = 0)	Case 1, p = 100 %	Case 2, p = 100 %
B	44.7 (B)	42.2 (B)	39.7 (C)	28.9 (D)	45.4 (B)	41.2 (B)	38.8 (C)	33.9 (C)
C	37.4 (C)	35.2 (C)	33.4 (C)	4.1 (F)	42.0 (B)	37.3 (C)	35.3 (C)	5.0 (F)
D	29.7 (D)	28.2 (D)	27.0 (D)	3.5 (F)	40.5 (B)	35.8 (C)	34.0 (C)	4.2 (F)

5.4 Comparison of the two movement systems

Two points stand out. First, the fraction of capacity lost to parking at a given p is identical in the two systems ($m\,p/N = p/3$), because the one-way street loses two of 6 lanes where the two-way street loses one of 3; the different outcomes come from the base v/c and, under S2, from friction. Second, friction is heavier on the one-way street: total friction delay for set A at $p = 0$ is 2.19 s on the two-way street versus 5.10 s on the one-way street, mainly from the pedestrian term (1.48 s versus 4.74 s), which grows with the crossing distance built into the friction model (Table 2). That growth is a model property, not an empirical finding.

5.5 Synthesis across the four geometries

Table 12 and Fig. 5 collect the cross-geometry measures. Equation (11) explains the critical-rate pattern: because N_d is the same for a two-way street and its one-way counterpart, the difference in p^* equals N_d times the difference in base v/c. For set C, the critical rate is 20.0% (two-way, 2 lanes) versus 31.1% (one-way, 4 lanes), and 15.0% versus 32.5% for the 3-lane/6-lane pair. Sets D and E have no margin on the two-way streets (0 %) and only 12.3–18.4 % (D) and 5.7–7.2 % (E) on the one-way streets. Under Case 1, the count of LOS F cells falls to 12, 6, 12, and 6 because friction, not capacity, is then the only parking effect; the one-way counts are lower mainly because their sets E are not over capacity at the base.

Consistency with field evidence. Eq. (1) implies a capacity loss of 50 % when the curb lane of a two-lane approach is fully occupied and 33 % on a three-lane approach. The 50% figure is of the same order as field results of about 49% capacity loss at very high side friction [6] and about 50% combined loss from legal parking (24.1%) and illegal double parking (25.89%) [5]. Consistent with the one-way results here, a simulation of stopped delivery vehicles found lower delay on one-way than on two-way streets [12], although its mechanism (a stopped vehicle in one lane, with overtaking in the adjacent lane) differs from the average lane loss modeled here. The field studies use different metrics, definitions, and roadways, so this is a plausibility check on magnitude and direction, not a calibration.

Table 12. Cross-geometry summary. TW2, TW3 = two-way with 2, 3 lanes per direction; OW4, OW6 = one-way with 4, 6 lanes. p^* from Eq. (11) (S1); LOS F counts are out of 36 cells; friction values are for set A at $p = 0$ (Case 2).

Measure	TW2	OW4	TW3	OW6
Through capacity, c (veh/h)	1620	3240	2430	4860
Base v/c, set C	0.900	0.845	0.950	0.892
p^*, set B (%)	80.0	87.4	≥100	≥100
p^*, set C (%)	20.0	31.1	15.0	32.5
p^*, set D (%)	0.0	12.3	0.0	18.4

Measure	TW2	OW4	TW3	OW6
p^*, set E (%)	0.0	5.7	0.0	7.2
LOS F cells, S1	22	21	22	20
LOS F cells, Case 1	12	6	12	6
LOS F cells, Case 2	22	21	22	20
Pedestrian blockage τ (s)	7.2	12.4	9.8	17.7
Friction delay, set A (s)	1.87	2.88	2.19	5.10
of which pedestrian (s)	0.80	2.35	1.48	4.74

Table 13 decomposes travel time for set B at p = 60 % under Case 2. Signal delay is the largest addition to the 60 s base free-flow time in all four geometries (22.2–31.4 s), friction delay adds 4.3–8.8 s, and the speed adjustments f_A and f_{pk} lengthen free-flow time to 64.0–66.4 s. Friction delay is smallest in absolute terms on the two-way streets and largest on the six-lane one-way street, in line with the pedestrian term discussed above.

Table 13. Travel-time components for set B at p = 60 % (Case 2). FFTT = adjusted free-flow time; d = signal control delay; d_f = friction delay; TT = travel time.

Geometry	X'	FFTT (s)	d (s)	d_f (s)	TT (s)	ATS (km/h), LOS
Two-way, 2 lanes/direction	0.857	66.4	31.4	4.4	102.2	35.2, C
One-way, 4 lanes	0.805	64.7	24.6	5.6	94.8	38.0, C
Two-way, 3 lanes/direction	0.813	65.0	25.4	4.3	94.6	38.0, C
One-way, 6 lanes	0.763	64.0	22.2	8.8	95.0	37.9, C

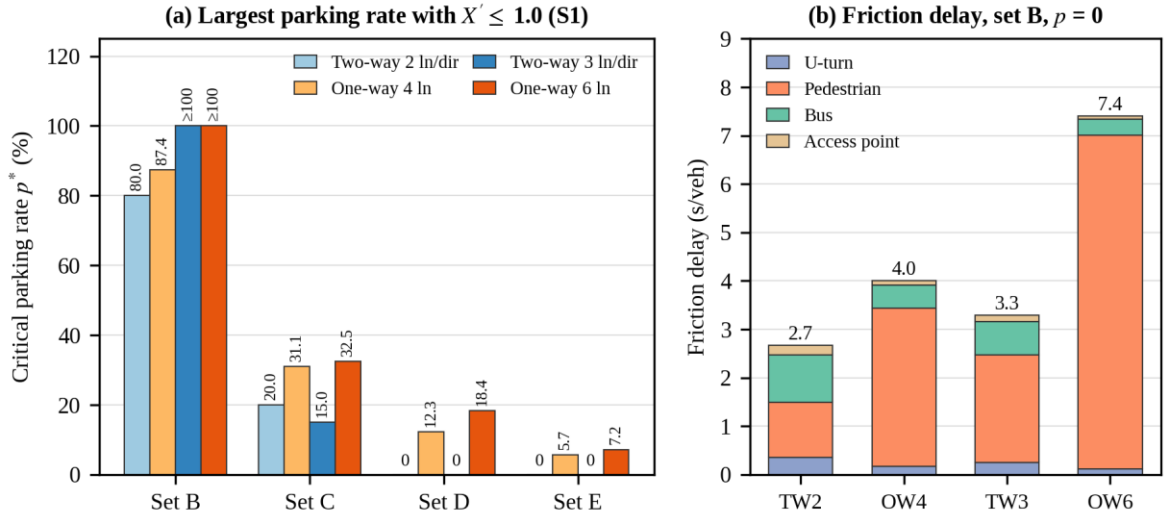


Figure 5. (a) Critical parking rate p^* (largest rate with $X' \leq 1.0$ under S1) by volume set; "≥100" means capacity is not exceeded even at 100 %. (b) Friction delay components for set B at p = 0 (Case 2). TW = two-way, OW = one-way.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Applying the HCM 7 urban street segment methodology to four geometries, six demand levels, and six parking rates supports the following conclusions, which hold within the modeling assumptions stated in Section 3.

(1) *Lane occupancy dominates.* When parked vehicles occupy through lanes, volumes in C–E lose their capacity margin (LOS F) at parking rates of 32.5% or less in every geometry (Table 12). Set A never exceeds capacity: its LOS falls from A to B under S1, and reaches C only on the 2-lane two-way street at 100 % parking under Case 2.

(2) *Parking outside the through lanes limits the modeled penalty.* Under Case 1, LOS changes by at most one level over 0–100% parking because parking acts only through the free-flow speed adjustment (−4.83 km/h at 100%). This excludes parking-maneuver delay and should not be read as parking having no impact.

(3) *One-way operation tolerated more parking in the model.* The one-way streets had critical rates of 31.1% and 32.5% for set C, compared with 20.0% and 15.0% for the two-way streets. This is because the base v/c is about 6% lower (demand is 1.877 times as high at twice the capacity); the fractional capacity lost at a given parking rate is the same in both systems.

(4) *Friction is heavier on wide one-way streets in the model.* Friction delay for set A at $p = 0$ is 1.87 s (2-lane two-way), 2.88 s (4-lane one-way), 2.19 s (3-lane two-way), and 5.10 s (6-lane one-way), chiefly through the pedestrian term, which scales with lanes crossed. This is a property of the friction model, not an observed result.

(5) *Friction alone can lower LOS.* Without any parking, the assumed pedestrian, bus, U-turn, and access-point friction lowers LOS by one level for 1 to 3 of the 6 volume sets in each geometry.

6.2 Recommendations

The following recommendations are drawn from the results and should be read as screening guidance pending field calibration.

R1. Screen parking in through lanes with Eq. (11). For $N_d = 2$ or 3, p^* is at most about one third whenever the no-parking *v/c* is at least 0.83 or 0.89, respectively. Test proposals that allow parking to occupy more than this share of a curb lane at peak for LOS F.

R2. Control parking in through lanes where v/c is high. Field and simulation studies report large gains when parking is removed or replaced [3], [5], [7], and parking prohibition, stronger enforcement, and use of dead-end roads for short-term parking have been proposed on that basis [5]. The results here are consistent with that direction.

R3. Prefer parking outside the through lanes, but verify maneuver effects. Case 1 suggests a bounded speed penalty from a separate parking lane. Before adopting such a layout, add maneuver delay through the HCM $_{other}$ term or the signalized-intersection parking factor [2].

R4. Pair one-way conversion with pedestrian crossing management. One-way conversion lowered *v/c* and raised the critical parking rate, but the friction model penalizes wide one-way cross-sections through pedestrian blockage. Treatments that consolidate crossing events (a larger group size in the model) merit evaluation.

R5. Report results with and without friction. Reporting LOS both ways separates parking effects from other mid-segment friction, and delay and speed values in LOS F cells should be treated as theoretical.

6.3 Limitations and future work

Several limitations bound these findings. (i) Parking-maneuver delay and the HCM maneuver-based parking factor are not modeled. (ii) The parking rate is used both as a lane-occupancy share, applied as an average lane loss at the signal approach, and as a length share for f_{pk}; if parking is banned near the stop line, Case 2 is pessimistic. (iii) f_{pk} is charged once on one-way streets even though both curbs are exposed, because HCM defines

it for right-side parking. (iv) Blockage times, pedestrian group size, and lane-share rules are engineering-judgment inputs, and the percentage-of-BFFS LOS thresholds approximate the tabulated HCM speeds. (v) Volume sets are matched by scenario label, not identical *v/c*, across geometries. (vi) Signal timing, progression, and intersection interactions are fixed. Future work should calibrate the friction inputs against field data (trajectory-based evaluation of the HCM 7 method [15] offers one route), add maneuver-based terms, vary signal timing and segment length, and validate the critical-rate screening against observed LOS.

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