SUVs and Parking Structures: *Is There a Weight Problem?*

How to design parking structures for today's vehicle sales trends

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In an article in the March 2002 issue of *Concrete International* (see "Sport Utility Vehicles and the Design of Parking Garages," p. 67), the author stated that wheel loads for all parking garage designs should be increased to 3000 lb (1400 kg). He also recommends that the uniform live load should be increased to 100 lb/ft^2 (500 kg/m^2) for slab spans up to 10 ft (3 m) and 70 lb/ft^2 (500 kg/m^2) for spans up to 20 ft (6 m). It was proposed further that live loads for spans over 20 ft (6 m) should not be reduced for the design of parking structure floors. Finally, he suggests that existing parking structures should be evaluated and may need to be retrofitted.

His analysis was focused on very short slab spans (2 to 6 ft [0.6 to 1.8 m]) and, in particular, on non-composite concrete slabs carried by steel bar joists—a system that is rarely used in parking structure design.

This point of view article is presented for reader interest by the editors. However, the opinions expressed are not necessarily those of the American Concrete Institute. Reader comment is invited. This article is also published in memory of Anthony P. Chrest, who died suddenly on April 23, 2002.

Moreover, the 3000-lb (1400 kg) loads from four rear wheels were applied to a single joist, without any distribution due to slab and bridging action. In our opinion, the analysis is too conservative. It essentially assumes that every vehicle in a parking structure will be a Ford F-350 pickup truck loaded to nearly its maximum payload; the maximum gross vehicle weight rating for the F-350 is 11,200 lb (5100 kg).

VEHICLE SALES TRENDS

Walker Parking Consultants has monitored the size of passenger vehicles annually since 1983. Our main purpose is to try to determine what vehicle trends are likely to affect parking dimension requirements over the next few years. Our analysis is of calendar-year sales as reported in the *Automotive News Annual Market Data Book*. The mixture of vehicles on the road will reflect the mixture in sales in 5 to 7 years. Figure 1 presents the trends in passenger vehicle sales by vehicle type since we began including light trucks, vans, and sport utility vehicles (LTVU) in the analysis. The classification of sport wagons is a recent one, and includes sport utility vehicles built on car chassis.

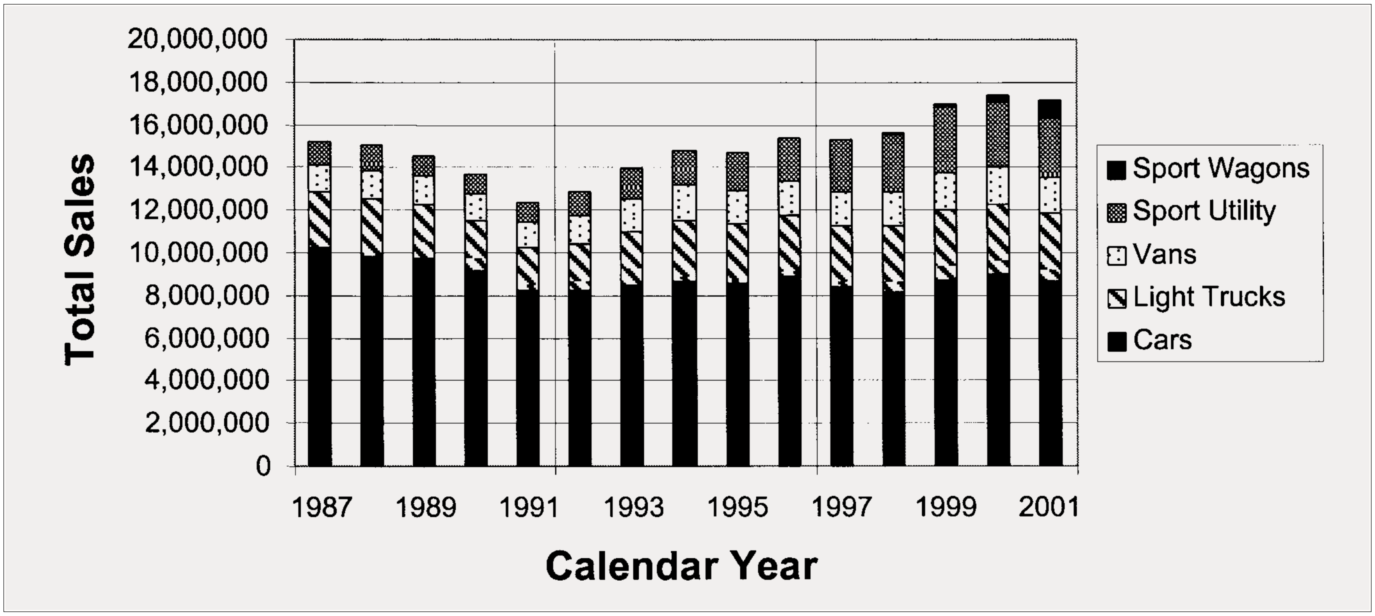

Fig. 1: Vehicle sales trends, by vehicle type, for 1987 through 2001

It was widely reported that LTVU sales comprised half the market in 2001, but the shift to LTVUs didn't happen overnight. The minivan, introduced in 1983 by Chrysler, rendered the old family station wagon (among the largest of all passenger vehicles) an endangered and nearly extinct species. As car prices increased through the 1980s, many families found smaller pickup trucks to be a useful second vehicle: economical for commuting by one spouse and handy for hauling. For their next purchase, a lot of those folks traded up to heavier-duty pickup trucks, and "compact pickups" pretty much disappeared from the market.

Then, in the mid-1990s, the sport utility vehicle (SUV) began to steal market share from many classifications, from sports cars to family sedans, as well as minivans. Both the typical SUV and the typical pickup truck became much larger through the 1990s, a trend that appears to be stabilizing. Those lured into Expeditions and Suburbans by their passenger-carrying capacity are now moving down to the newest segment: the sport wagon. Also called crossovers or hybrids, these are sport utility-type vehicles built on car chassis instead of truck chassis; thus, they tend to ride and handle like cars rather than trucks.

The emergence of the sport wagon (SW) is the most significant trend as of this writing. Sales of SWs doubled in 2001 from 2000, with more than 820,000 sold in 2001. According to JD Powers' count, the first SW was the 1996 Toyota RAV 4. Today there are 18 SW models, and by 2006, there could be 46.[1] It appears that SW sales are coming from large cars, minivans, and SUV sales. The good news is SWs are lighter than SUVs.

Sales of the largest LTVUs (Classes 10 and 11) comprised about the same market share in 2001 as in 2000. It appears that the trend to mammoth SUVs has reached a plateau, and therefore, neither parking dimensions nor design loads are expected to increase significantly beyond those required today. Conversely, the failure of an effort last spring by some members of Congress to improve the fuel efficiency of LTVUs also means that those vehicles will probably not get significantly smaller or lighter in the near future.

Moreover, while all car and LTVU sales have been tabulated, many of the heaviest-duty vans and pickup trucks are primarily used for commercial purposes, and are rarely parked in visitor and commuter parking facilities, particularly parking structures. In a study conducted in March 2002 in seven U.S. cities (Austin, TX; Boston, MA; Denver, CO; Hartford, CT; Indianapolis, IN;

TABLE 1:
COMPARISON OF VEHICLE TYPES PARKED VERSUS THOSE PURCHASED IN 1996 THROUGH 2001

Vehicle type	Parked vehicles	Average mixture	96-01 Sales
Cars	21,194	69%	53%
SUV/SW	5220	17%	18%
Pickups	2348	8%	19%
Vans	2106	7%	10%

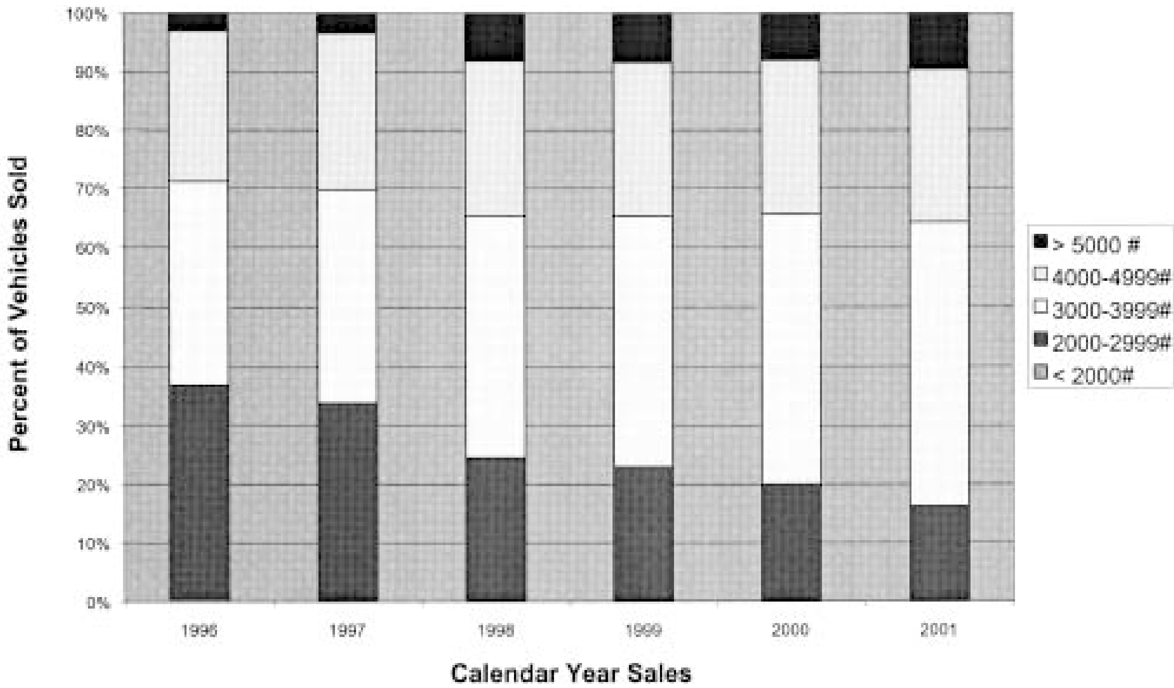

Fig. 2: Passenger vehicle weight distribution based on vehicle curb weight for 1996 through 2001

Kalamazoo, MI; and Los Angeles, CA), we compared the populations of parked vehicles in public parking facilities to the mixture of vehicles sold in the last 6 years (Table 1).

Some regional variations do occur: Denver had 33% SUVs; Austin had 22% pickups; and Kalamazoo had 10% vans. However, on average, it appears that about 1/3 of pickup sales and 1/2 of van sales could be discounted in a typical parking vehicle mixture.

VEHICLE WEIGHTS

Although the footprint of vehicles has been the primary focus of our analysis, weight and height have recently become of increasing concern in parking facility design. Therefore, we recently evaluated our database of vehicle sales from 1996 through 2001 for weight trends. Figure 2 shows the percent of vehicles sold each calendar year having a curb weight (parked and empty of passengers and cargo) in incremental categories. This figure does not discount any vans or pickups and thus, is likely to be conservative with regard to parking conditions.

It should be noted that *Automotive News* typically reports weights only for the base model. It further reports only curb weight for cars. For LTVUs, which include pickup trucks, vans, SUVs, and SWs, it reports the Gross Vehicle Weight Range (GVWR) and Payload Range, not curb weight. However, the manufacturers often don't supply the payload ranges for SUVs, SWs, and minivans. In such cases, *Automotive News* notes the weight as "not available." To enhance the analysis of vehicle weights, we have used multiple Internet sources, including the *Automotive News* website, the manufacturers' home pages, and vehicle comparison services such as carsdirect.com and autosite.com.

A further complication is that industry sources such as *Automotive News* don't report sales by submodels. For example, four-door sedan and wagon versions of the Taurus are reported in one line. This hasn't been a problem for cars because in nearly all cases, all versions fall into the same size classification. It is more of a problem when all Ford F-Series pickups (F-150, F-250, and F-350 models) are reported together. The curb weights of Ford F-series pickups range from 3900 to 6600 lb (1800 to 3000 kg); the GVWR varies from 6000 to 11,200 lb (2700 to 5100 kg).

Therefore, it is impossible to accurately determine the sales of vehicles by weight classifications, except in broad ranges. According to industry sources, the F-150 series vehicles comprise about half the annual sales with the remainder being F-250/F-350 heavier-duty vehicles. Using that apportionment, roughly 2/3 of the vehicles sold in the U.S. over the 6-year period studied weighed less than 4000 lb (1800 kg), and over 93% weighed less than 5000 lb (2300 kg). Note, however, that the trend is toward heavier vehicles. In 2001, 90.5% weighed less than 5000 lb (2300 kg).

The *CI* article, noted earlier, presented a list of the weights and sizes of a few of the larger LTVUs. We expanded the list (Fig. 3), particularly to provide more detail about variations (for example, we have added Ford

Class	Model	Maximum Curb Weight Pounds	Max GVWR Pounds	Front Axle GVWR Pounds	Track Inches	Rear Axle GVWR Pounds	Tread Inches	Tir Contact Area Sq In
9	Chevy Trailblazer	5123	7200	3600	63	4000	62	
11	Chevy Suburban 1500 4 x 4	5123	7200	3600	65	4000	66	
11	Chevy Suburban 2500 4 x 4	5760	8600	4180	65	6000	66	
11	Chevy Express 1500 passenger *	5015	7100	4410	68	6000	68	
11	Chevy Express 2500	5985	8600	4410	68	6084	68	
12	Chevy Express 3500 (extended)	6122	9500	4410	68	6084	68	
10	Chevy Silverado 1500	4073	6100	2950	65	3750	66	
11	Chevy Silverado 2500	4995	8600	4100	65	6000	66	
11	Chevy Silverado 3500	5935	11400	4670	69	8550	75	
8	Ford Explorer 4 x 4	4334	5835	2635	61	3000	61	49
10	Ford Expedition 4 x 2	4895	7000	3450	65	4128	66	52
11	Ford Expedition 4 x 4	5468	7200	3450	65	4128	66	56
11	Ford Excursion 4 x 2	6650	8900	3800	68	5240	68	53
11	Ford Excursion 4 x 4	7190	9200	3800	68	5240	68	56
10	Ford Windstar	4355	5555	NA	64	NA	63	45
10	Ford F 150	4995	6500	3400	65	3660	65	64
11	Ford F 250	6484	8800	4000	69	6084	68	51
12	Ford F 350 (extended)	6629	11200	3600	69	8250	68	53
11	Ford Econoline 250 Supercargo	4399	8600	3400	69	4265	67	49
11	Ford Econoline 350 Supercargo	5616	9400	3400	69	6195	67	
11	Ford Econoline 350 Extended Wagon	6212	9100	4600	69	6340	67	
10	Chrysler Town and Country	4107	5600	NA	63	NA	64	
9	Toyota Land Cruiser	5115	6860	NA	64	NA	64	
10	Lincoln Navigator	5723	7200	NA	65	NA	66	
10	Hummer	6814	10300	4100	72	6800	72	
	Average			3777		5390		

* Cargo version has same GVWR but less curb weight

NA = Not Available

Sources: *Automotive News*, carsdirect.com and autosite.com

Fig. 3: Weight and track width information for selected light trucks, vans, and sport utility vehicles

F-150 and F-250 pickups for comparison with the F-350). We have also provided GVWR by axle and track width (where published). The "class" shown in the far left column is a vehicle footprint classification system adopted by the Parking Consultants Council of the National Parking Association. Classes 5, 6, and 7 are considered small vehicles, and Classes 8 through 11 are considered large. We provide the classification here as an indicator of relative vehicle size.

The primary purpose of Fig. 3 is to double-check assumptions for maximum wheel load and the distribution of weight to the axles. The only vehicles that have a rear-axle GVWR substantially greater than 6000 lb (2700 kg) are the Ford and Dodge 350 Series, and Chevy 3500 series pickups. Even extended vans' rear-axle GVWRs result in a maximum wheel load of 3000 lb (1400 kg).

The author of the previous *CI* article assumes a GVWR distribution of 40% on the front axle and 60% on the rear. Although we are not sure of the derivation of that assumption, taking a straight average (that is, not weighted by sales), the front axles of the above vehicles carry 41% and the rear 59%. Thus, the 40/60 assumption is reasonable. However, it is still more accurate to use the GVWR by axle where it is available. Pickups tend to have a higher GVWR for the rear axle than would be indicated by a 40/60 split of the total GVWR, but SUVs may have load distributed more evenly to front and rear axles. Moreover, this list remains quite limited. Figure 4 summarizes the curb weight, payload, and GVWR for virtually all LTVUs.

DESIGN WHEEL LOADS

The prior *CI* article also noted that the 1997 Uniform Building Code (UBC) requires that the concentrated

Class	Pickups	Curb weight	Payload	Gr Veh Wt
7	Toyota Tacoma, Nissan Frontier (pre 2000)	3300	1400-1800	4700-5100
8 and 9	Chevy S, Ford Ranger, Dodge Dakota, Isuzu GMC Sonoma, Mazda, Nissan Frontier, Toyota PreRunner	3000-4500	1000-2200	4200-6000
10	Chevy C/K Silverado 1500,GMC Sierra 1500, Ford F150, Ram 1500	4000-5000	1400-3000	6000-7700
11	Blackwood, Avalanche, Escalade (luxury pickups)	5500-6000	1250-2250	7000-8600
11 and 12	Chevy C/K Silverado 2500/3500, GMC Sierra 2500/3500,Ford F250/350, Ram 2500/3500	5000-6600	2000-5500	6000-11400
	SUVs			
5 and 6	Tracker, Sidekick, Viatra, X90, Wrangler,	2800-3500	700-1000	3500-4500
7	Cherokee, Sportage, Grand Viatra, 97 Passport, 97 Jimmy, Montero, 97 Bravada, 4Runner, 97 Rodeo, Amigo	3000-4200	900-1500	3900-5000
8	Blazer, Bravada, Jimmy, Passport, Rodeo Liberty, Grand Cherokee, Xterra, Axiom, SLX, QX4 Trooper, Durango, 97 Envoy, Explorer, Mountaineer	3800-5000	900-1600	4900-6400
9	Trailblazer, 02 Bravada, 02 Envoy, LX 470 Sedona, Land Cruiser	4500-5400	1100-1800	5800-7000
10	Tahoe, Escalade, Expedition, Navigator	5000-6800	1400-3200	6800-8600
11	Suburban, Excursion	5000-7200	1950-3200	8600-9200
10	Hummer	6800	3500	10300
	Spt Wag			
7	RAV4, Escape	2700-2900	1000-1200	3800-4000
8 and 9	Tribute, Santa Fe, RX300,CR-V, Vue, Mercedes (all) Highlander, Aztec, Rendezvous, BMW, MDX	3300-4300	1000-1500	4300-5900
	Vans			
8	MPV, Oasis, Previa, Transport, Aerostar	3700-4400	1600-2000	5400-5900
9 and 10	Quest, Villager, Sienna, Venture, Montana, Silhouette, Astro, Safari, Odyssey, Town and Country, Voyager, Sequoia, Windstar	3700-4400	1600-2000	5400-6100
11 and 12	Full size Ram, Econoline, Express vans	3800-6100	2500-4400	6400-9500

Sources: *Automotive News*, carsdirect.com and autosite.com

Fig. 4: Gross vehicle weights and curb weights for selected light trucks, vans, and sport utility vehicles

design wheel load be 40% of the gross weight of the maximum size vehicle to be accommodated where “vehicles are used or stored.” It was stated that this provision considers, among other things, centrifugal forces for shifting loads as vehicles turn corners. The requirement for 40% distribution of gross weight to one wheel has actually been present in the UBC code since at least the mid-1980s, but it has always been clearly superseded by the specific requirement for a 2000-lb (900 kg) wheel load for parking of “private or pleasure type motor vehicles” in “parking structures,” as specifically defined in the UBC code. Certainly, SUVs and minivans are private, pleasure-type vehicles.

Forty percent of the maximum gross weight of the largest cars in the mid-1980s would have resulted in a wheel load over 2000 lb (900 kg). In 1981, before larger vehicles were downsized, the maximum curb weight among passenger cars in the U.S. was about 5000 lb (2300 kg) for a Rolls Royce; the curb weight of the Cadillac Fleetwood sedan was 4300 lb (1900 kg). Without even considering trunk capacity, 40% of the gross weight for the Fleetwood (including six adults) would have been approximately 2100 lb (1000 kg), more than was then required by code for design of parking facilities. When another 1000 lb (450 kg) was present in the trunk, the GVWR was 6300 lb (2900 kg) and the 40% wheel load would be 2500 lb (1100 kg). The family station wagon of that era could have carried much more weight in the cargo space. Therefore, it would appear that a 2000 lb (900 kg) wheel load for private, pleasure-type motor vehicles, even if presumed to be only for cars, never was based on the criterion that a single wheel load is 40% of the maximum GVWR of the heaviest vehicle expected in the facility.

				Weight (pounds)	Wheel Loads (pounds) Front (40%)	Rear (60%)
Design Vehicle:	Ford Expedition 4 x2					
Curb weight:				4891		
Passengers (max):		6 adults @	175	1050		
Cargo:				1059		
Total Weight when driving (= gross vehicle weight rating)				7000	1400	2100
Total Weight when parked				5950	1190	1785
Wheel base:	10 ft					
Track	5'-6"					

Parking Geometrics: 8'-6" stalls @ 90 degrees on 60 ft modules

Assume Expeditions at 7000 lb at 24′ headway are driving both ways down the aisle

Assume Expeditions at 5950 lb are parked in every stall.

Fig. 5: Weight distribution and total weight for the design vehicle, a Ford Expedition

The 2000 International Building Code (IBC) appears to follow the ANSI/ASCE Standard 7-98, *Minimum Design Loads for Buildings and Other Structures*; both simply require a wheel load of 2000 lb (900 kg) for "passenger cars accommodating not more than nine passengers." This definition technically would exclude the extended version of the largest vans, which can accommodate 11 passengers. Neither IBC nor ASCE has a similar requirement to the UBC's 40% GVWR distributed to one wheel, although we presume that the committees were aware of the UBC requirement. Therefore, we submit that a 40% distribution of GVWR to one wheel is simply not intended for application to vehicles in parking structures as defined by code. Indeed, the appropriate speeds are such that centrifugal forces and significant shifts of payload should not be a concern in parking structures.

When determining an appropriate wheel load, it would seem rather unlikely that a full size F-350 pickup, loaded to the highest GVWR, would be driven into any parking structure. On those rare occasions, the rear wheel load for such a vehicle, using the 40/60 split of load to the front and rear axles, would be 3400 lb (1600 kg.) Using the maximum GVWR for the F-350 rear axle, 4100 lb (1900 kg) could occur as a rear wheel load. Full-size extended vans can carry up to 9500 lb (4300 kg) but would have a rear wheel load of 3000 lb (1400 kg) using the rear-axle GVWR.

The SUV with the highest GVWR is the Hummer at 10,300 lb (4700 kg.) The wheel load based on the rear-axle GVWR would be 3400 lb (1500 kg). In recent years, only about 750 Hummers have been sold per year. The next heaviest SUV is the Ford Excursion, which can handle 9200 lb (4200 kg) with a 2600-lb (1200 kg) wheel load using the GVWR of the rear axle.

Given that the 2000-lb (900 kg) load requirement has never reflected 40% of the maximum GVWR for all cars sold in the U.S., but the SUVs of today definitely can be heavier than they were at the time the 2000-lb (900 kg) wheel load was established, we can't disagree with the proposal made in the previous *CI* article that any one wheel load could be 3000 lb (1400 kg). What does concern us is the assumption that multiple vehicles parked in an area all have those wheel loads. This is essentially a 99th percentile or higher design standard—far above any practical loading. Also, while the track width of cars is typically around 5 ft (1.5 m), the track width of heavier SUVs, minivans, and pickups is typically at least 5.5 ft (1.7 m). If the wheel load is increased, the assumed track width should also be increased.

The other factor related to wheel load is the area over which it is applied. All of the national building codes currently employ a 2000 lb (900 kg) wheel load applied over 20 in^2 (130 cm^2). In a check of parked vehicles on a Ford dealer's lot, which means the vehicles were not loaded beyond curb weight, we found tire footprints (contact area between tire and pavement) ranging from 35 to 45 in.^{2} (230 to 290 cm^2) for cars, and from 45 to 65 in^2 (290 to 420 cm^2) for LTVUs (Fig. 4). With heavier loads and/or inadequate inflation, the footprint only gets larger. Therefore, the use of a 20 in.^{2} (130 cm^2) footprint area is extremely conservative; if wheel loads are to be increased to 3000 lb (1400 kg), it would make sense to increase the application area to at least 30 in.^{2} (190 cm^2).

DESIGN UNIFORM LOADS

For the determination of uniform loads, we propose that the 85th-percentile vehicle in the range from lightest to heaviest curb weight be used as the design vehicle (DV). The 85th-percentile standard has become widely accepted for parking geometrics (the dimensions of stalls and aisles) and parallels that used throughout transportation engineering. The DV used for geometrics is based on footprint; for 2001 sales, it was a Ford F-150 truck. The design vehicle by curb weight for 2001 sales is the Ford Expedition. The data used to determine the design vehicles do not discount any pickup or van sales, so it is conservative with respect to the mixture of parked vehicles.

With this approach, we assume that all parking spaces in a structural bay (defined as the floor area contributing to the load carried by four columns) are occupied by DVs, and that a string of DVs is driving each way down the aisle. The likelihood that one 85th-percentile vehicle (or larger) will be present in a structural bay is 150/1000. The likelihood that two will be present is 22.5/1000; the likelihood of three is 3.4/1000. Beyond that, the likelihood drops to less than 1/1000. Using a typical 24 x 60 ft (7 x 18 m) bay, the likelihood that three DVs (or larger) will be parked in the aisle on one side, three more on the other, while one DV is driving by in each direction is 0.26/1,000,000. The likelihood that 10 vehicles in an area are all DVs or larger is 0.6/100,000,000. The odds that more than one—much less all—of these vehicles are loaded to the full GVWR are astronomically low.

In sum, assuming that a parking area is entirely occupied by Ford Expeditions, all carrying heavy loads of cargo and passengers, is extremely conservative. Using the base model, the curb weight is 4900 lb (2200 kg) and the GVWR is 7000 lb (3200 kg). Figure 5 provides information on this vehicle.

We then considered how the loadings would be distributed for the framing systems commonly employed in parking structures in the U.S. today:

- Precast double tees and beams;
- Post-tensioned, cast-in-place concrete with one-way slabs and beams;

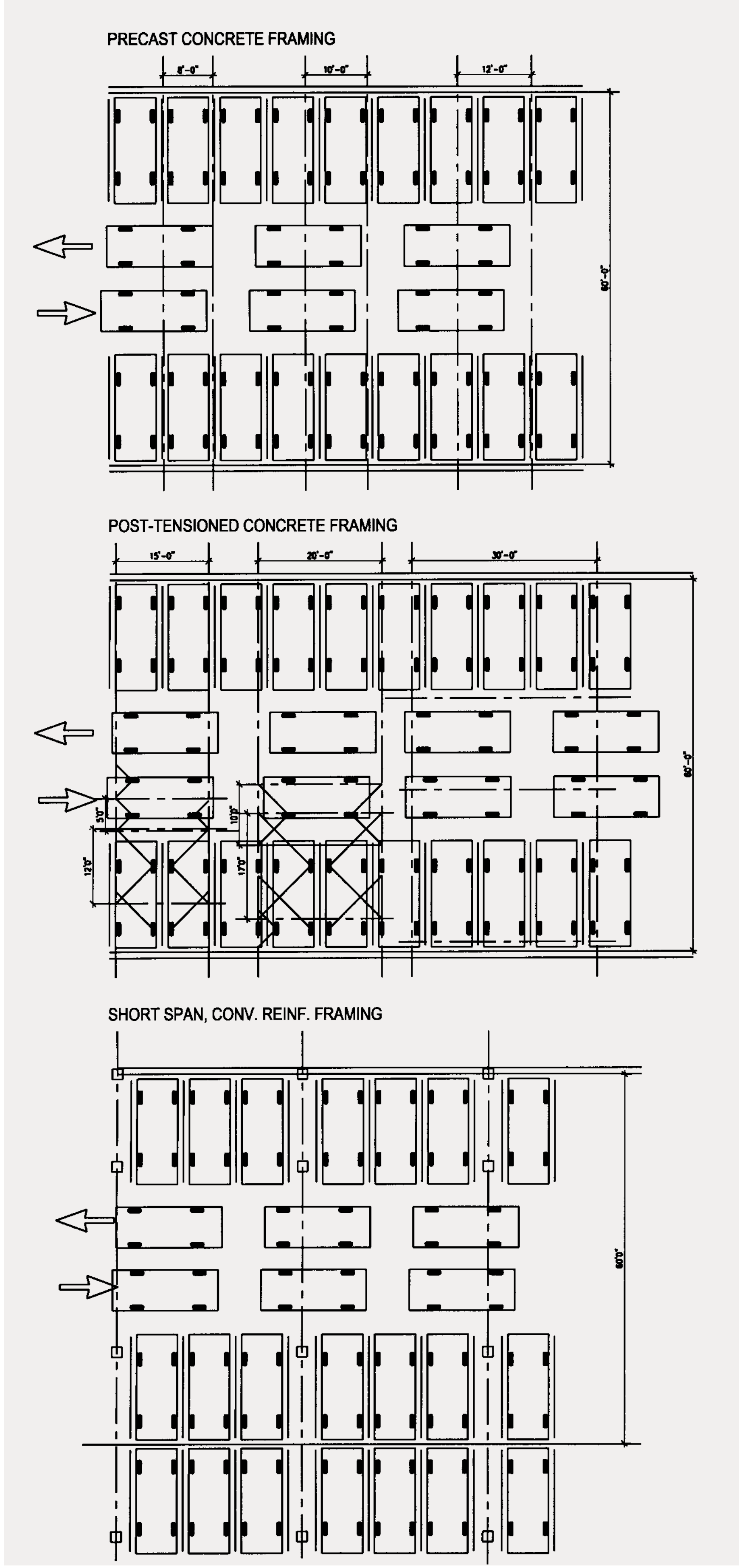

Fig. 6: Typical parking layout (per structural systems used) for parking garages in the U.S.

Element	L (ft)	W (ft)	Parked veh tires		Parking	Driving veh tires		Aisle	Total	Equiv
Precast Structures			Front	Rear	Live Load	Front	Rear	Live Load	Live Load	PSF
8 ft tee	60	8	4	4	11900	0	4	8400	20300	42.3
24 ft beam	24	60	12	12	35700	6	6	21000	56700	39.4
32 ft beam	32	60	16	16	47600	6	6	21000	68600	35.7
10 ft tee	60	10	6	6	17850	0	4	8400	26250	43.8
30 ft beam	30	60	16	16	47600	6	6	21000	68600	38.1
40 ft beam	40	60	18	18	53550	8	8	28000	81550	34.0
12 ft tees	60	12	6	6	17850	4	4	14000	31850	44.2
36 ft beam	36	60	18	18	53550	8	8	28000	81550	37.8
48 ft beam	48	60	22	22	65450	12	12	42000	107450	37.3
8 ft tee with valet parking	60	8	4	6	15470	0	4	8400	23870	49.7
10 ft tee with valet parking	60	10	8	8	23800	4	4	14000	32200	53.7
12 ft tee with stacked parking	60	12	8	8	23800	4	4	14000	37800	52.5
Steel Framed, Precast Tee floor: Same as Precast Structure										
Post-tensioned Structures										
15' slab span, parking	15	12	0.33	4	7537				7537	41.9
15' slab span, aisle	15	5			149	1	1	3500	3500	46.7
15' slab span, beam & column	15	60	8	8	23800	4	4	14000	37800	42.0
20' slab span, parking	20	17	1.21	5	10360	0.5	0.5	1750	12110	35.6
30' slab span, beam & column	30	60	16	16	47600	6	6	21000	68600	38.1
15′ slab with valet parking, parking area	15	12	0.83	4.5	9024				9024	50.1
15′ slab with valet parking, aisle	15	5	0.5	0.5	1488	1	1	3500	4988	66.5
15′ slab with rental car storage	15	9.75	2.29	2.29	5590				5590	38.2
20′ slab with rental car storage	20	18	3.7	10	16753				16753	46.5
Steel Framed, P/T floor: Same as Post-tensioned Structure										
Short Span, conventionally reinforced structure (3 stalls between columns)										
30 x 30 aisle	30	30			0	4	8	22400	22400	24.9
30 x 15 parking	30	15	6	6	17850			0	17850	39.7
30 x 30 parking	30	30	12	12	35700			0	35700	39.7
30 x 30 column	30	30	6	6	17850	2	4	11200	29050	32.3
25.5 x 26 aisle	25.5	26			0	4	6	18200	18200	27.5
25.5 x 17 parking (LOS D design)	25.5	17	6	6	17850	0	0	0	17850	41.2
Short Span, conventionally reinforced structure (2 stalls between columns)										
16' x 16' parking (LOS D design)	16	16	4	4	11900			0	11900	46.5

Fig. 7: Uniform load calculations for various structural, parking garage-framing systems

- Conventionally reinforced concrete with a 30 x 30 ft (9 x 9 m) column grid;
- Steel beams and columns with precast tees; and
- Steel beams and columns with a cast-in-place post-tensioned slab.

The layout of a typical parking area is shown in Fig. 6.

All other things being equal, 90-degree parking with two-way traffic will result in the highest density of loading in a single structural bay. We determined the maximum number of wheel loads for parked vehicles and moving vehicles that could be applied to a wide variety of typical parking structure slab-framing systems. We assumed the vehicles were centered in the stall or drive lane, and used the wheelbase (10 ft [3 m] center-to-center of axles) or track (5.5 ft [1.7 m] width, center-to-center of tires) of the Ford Expedition to determine what combination of front- and rear-tire loads could contribute to the loading of a particular component. We also assumed that the closest feasible headway of the vehicles when driving down the aisle is 24 ft (7 m).

For a double tee, it is relatively easy to determine the width over which a wheel load would be distributed, if one (conservatively) assumes that no load is transferred to adjacent tees. It is much more difficult to determine the width that carries loads in a post-tensioned (PT) slab. A major factor is the reinforcement provided in the transverse direction to distribute the loads. Concentrated loads applied to slabs are usually presumed to distribute at a 45-degree angle from the direction of span. However, when multiple loads are applied, the distribution quickly begins to overlap other wheel loads and the load becomes uniform.

As seen in Fig. 7, all of the precast concrete framing possibilities have less than 50-lb/ft^2 (250 kg/m^2) equivalent uniform loading (except for valet and rental car parking, which will be discussed shortly). Using the 45-degree load distribution, all of the PT slab possibilities also have less than 50-lb/ft^2 (250 kg/m^2) equivalent uniform loading. We then checked a typical short span situation with a 30 x 30 ft (9 x 9 m) grid. The load on the slab in the aisles is 25 lb/ft^2 (120 kg/m^2); the load in the parking areas is 40 lb/ft^2 (200 kg/m^2) and the load to the columns is 32 lb/ft^2 (160 kg/m^2). The uniform loads carried to beams and columns for a bar joist system with a 30 x 30 ft grid would be similar.

On occasion, some short-span systems are designed with extremely tight geometrics; for example, three stalls are provided between columns 25.5 ft (8 m) center-to-center. We evaluated such designs as well, but the loads are still less than 50 lb/ft^2 (250 kg/m^2). Finally, we determined the equivalent uniform loads for a short span system using two stalls between columns and 16 ft (5 m) spans. This would be similar to the system employed in the previous article. At least by the time the loads are transferred to the beams and columns, they are equivalent to a uniform load of 46.5 lb/ft^2 (230 kg/m^2) on the contributing floor area.

None of the typical framing-system components of the parking structure has an equivalent uniform load exceeding 50 lb/ft^2 (250 kg/m^2). Quite simply, except for a scenario with closely spaced joists, a 50-lb/ft^2 live load is adequate, particularly considering that the likelihood of eight vehicles equal to or larger than Expeditions parking in the same areas is less than 1/1,000,000, and it is significantly less likely that they are all loaded to the maximum GVWR as assumed herein.

STACKED PARKING SYSTEMS

The above analysis assumes conventional self-park structures, with vehicular circulation to and from every stall. Where there are vehicles parked and stored by employees without circulation to every stall, a heavier vehicle density presumably might occur. For example, in the storage areas of rental car facilities, the vehicles may be parked in columns, nose to tail, with the column width 8.3 ft (2.5 m) and the spacing longitudinally at 18 ft (6 m). There would be seven columns of vehicles in a 60-ft (5 m) parking bay.

Conversely, such vehicles would never be loaded to the full GVWR when parked in such areas, as the renter's belongings would be removed in the return area. The vehicle weight then should be the curb weight, or 4900 lb (2200 kg). It is questionable whether any one rental car agency has enough Expeditions at a locality to fully load a structural bay, but let's test it as a worst case. The load on the 10-ft (3 m) tee increases to 69 lb/ft^2 (340 kg/m^2), while the load on the 12-ft (4 m) tee would increase to 58 lb/ft^2 (280 kg/m^2). Car dealership storage areas could have a similar density of vehicles, but again, they would not be loaded to GVWR. Note that this projection assumes that loads on the cantilevered flanges of the tee are not distributed to the adjacent tee via the tee-to-tee connections, which is conservative.

Occasionally, self-park facilities are converted to valet parking by parallel parking one vehicle in the drive aisle, across the back of stalls (Fig. 8). The areas that were the most heavily loaded in the self-park scenario were evaluated for the addition of a parked vehicle in the aisle. The load on the 10-ft (3 m) tee increases to 54 lb/ft^2 (260 kg/m^2), while the load on the 12 ft (4 m) tee would increase to 53 lb/ft^2 (260 kg/m^2). The load in the aisle with valet parking is 67 lb/ft^2 (330 kg/m^2), in a very limited area that is better modeled by using wheel loads rather than uniform loads. It is further questionable that Expeditions would be parallel-parked in a 24-ft (7 m) drive lane while still allowing Expeditions to drive by in both directions. In sum, 50 lb/ft^2 (250 kg/m^2) also is reasonable for stacked/valet parking.

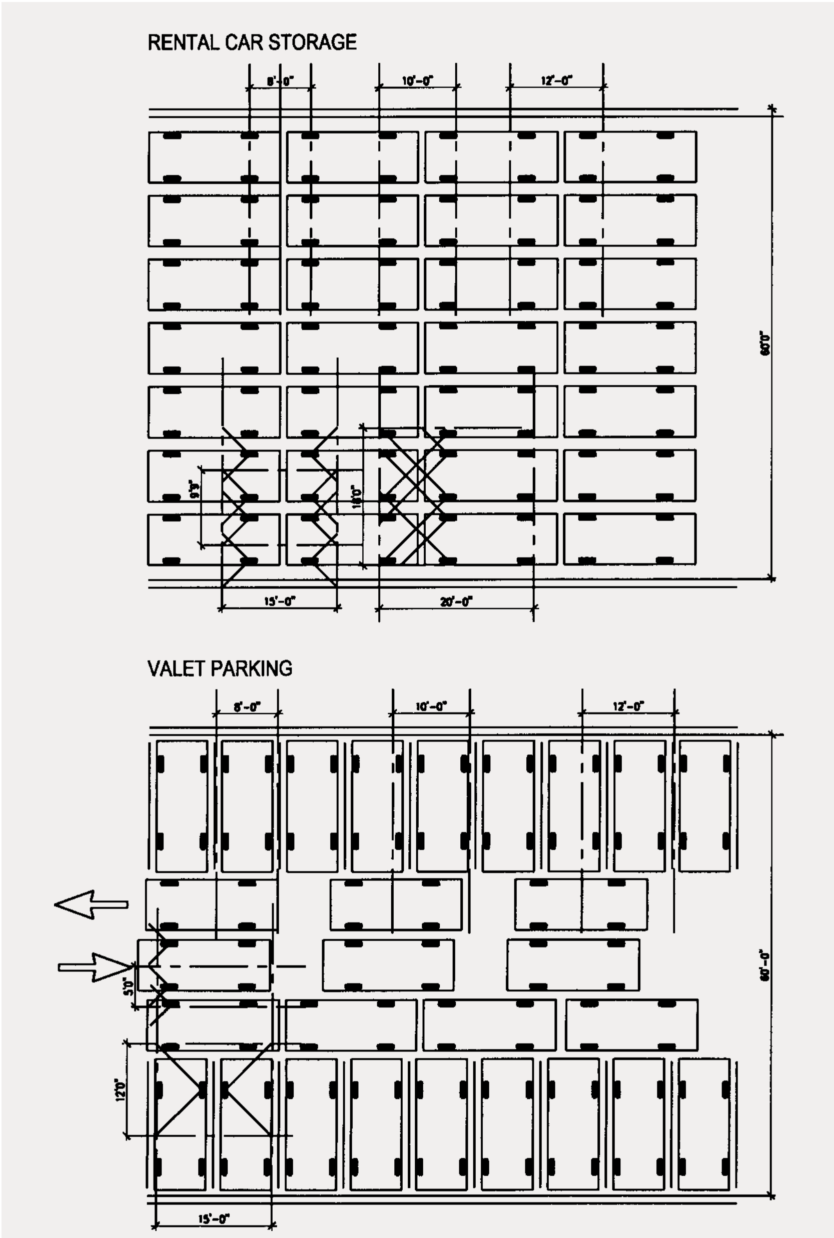

Fig. 8: Typical vehicle layout for stacked/valet parking structures

REDUCTION OF LOADS APPLIED TO BEAMS AND COLUMNS

Live load reductions of up to 40% are currently allowed by UBC and SBC for parking structure beams and columns. BOCA and ANSI/ASCE 7-98 only allow reduction of live loads by 20% for parking structure members (generally columns and foundations) supporting two or more floors. IBC includes the same language as ANSI/ASCE in Section 1607.9.1.2. However, Section 1607.9.2 of IBC provides an alternate live load reduction of up to 40% based on the tributary loaded area—the same provision found in the UBC and SBC codes. According to the IBC code commentary, the alternate live load reduction of Section 1607.9.2 may be used instead of Sections 1607.9.1.1- 4.

The premise of reduced live loadings is that, while any one small area may be loaded to the maximum live loading, it is unlikely (at least with most building occupancies) that the entire building is fully loaded simultaneously on all floors. We have already established that it is extremely unlikely that all vehicles on the contributory area for a beam (much less a column supporting multiple floors) will be Expeditions or larger, all loaded to the maximum GVWR. Since 2/3 of the vehicles weigh less than 4000 lb (1800 kg), it would be reasonable, yet quite conservative, to assume that the average weight of parked vehicles, including some cargo, is 5000 lb (2300 kg) for the purposes of live load reductions.

The vehicles in motion then could have an average of 4 adults at 175 lb (80 kg), or 700 lb (320 kg). For a beam with a contributory area of 15 x 60 ft (5 x 18 m), the maximum loading would be two parked vehicles on each side of the aisle and two in the aisle: [(5000 * 4)+(2 * 5700)]/(15 * 60) = 35 lb/ft^2 (170 kg/m^2). A parking area with a 5000-lb vehicle in every 8.5-ft (3 m) stall, but without any vehicles in the aisles, would have a live load of (5000 * 2)/(8.5 * 60) = 20 lb/ft^2 (100 kg/m^2). Therefore, a 20% reduction (from 50 to 40 lb/ft^2 [250 to 200 kg/m^2]) for any one beam design from the equivalent uniform load on slabs seems reasonable.

For columns, it is again very unlikely that an Expedition would be parked in every stall and there would be vehicles densely packed in all drive aisles on all floors stacked above one another. The UBC code provision for mechanical ventilation of garages states that if there are no empirical data, the number of vehicles in motion instantaneously in a structure shall be assumed to equal 2.5% of the capacity. Adding 2.5% * 5700 lb for each driving vehicle to the weight of each parked vehicles results in {[5000 + (0.025 * 5700)] * 2}/(8.5 * 60) = 20 lb/ft^2 (100 kg/m^2).

How realistic is the 2.5% factor? Retail parking garages are among those with the highest turnover; that is, more vehicles are in motion at any one time while nearly all stalls are full. In a very busy peak hour, about 55% of the garage capacity can arrive in the same hour during which up to 60% depart. The total number of vehicles in motion is thus 115%, but this volume occurs over 60 min. If it takes 2 min. to drive the parking facility to find a space or to exit, the average percentage of the capacity that will be in motion at any one moment will be (115%/60) * 2 = 3.8%. Even at an average search/exit time of 5 min., less than 10% of the vehicles will be in motion.

Therefore, we have found that the 2.5% figure is reasonable for ventilation design for most circumstances except for "dumps" after an event. During such concentrated exiting, a vehicle in motion is a vehicle no longer parked in a stall, and the maximum number of vehicles present in the facility is at the start of the dump, when 100% of the capacity is parked, but no vehicles are in motion. Let's assume that four adults per car are approaching and getting into each car to exit. The load at that moment is (5700 * 2)/(8.5 * 60) = 22 lb/ft^2 (110 kg) but it is essentially uniformly distributed to all parking areas. Later in the exiting process, vehicles will be concentrated in the aisles on lower levels, but those vehicles will have exited from parking areas higher in the structure.

Working backwards from a 30-lb/ft^2 (150 kg/m^2) uniform live loading throughout the facility, approximately 93% of the capacity would have to be in motion at any one moment in time with all stalls still occupied. We can imagine no circumstance where vehicles totaling 193% of the capacity of a parking facility would be present (either in motion or parked) at any one instantaneous moment.

Therefore, it seems entirely reasonable to continue to allow 40% reduction of live loads—that is, 50 to 30 lb/ft^2 (250 to 150 kg/m^2)—for parking structure columns and foundations supporting more than one floor, and to allow a 20% reduction for beams as well as columns supporting only one floor.

RECOMMENDATIONS

A 50-lb/ft^2 (250 kg/m^2) live load remains appropriate for parking facilities. Slabs in typical systems should be checked for both a single concentrated wheel load of 3000 lb (1400 kg) applied over 30 in^2 (190 cm^2) and a uniform load of 50 lb/ft^2. Where there are closely spaced joists, it is possible that tires from several relatively heavy vehicles could rest over a single joist. If the loading on a small area needs to be evaluated, the designer could employ multiple wheel loads of 3000 lb (1400 kg), assuming a vehicle track width of 5.5 ft (2 m), 3 ft (1 m) spacing between adjacent vehicles' tires when parked, and a wheelbase of 10 ft (3 m). A 40% reduction of loads to members supporting more than one floor and 20% reduction of loads to members supporting only one floor are also quite reasonable.

We believe that the increase in wheel loads from 2000 to 3000 lb (1400 kg) will not affect post-tensioned concrete slabs, but could require an additional layer of mesh in pretopped, precast tees. Based on conversations with several precasters, this may increase the cost of a precast parking structure about \$0.25/ft^2, or less than 1%. It should not increase the dead load of precast concrete framing systems.

As previously noted, BOCA and ANSI/ASCE currently are more restrictive regarding reduction of uniform loads than the other codes, including IBC. Our proposal regarding reductions will result in an increase in uniform loads on members supporting one floor for designs under IBC, UBC and SBC, to the same as that now allowed under BOCA and ANSI/ASCE. However, the reduction of live loads by 40% for elements supporting more than one floor will result in the same designs as currently allowed under IBC/UBC/SBC, but a reduction in cost under BOCA and ANSI/ASCE. Our final conclusion is that there is no need to inspect and/or fortify parking structures designed under current and/or older codes.

Reference

1. Henry, J., "2001: A Sales Odyssey," *Automotive News*, January 14, 2002.

Selected for reader interest by the editors.

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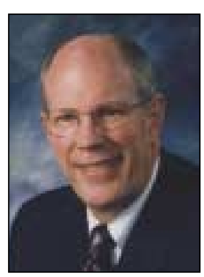

At his untimely death (reported in *CI*, July 2002, V. 24 No. 7, pp. 20), **Anthony P. Chrest** was a Senior Vice President of Walker Parking Consultants, and Corporate Chief Engineer. He was a member of ACI Committees 301, Specifications for Concrete, and 318, Structural Concrete Building Code, and a Fellow of both the American Concrete Institute and the Prestressed Concrete Institute. Smith and Chrest are among the co-authors of *Parking Structures: Planning, Design, Construction, Maintenance, and Repair*.