of queuing theory to both single- and multiple-lane service systems is needed. Further development of the geometric design of parking and queuing areas is needed so that the interference of queued vehicles with the use of parking spaces and/or pedestrians can be minimized. Additional information for estimating arrival rates and service times is needed. The development of a microcomputer program to carry out the analysis would be desirable.

CONCLUSION

This paper has presented some tools and guidelines to help traffic engineers and planners understand the impacts of drive-up windows, as well as to suggest ways in which the negative impacts may be reduced.

REFERENCES

1. F.S. Hillier and G.J. Lieberman. Introduction to Operations Research. Holden-Day, Inc., San Francisco, 1980, pp. 400-484.
2. ITE. Transportation and Traffic Engineering Handbook. Prentice-Hall, Englewood Cliffs, NJ, 1976, pp. 302-388.
3. D.L. Gerlough and M.J. Huber. Traffic Flow Theory. TRB, Special Rept. 165, 1976, pp. 137-173.
4. Procedure for Estimating Highway User Costs, Fuel Consumption, and Air Pollution. FHWA, 1980.
5. R.B. Shaw. Traffic Generation and Fast-Food Restaurants. Traffic Engineering, March 1975, pp. 36-37.
6. R.H. Lopata and S.J. Jaffe. Fast-Food Restaurant Trip Generation: Another Look. ITE Journal, April 1980, pp. 28-31.
7. D.L. Woods and C.J. Merser. Design Criteria for Drive-In Banking Facilities. Traffic Engineering, Dec. 1970, pp. 30-37.
8. P.N. Scifres. Traffic Planning for Drive-In Financial Institutions. Traffic Engineering, Sept. 1975, pp. 21-24.

Influence of Arterial Access Control and Driveway Design on Energy Conservation

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Driveway design standards influence turning maneuver performance and are most critical on arterial streets. The speed disparity between outside lane arterial vehicles and driveway right-turn entry vehicles directly affects both operations and safety. This study used fuel consumption as a measure of effectiveness between minimum, typical, and desirable driveway design standards for the driveway right-turn entry maneuver. A simplistic model analysis illustrated the differences in fuel consumption incurred by arterial vehicles in the outside lane traveling at a given speed (i.e., 35 mph), which are forced to negotiate a deceleration-acceleration speed-change cycle due to right-turning vehicles that enter driveways that exhibit various levels of design standards. The results for the stated condition of 35-mph arterial speed indicate little difference in annual fuel consumption as influenced by design at an arterial-driveway hourly volume product of less than 100 000 vehicles. Between the 100 000 and 500 000 arterial-driveway hourly volume product range there is demonstrated fuel savings incurred through the institution of desirable versus minimum driveway design standards. Above a 500 000 arterial-driveway hourly volume product, the fuel savings are substantial and warrant the application of desirable driveway standards on all such facilities, with special consideration given to parallel deceleration right-turn lanes. Further research is needed to fully simulate and quantify the arterial-driveway traffic operational interaction for the right-turn driveway entry maneuver.

Ordinances that manifest regulatory policy and procedures for access control have been instituted in most U.S. cities with populations greater than 25 000 persons. These statutory guidelines have been based on safety and operational criteria that have served as the measures of effectiveness for driveway design on urban streets and highways.

Studies in Texas (1) have indicated that there exists a great inconsistency in the objectives of driveway regulations (safety, operations, etc.) and a general lack of uniformity in design standards and specifications. Table 1 (1) presents a summary of both commercial and residential driveway design standards from 34 Texas municipalities. As shown, there is a considerable range in both the importance associated with a specific driveway design element under regulation and the standard values designated to any particular element. Many cities assign absolute minimum and/or maximum design limits but do not state desirable design criteria. Most cities do not recognize the interaction between driveway design features. This seems to be reflective of national trends as well.

There is a need to relate the individual and interactive effects of standards for driveway design elements to a single measure of effectiveness. In recent years, energy conservation has become increasingly important as a measure of effectiveness to various federal agencies, as can be seen by the Emergency Energy Conservation Act of 1979 and Executive Order 12185 of the Federal Highway Administration (FHWA), December 17, 1978. The objective of this paper is to assess driveway design standards on arterial streets in terms of the affected operational speed differential between arterial vehicles and vehicles turning right into driveways of various design standards. Fuel consumption of arterial vehicles forced to decelerate due to driveway entry vehicles is calculated and compared for various design standards.

OPTIMAL DRIVEWAY DESIGN

Optimal driveway design, and subsequent turning maneuver performance, is extremely critical on arterial streets. Arterial streets constitute those streets without full access control that carry traffic entering, leaving, or passing through an urban area or intra-area traffic between the central business district and outlying residential areas, between major inner city communities, or between major suburban centers. Primary arterial streets serve very high traffic volumes at moderate speeds and are

Table 1. Summary of commercial and residential driveway design standards in 34 Texas cities.

Design Feature	Commercial Range of Values (ft)	Commercial Cities with no Guidelines (%)	Residential Range of Values (ft)	Residential Cities with no Guidelines (%)
Minimum throat width	12-25	37	9-20	44
Maximum throat width	24-45	3	12-40	9
Minimum curb return radius	2-15	9	1.5-10	15
Maximum curb return radius	5-50	44	4-50	43
Minimum spacing between driveways	10-45	18	8-30	26
Minimum spacing to intersections	20-100	20	20-100	23

Table 2. Arterial driveway design standards—curb return radius.

	Curb Return Radius (ft)					
	One-Way Driveways			Two-Way Driveways		
Driveway Type	Typical	Desirable	Minimum	Desirable	Maximum	Minimum
Residential	5	13	2.5	5	15	2.5
Commercial	20	30	10	20	30	10
Industrial	30	-	15	30	-	15

Table 3. Arterial driveway design standards—throat width.

	Width (ft)						
	One-Way Driveways						
	Typical				Two-Way Driveways		
Driveway Type	Entry Drive	Exit Drive	Desirable	Minimum	Desirable	Maximum	Minimum
Residential	15	15	20	12	20	25	12
Commercial	18	16	20	15	30	35	25
Industrial	20	20	25	15	35	40	30

vital transportation links within an urban area. In most jurisdictions, every land parcel abutting an arterial is guaranteed access. Conflicts between through and turning vehicles pose a major operational and safety problem.

Bochner (2) reported that the capacity of a four-lane arterial street is reduced 1 percent for each 2 percent of the traffic that turns between the right lane and unsignalized access points. For example, if a street carries 1200 vehicles/h in a given direction and 120 vehicles turn into driveways and 120 turn out of driveways (20 percent turns), then the capacity in that direction will be reduced by 10 percent. He also stated that, "as the level of design of the driveway is increased (allowing turns to be made at higher speeds), the capacity loss is reduced and level of service on the arterial is maintained."

Various studies (3,4) have supported the fact that speed differential is the major cause of rear-end accidents associated with the driveway turn maneuver. From the standpoint of safety, it has been suggested that the speed differential between the average speed of through traffic and vehicles entering and leaving the arterial be limited to 10 mph or less.

It is desirable that driveway design standards minimize the speed disparity between arterial and driveway turning movements to optimize operational and safety performance. Maximizing driveway turning speed is a viable measure of effectiveness for driveway design elements and may be expressed in terms of fuel consumption (energy conservation).

DRIVEWAY DESIGN ELEMENTS

The Texas Transportation Institute conducted proving-ground studies (5) that assessed the effects of various driveway geometric design elements on speed in the turn maneuver. Recommended values and corresponding effects on turning speeds are discussed independently by design element.

Throat Width and Curb Return Radius

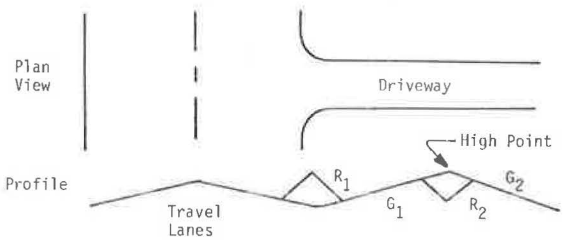
Driveway width and curb return radius interact to affect vehicle speed and path. The selection of an appropriate width must be coordinated with curb return radii selection to achieve desirable driveway operation and safety. Tables 2 and 3 present width and curb return radius requirements for one- and two-way driveways. The desirable values shown should be used whenever possible. If variation from these values is required because of site conditions, the width and radii selected should be as close as possible to the desirable values. The use of both a small width and curb return radius should be avoided. Generally, if the width must be greatly reduced, then curb return radius should be increased, and vice versa. Throat width and curb return radius may individually impact turning speed by ±2 mph.

Angle

The angle at which a driveway intersects the street affects the speed and path of vehicles that use the driveway. Approach angles interact with other design features (e.g., width, curb return radius, throat length, channelization, etc.) to influence driveway operation and maneuvers. Recommended standards are presented in the table below. However, no assessment of impact on turning speed was possible with available data.

Figure 1. Profile key to guidelines for typical driveways on a curbed street.

1) Profile Key



Driveway Type	Angle of Intersection (°)		
	Maximum	Desirable	Typical
Residential	60	70	90
Commercial	45	70	90
Industrial	30	70	90

In regard to the above table, note that all two-way driveways and one-way driveways with unrestricted turning movements should intersect the street at a 90° angle. If site conditions (e.g., terrain, lot size and shape, etc.) will not permit a 90° approach angle, the angle may be reduced, but not below these values: 70° for commercial and industrial driveways and 60° for residential driveways.

At one-way driveways where only right turns are permitted (e.g., one-way driveway pair on a divided street), it may be desirable to flatten the approach angle below 90° to increase entry and exit speeds. Under these conditions, an angle of approximately 60° is recommended, with the following exceptions:

1. At driveways where sidewalk pedestrian traffic is heavy, the approach angle should not be reduced below 70°. Lesser angles encourage high vehicle speed and a pedestrian safety problem may result.
2. If an acceleration or right-turn lane is provided at an exit driveway, the angle may be reduced down to 45°.
3. At industrial driveways that service large trucks, the angle may be reduced to as low as 30° to facilitate driveway operation. Angles less then 30° result in severe visibility limitations and are discouraged.

Profile

Driveway profile is a critical element of driveway design. It influences the speed and path of driveway users and therefore affects driveway operation and safety. It is difficult to recommend a single set of standards for driveway profile, since site conditions vary greatly. Currently, there are no standards available that have received widespread acceptance. Some general profile guidelines for typical driveways on a curbed street are given in the table below (note, the profile key for this table is shown in Figure 1):

Profile Parameter	Desirable	Typical	Minimum
R_1 (ft)	75	50	25
G_1 (in/ft)	0.125	0.25	0.5
R_2 (ft)	100	75	50
G_2 (in/ft)	1	1.75	2.5

Variations from typical values may impact turning speed by ±1 mph.

Other Driveway Design Elements of Influence

Throat Length

Even if existing vehicle storage requirements are minimal, throat length should be as great as practical in order to (a) move the parking and circulation area conflict point away from the driveway entrance and (b) encourage proper use of the driveway, in the case of two-way driveways, by exiting traffic. A minimum throat length of 25 ft is suggested.

Number of Driveways

As greater numbers of driveways are constructed along a street, the accident rate increases and roadway capacity decreases. Therefore, every development (or land parcel) should have only the minimum number of driveways needed to efficiently handle the traffic volumes generated by the development.

Spacing

Driveways should be spaced far enough apart so that conflicting movements at adjacent driveways do not overlap, thus increasing accident potential and/or reducing roadway capacity. Desirable minimum driveway spacings for arterials with a speed range of 35-40 mph is 200 ft measured from driveway throat to driveway throat.

Summary

The following general statements summarize the individual and combined effects of driveway design elements on right-turn entry speed:

1. Right-turn entry speed decreases as the available width and/or curb return radius decreases;
2. Right-turn entry speed increases as the angle of entry is decreased to an optimum level; further decreases promote excessive driveway speeds; and
3. Right-turn entry speed increases as relative disparities in profile are minimized.

Estimates of the quantifiable effects of driveway design standards on right-turn entry speeds may be drawn from the field investigations by the Texas Transportation Institute (5). For a driveway constructed under typical standards, which exhibits a nominal turning speed of approximately 10 mph, the comparative cumulative speed effect between minimum and desirable standards is given in the table below (note, the nominal turning speed under typical standards is assumed to be 10 mph, and the cumulative turning speeds for the various levels are as follows: minimum = 5 mph, typical = 10 mph, and desirable = 15 mph):

Design Element	Effect on Turning Speed (mph)		
	Minimum	Typical	Desirable
Throat width	-2	0	+2
Radius	-2	0	+2
Angle	0	0	0
Profile	-1	0	+1

IMPACT ON FUEL CONSUMPTION

The evaluation of the impact of specified levels of driveway design standards on fuel consumption consists of a limited, simplistic model of the driveway right-turn entry maneuver. Arterial operating speed is assumed to be 35 mph with volume ranges from 400 to 1600 vehicles/h in the outside lane during the peak hour. Driveway right-turn entry volumes represented 5, 10, and 20 percent of arterial volume under turning speeds of 5 mph (minimum), 10 mph (typical), and 15 mph (desirable), respectively, as dictated by design.

Fuel consumption is calculated based on the disparity between arterial operating speed and driveway

Table 4. Summary of arterial traffic volume impacted by driveway right-turn entry volume.

Peak-Hour Arterial Through Street Volume (vehicles/h)	Driveway Right-Turn Entries (%)	Driveway Design Standards: Minimum (5 mph) P_T	EFV	V_T	Typical (10 mph) P_T	EFV	V_T	Desirable (15 mph) P_T	EFV	V_T
1600	5	0.048	4	308	0.048	3	231	0.048	2	154
	10	0.099	4	632	0.099	3	474	0.099	2	316
	20	0.160	4	1024	0.160	3	768	0.160	2	512
1200	5	0.048	3	174	0.047	2	112	0.047	1	56
	10	0.098	3	354	0.098	2	236	0.097	1	116
	20	0.159	3	573	0.158	2	380	0.157	1	188
800	5	0.047	2	76	0.046	1	37	0.044	1	35
	10	0.097	2	156	0.095	1	76	0.091	1	73
	20	0.156	2	250	0.153	1	122	0.148	1	118
400	5	0.039	1	16	0.036	1	14	0.018	1	7
	10	0.081	1	32	0.073	1	29	0.037	1	15
	20	0.130	1	52	0.118	1	47	0.059	1	24

Note: P_T = total probability of any following vehicle in the outside lane of an arterial being impacted by a driveway right-turn entry, EFV = number of equivalent following vehicles impacted by a driveway right-turn entry, and V_T = total number of arterial vehicles in the outside lane impacted per hour for the total number of driveway right-turn entries specified.

right-turn entry maneuver speed. This follows as a function of arterial volumes and driveway right-turn volume. An estimate of the number of arterial vehicles impacted by driveway turning vehicles for conditions of volume and speed may be formulated through a series of probability statements.

The first probability involved in calculating speed impact is the probability that the lead vehicle of any two vehicles will actually be a turning vehicle (P_{Turn}). This binomial condition may be calculated for each driveway turn by the relation

$$P_{Turn} = Q_{Turn}/Q_A \quad (1)$$

where Q_A is the arterial volume (vehicles/h) in the outside lane, and Q_{Turn} is the driveway turning volumes (vehicles/h).

The second probability involves the determination of the time headway between two vehicles such that, given designated operating conditions, no impact of reduction in through arterial speed will be incurred by a vehicle (P_{Impact}). Physically, this is the time headway between vehicles sufficient that, as the lead vehicle decelerates to negotiate the driveway turning maneuver, the following vehicle can maintain its operating speed unimpeded to within a minimum 2-s headway of the lead vehicle.

Any time headway less than the derived values, under specified conditions (by design constraints), will generate a speed impact. These critical headways, which assume a deceleration rate of -3 ft/s^2 nominal, are calculated as T_5 = 16.67 s (minimum standard, 5 mph driveway turn), T_{10} = 14.23 s (typical standard, 10 mph driveway turn), and T_{15} = 11.78 s (desirable standard, 15 mph driveway turn).

By substituting the critical deceleration time headway (T) for all specified conditions, the following equation allows the calculation of the probability of two consecutive vehicles that exhibit a gap headway of size T or less, which results in an impact to the following vehicle:

$$P_{Impact} = 1 - e^{-q_A T} \quad (2)$$

where

P_{Impact} = probability of speed impediment to following vehicle,
q_A = arterial volume (vehicles/s) in the outside lane,
T = critical gap headway (s), and
e = logarithmic constant = 2.718 28.

A third probability--the probability that the following vehicle of any two vehicles will be a straight or through vehicle (P_{Thru})--must also be considered. This binomial condition may be calculated by

$$P_{Thru} = 1 - P_{Turn} \quad (3)$$

The probability that any two vehicles on the arterial will be involved in a turn maneuver, such that a speed-reduction cycle is imposed on the following through vehicle under given operating conditions, is the multiplicative function of the three previously discussed probabilities (P_T). The equation is as follows:

$$P_{Total} = P_{Turn} \times P_{Impact} \times P_{Thru} \quad (4)$$

The total probability function multiplied by the arterial volume in the outside lane provides an estimate of the number of immediate vehicles impacted per hour. This does not give an indication of the extent of impact (degree of imposed deceleration/acceleration speed cycle) on this vehicle or on subsequent vehicles. An estimate of the equivalent following vehicles (EFV) impacted may be derived by a cursory comparison of the mean gap headway for designated arterial volumes with critical impact gap as established by design levels. The extent of impact is assumed to be an average between the first and last vehicles impacted.

Table 4 summarizes those calculated values for the total probability (P_T) of any arterial vehicle in the outside lane being impacted by a driveway right-turn entry, the number of EFV subsequently impacted by a driveway right-turn entry, and the total number of arterial vehicles (V_T) in the outside lane impacted per hour for levels of driveway design standards and arterial-driveway volume combinations. The total vehicles impacted are converted to gallons of fuel consumed by referenced standards (6) for the driveway turn speed cycles specified. Figure 2 depicts the annual fuel consumption plotted against the parameters of arterial street volume in the outside lane multiplied by the driveway right-turn entry volume for each specified design level. Conversion from peak-hour fuel consumption to annual fuel consumption was accomplished by using a peak-hour factor of 0.10 multiplied by 5 days/week and 52 weeks/year.

It should be noted that the curves shown on this graph are for only one condition of arterial operat-

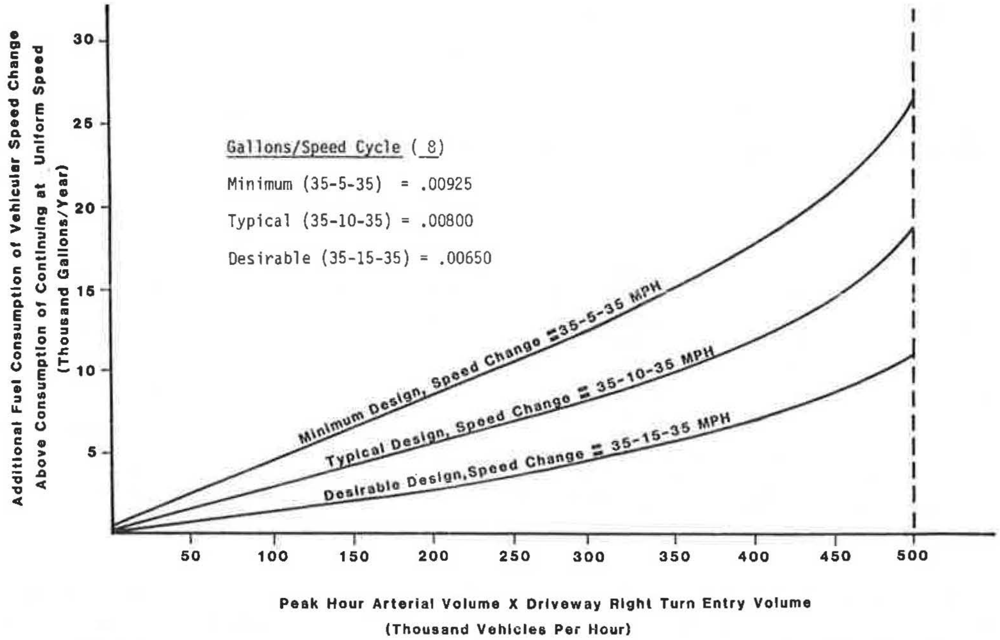


Figure 2. Annual additional fuel consumption as affected by driveway design standard levels and arterial-driveway hourly volume product.

ing speed--35 mph. A more complete analysis requires the extension of this methodology to produce a family of curves that represent a range of arterial operating speeds.

CONCLUSIONS

Figure 2 reveals there to be little apparent difference in the effect on fuel consumption between the previously designated minimum and desirable driveway standards below the 100 000 arterial-driveway hourly volume product level. This represents an arterial facility with a maximum of approximately 750 vehicles/h in the outside lane and 150 driveway entry right turns per hour.

Between the 100 000 and 500 000 arterial-driveway hourly volume product there is demonstrated fuel savings incurred through the institution of desirable over minimum driveway design standards. At the maximum combined volume level of approximately 1600 vehicles/h on an arterial in the outside lane and more than 300 vehicles/h driveway entry right turns, additional annual fuel consumption, which represents the measure of effectiveness between driveway design standards, approaches 15 000 gal/year.

Above the 500 000 arterial-driveway hourly volume product level, the annual fuel savings to be gained through employing desirable driveway design standards are obvious and continue to increase dramatically as volumes increase. Also, above this volume level, if generated by a single driveway, serious consideration should be given to the construction of parallel deceleration right-turn lanes, which can be justified through fuel savings that approach 30 000 gal annually.

It should be stated again when reviewing these values that they are the result of a very simplistic modeling analysis with various assumptions subject to question. However, the generalized direction and magnitude of the effect is reasonable and supportive of the specified conclusions. Also, this analysis made no mention of the documented safety benefits derived when speed disparity between through and turning vehicles is minimized as a result of desirable driveway design standards.

RECOMMENDATIONS

There is indication of the potential for substantial fuel savings through the upgrading of driveway design standards for the right-turn entry maneuver. Tentative arterial-driveway design volume product values for application of standards are designated; however, the limited scope of this study precludes the use of these results.

Further research is needed beyond that previously cited (5) to establish in more detail the specific operational effects of individual and combined driveway design elements. Also, there is a need to collect data associated with the arterial-driveway traffic operational interaction needed to calibrate a simulation model for depicting, in more quantifiable detail, the effects on the traffic stream of those vehicles impacted by a right-turn driveway entry maneuver.

REFERENCES

1. S.H. Richards. Guidelines for Urban Driveway Regulation, Volume 3. Texas Transportation Institute, Texas A&M Univ., College Station, Rept. 5183-3, Oct. 1980.
2. B.S. Bochner. Regulations of Driveway Access to Arterial Streets. Public Works, Oct. 1978.
3. D. Soloman. Accidents on Main Rural Highways Related to Speed, Driver, and Vehicle. Public Works, July 1964.
4. W.W. McGuirk and G.T. Satterly, Jr. Evaluation of Factors Influencing Driveway Accidents. TRB, Transportation Research Record 601, 1976, pp. 66-72.
5. S.H. Richards. Driveway Design and Operations, Volume 3. Texas Transportation Institute, Texas A&M Univ., College Station, Rept. 5183-2, April 1980.
6. C.W. Dale. Procedure for Estimating Highway User Costs, Fuel Consumption, and Air Pollution. FHWA, March 1980; revised April 1981.