CHAPTER 12

Interchanges

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TASK ANALYSIS OF DRIVER MERGING BEHAVIOR AT FREEWAY ENTRANCE RAMPS

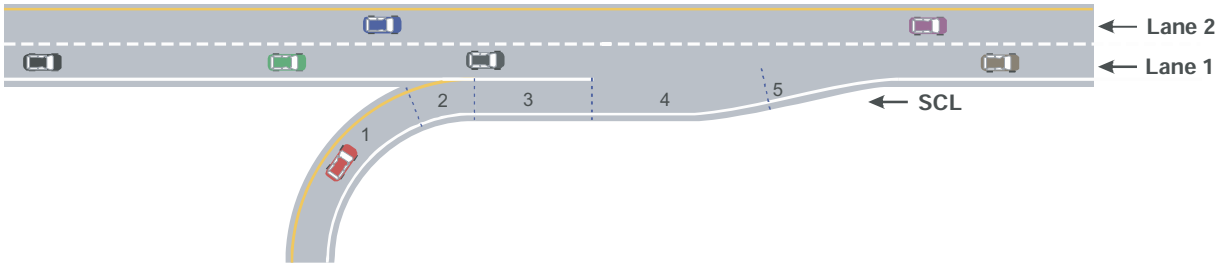
Introduction

Merging from an entrance ramp onto the freeway mainline can be a challenging task for drivers. For example, 36% of all ramp accidents on urban interstates in Northern Virginia occurred when drivers were entering the freeway (*1*). In addition, simulator data showed that, when merging, drivers move their hands to positions in which they can exert more vehicle control (*2*). Although the driver task can be broken up into a series of subtasks, the process is more dynamic than mechanistic: both mainline and merging drivers can detect the gaps available and decide to change their speed accordingly.

Design Guidelines

Task	Distance/Time Derivation	Driver and Roadway Factors
1. *Initial steering component*: Drivers steer to transition from the entrance ramp to the Speed-Change Lane (SCL).	• Constant time of approximately 1 s, derived from research.	NA
2. *Acceleration*: Drivers accelerate to obtain an unobstructed view of mainline freeway traffic.	• Time determined by the travel distance required to see approaching vehicles on the mainline. • The observed 85th percentile maximum comfortable acceleration is 2.0 m/s^2 (*3*).	• Affected by the controlling ramp curvature (*4*).
3. *Gap search*: After seeing the ramp nose, drivers begin to search for a gap in the mainline traffic to use for their merge.	• 0.25 to 0.5 s is required to detect the angular velocity of the lag vehicle on the freeway mainline.	• No stable base for judging speed/position of freeway vehicles (*4*). • Drivers who force in accept smaller gaps and accelerate (*5*). • With heavy congestion, zip merging at ramp end happens instead of gap search (*6*).
4. *Merge steering*: Drivers steer to transition from the SCL to the freeway mainline.	• 85% of observed vehicles merge comfortably in 375 m (*7*). • SCL lengths over 425 m do not improve merging behavior (*7*).	On tapered ramps vs. parallel ramps: • A greater ramp length is used to merge (*8*). • Drivers merge more aggressively (*9*).
5. *Abort*: Drivers who do not find a gap to merge into decelerate to a stop before running out of SCL.	• Time determined by the angular velocity of the approaching ramp end.	NA

SUBTASK LOCATIONS



Source: adapted from Ahammed et al. (*3*)

Discussion

Initial steering component: The initial steering component occurs when drivers transition from the entrance ramp onto the SCL. This steering time is approximately 1 s in length, derived from empirical research on steering (*4*).

Acceleration component: During the acceleration component, drivers accelerate to obtain a view of the mainline traffic on the freeway. This acceleration is controlled by the ramp curvature (*4*). Additionally, drivers cannot begin the next component, gap search, until they have an unobstructed view of the mainline traffic. Hunter and Machemehl (*7*) found that ramps with adequate sight distance and SCL lengths led to small acceleration levels, while ramps without adequate sight distance and SCL lengths caused larger positive and negative acceleration levels.

Gap search component: In general, drivers do not begin searching for a gap in the mainline traffic until they can see the nose of the entrance ramp (*10*). On cloverleaf ramps, drivers focus on navigating the curves until they are on a transition spiral to the straight portion of the lane (*10*).

Merge steering component: Two types of merges have been described in the literature. The first, a short merge, occurs when the driver merges before or near the end of the entrance ramp nose. This type of merge is likely to occur on ramps with poor geometry where drivers merge aggressively to avoid being trapped at the end of the lane (*11*). The second type, the long merge, occurs when the driver uses almost the entire length of the acceleration lane. This type of merge occurs when the geometry is good and traffic volumes are high (*11*). Sarvi et al. (*6*) suggest that when there is heavy congestion, gap search does not actually occur; instead, zip merging happens at the end of the ramp (i.e., where ramp and freeway vehicles merge one by one in an alternating pattern). There is some disagreement as to which geometric component has the greatest effect on gap acceptance: right lane volumes (*11*), ramp design (*6*), or gap distribution (*4*). Overall, Hunter and Machemehl (*7*) found that 85% of entering vehicles merged comfortably in 375 m as measured from the point where the ramp and mainline pavement edges are 1.25 m apart to the end of the taper. Limited-length SCLs over 425 m are not necessary to improve merging behavior.

Abort component: The abort maneuver only occurs if drivers do not find a suitable gap within the length of the SCL. Their focus changes from gap search to an avoidance maneuver and they decelerate to stop before the end of the SCL (*4*).

Design Issues

Merging speeds of elderly drivers are lower than those of younger drivers when there are no cars in the mainline right lane. These speeds decreased further when there were cars on the through lane. Merge point distributions were similar for young and old drivers (*12*).

Cross References

Key Components of Sight Distance, 5-2

Key References

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REDUCING WRONG-WAY ENTRIES ONTO FREEWAY EXIT RAMPS

Introduction

Reducing wrong-way entries onto freeway exit ramps refers to treatments that can be used to reduce the frequency of drivers entering freeways by using the exit ramps. An average of 350 fatalities occur each year in the United States as a result of wrong-way crashes on freeways (*1*). Furthermore, exit ramps were found to be the most frequent origin of wrong-way incidents. In the sample of wrong-way drivers, elderly drivers are overrepresented by experiencing twice the wrong-way crashes than would be expected. Crashes often occur in the early morning hours, although this may be linked with the high frequency of impaired drivers.

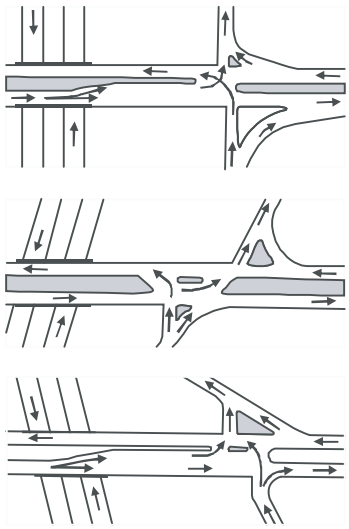
Design Guidelines

This guideline can be used to identify roadway treatments or geometric countermeasures that address specific issues contributing to wrong-way driving, thereby reducing the occurrence of drivers entering freeways via exit ramps.

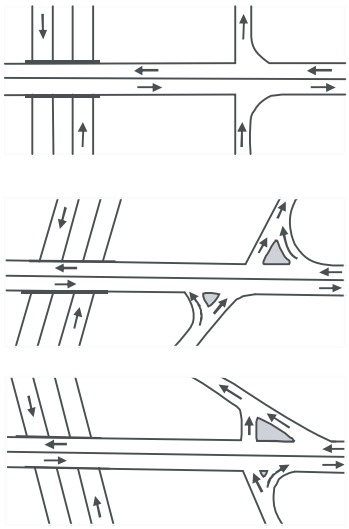
Issues Contributing to Wrong-Way Driving (*2*)	Roadway Treatments or Geometric Countermeasures
Light land use	• Increase conspicuity, e.g., use wrong-way arrows or red reflectorized raised pavement markings (RRPMs) (*3*) • Monitor interchanges in areas of light land use and low traffic volumes
Low traffic volumes	
Poor visibility	• Increase/improve roadway lighting
Adequate directional signing (except at driveways)	• Lower "Do Not Enter" and "Wrong Way" signs (*4*)
Confusing or poorly visible access point configurations	• Avoid freeway left-side exit ramps (*4*) • Provide more cues using the ramp geometry (e.g., more severe angles on the right side as the vehicle passes the exit ramp on the roadway; *5*) • Median installations (*6*)

GEOMETRIES TO DISCOURAGE WRONG-WAY ENTRY

Divided Crossroads



Two-Lane Crossroads



Source: recreated from AASHTO (*5*)

Discussion

All of the characteristics listed in the guideline on the previous page correspond to missing cues that can help drivers determine that they have started down the roadway, particularly an exit ramp, in the wrong direction.

Light land use and low traffic volumes: Wrong-way driving crashes tend to occur in areas with light land use and low levels of traffic. Both of these situations likely indicate occasions when few cars would be traveling in the opposing direction to signal to drivers that they are going to be traveling the wrong way. In these cases, drivers need another indication that they have started traveling in the wrong direction. In a laboratory study of straight multilane roads, Miles, Carlson, Ullman, and Trout (*3*) found that the addition of directional arrows or red RRPMs led to more correct identifications of the proper travel direction on a roadway, though the effects were moderate.

Poor visibility: Wrong-way movements tend to occur when visibility is poor (*2*). In a study of wrong-way crashes, 74% were found to occur during the dark hours of the day. An obvious potential solution is to increase the level of artificial lighting at the access points. An increase in lighting levels would make some of the cues that are available to drivers more apparent at nighttime.

Adequate directional signing: Scifres and Loutzenheiser (*2*) found that in most cases, the signing at most of the origins was adequate (with the exception of driveways). However, signing improvements have been suggested by Cooner, Cothron, and Ranft (*4*). Notably, they refer to a lower mounting of "Do Not Enter" and "Wrong Way" signs, shown to be effective in the state of California. The lower height avoids sight restrictions, is in the range of low-beam headlights for night driving, and is potentially more visible to impaired drivers who drive with their eyes on the pavement. The bottom of the sign package is installed 2 ft above the edge of the pavement (though this is inconsistent with the MUTCD).

Confusing or poorly visible access point configurations: Wrong-way movements were increased when the design of the access point was difficult to see or understand (*2*). The simplicity of the access points can be improved in multiple ways. The first is to avoid the construction of left-side exit ramps and install reflectorized wrong-way pavement arrows on existing left-side ramps (*4*). During a crash analysis, left-side exits experienced multiple crashes due to wrong-way entries. Drivers are familiar with turning right to enter a freeway and may end up traveling the wrong way up a left exit ramp by using this maneuver. Additionally, AASHTO (*5*) recommends sharp or angular intersections between the crossroad and the ramp, making the incorrect maneuver less natural to execute. Median islands can also make incorrect turning movements more difficult. The diagrams on page 12-4 provide sample road geometrics that discourage wrong-way entry.

Design Issues

Drivers who are under the influence of alcohol and/or other drugs compose a considerable portion of wrong-way drivers. Although these drivers cannot specifically be designed for, countermeasures that reduce the affordance of driving the wrong way (such as geometric alterations) may be more effective than those which require the perceptual abilities of the drivers to function at a certain level (such as signage or pavement markings). These trade-offs can be considered in areas near bars or other locations where drunk drivers may be more prevalent.

Short sight distance has been found to be a contributor to wrong-way crashes (*7*). Improving sight distance may decrease the number of drivers driving the wrong way by increasing the odds that they will see an approaching right-way driver's headlamps. However, improving sight distance is more of a crash avoidance measure for right-way drivers who will see wrong-way drivers approaching from a greater distance.

Cross References

Lighting Guidelines, 21-1

Key References

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DRIVER EXPECTATIONS AT FREEWAY LANE DROPS AND LANE REDUCTIONS

Introduction

Matching *driver expectations at freeway lane drops* is important because lane drops represent a situation that may violate driver expectations and cause confusion when the driver expects the lane to continue on the freeway mainline. This confusion can result in high speed variability, erratic maneuvers, and driver frustration (*1*). Additionally, a left lane drop situation violates multiple driver expectations and can cause more problems. All of these results have negative safety implications; thus, the more accurately that lane drops conform to driver expectations, the safer the situation will be. This guideline refers specifically to lane drops on freeway sections that do not include exit ramps.

Design Guidelines

Consideration should be given to the following principles related to lane drops and lane reductions to promote driver behavior that is consistent with the safe use of such facilities (based on Goodwin (*2*)).

Principle	Guideline
Visual Principles	
Provide continuous visibility	The minimum distance that should be visible to a driver is that required to: a. Perceive that the lane is ending, b. Evaluate maneuver options, and c. Maneuver to an adjacent lane.
Minimize attention-dividing conditions	Place the lane drop away from other distractions such as ramps or complicated signage.
Provide adequate transition cues	Provide a taper of sufficient length so that drivers who enter it with no knowledge of the lane drop will have sufficient time to maneuver.
Coordinate the visual and operational drop	Create a lane reduction such that the lane does not appear to continue beyond the operational reduction, even if the pavement does continue.
Geometric Principles	
Provide an adequate escape area	Provide an adequately sized escape area at exit lane drops for drivers who have insufficient time before the exit gore to make a normal lane change.
Signing Principles	
Notify the driver that the lane is not continuous	Warn drivers who enter the freeway by using an add-drop lane that the lane is not a permanent addition.
Use adequate traffic control devices	Use adequate and consistent traffic control devices to inform drivers: a. What is going to happen b. Where it is going to happen, and c. What they need to do.

SPECIFIC GUIDANCE FOR LANE DROPS AT EXITS WITH OPTION LANES

For lane drops with option lanes, clearly communicate (*3*):

1. The dropped lane can only reach the exit
2. The option lane leads to either the exit destination or the mainline
3. Any other lane only reaches the mainline
4. The identifying information for each destination (e.g., street name, destination name)

Discussion

It should be noted that the lane drop guidance provided by Goodwin (*2*) is not specific to exit lane drops as they are commonly referred to today. This guidance was also formulated based on the study of lane reductions on freeways.

Visual principles: Lane drops should be located where drivers can see them continuously for a long enough period of time to perceive that the lane is about to end, decide on a maneuver, and execute that maneuver. Thus, lane drops should not be located just over the crest of a vertical curve or around a horizontal curve (*2*). Lane drops should be located away from other conditions which require the driver's attention, as these locations increase the probability of drivers missing lane drop cues while looking at other roadway features. A major visual cue for navigating lane drops is the lane drop taper. An inappropriately short taper may cause drastic lane changes, while an overly long taper does not provide cues that the lane is ending. From the driver's viewpoint, operational and physical lane reductions should be coordinated. So, if the pavement continues beyond the operational lane drop, it should be apparent that the lane does not continue onto that pavement.

Geometric principles: Cornette (*4*) found that lane drops, lane splits, and lane reductions at sites with poor geometrics (i.e., high rates of curvature, sight distance restrictions) had higher conflict rates than those at sites with better geometric features. Drivers who do not expect the lane drop should have a reasonable opportunity to recover and stay on their route. An adequate escape area should be provided at/after an exit lane drop to provide drivers who do not want to exit a chance to recover and remain on the mainline (*2*).

Signing principles: A subset of the drivers who encounter a lane drop may have just entered the freeway. If drivers are able to enter using an add-drop lane, they should be warned that their lane is not continuous for through travel (*2*). For all drivers, adequate and consistent information should be provided by the traffic control devices. It is important for drivers to know if they are required to take an action, or if other drivers are required to act. Additionally, excess information not related to the lane drop segment should be minimized (*2*).

Lane drop exits with option lanes provide particularly difficult circumstances for drivers. It is often unclear to drivers that the option lane serves both the mainline and the exit destinations. The underutilization of the option lane can lead to a loss of service volume for the roadway as well as a number of unnecessary merge maneuvers.

Design Issues

On United States border roadways that are used by a large percentage of Spanish-speaking drivers, additional signage with Spanish legends may be appropriate. To convey the message "Right Lane Ends," the sign that had the highest overall comprehension level among Spanish-speaking drivers was "Carril Derecho Termina" (*5*). This sign also had the highest comprehension levels among English-speaking drivers among the three Spanish-legend signs that were tested.

Dynamic late-merge systems have been developed for use in work zone lane closure situations. These systems utilize a series of changeable message signs and static work zone signs to provide merge information to the driver based upon the current traffic volume through the work zone. The basic principle supports early merging when the traffic flow is light and late merging (closer to the gore point) when the traffic volume is heavier.

Cross References

Passing Lanes, 16-2
Effectiveness of Symbolic Markings, 20-4

Key References

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DRIVER INFORMATION NEEDS AT COMPLEX INTERCHANGES

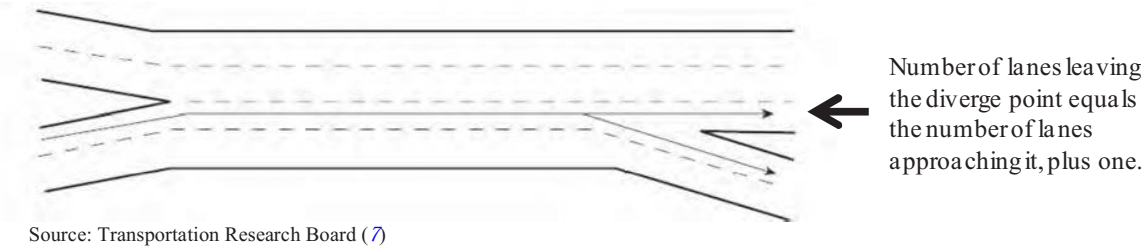
Introduction

Accommodating driver expectations at interchanges is paramount to navigational success. Expectations refer to "a driver's readiness to respond to situations, events, and information in predictable and successful ways" (*1*). Complex interchanges should be designed to give the drivers what they expect to see (*2*). Information that reinforces expectancies helps drivers respond faster, whereas information that violates expectancies leads to longer task times and/or errors (*3*). Thus, more predictable design and operation leads to fewer errors (*4*).

Design Guidelines

Geometric Elements
Route continuity: • Provide a route on which changing lanes is not necessary to continue on the through route (*5*). • If possible, provide the greatest number of lanes for the through movement (*6*).
Lane balance: • "The number of lanes leaving a diverge point is equal to the number of lanes approaching it, plus one" (*7*; see figure). • Minimize the required number of lane shifts by using option and auxiliary lanes (*6*).
Ramp spacing: • Provide adequate ramp spacing to allow for clear and simple guide signing, and to prevent congestion from heavy traffic entering and exiting (*6*).
Error handling: • Provide a forgiving roadside at critical features (*2*). • Avoid creating compound geometric features (*2*).
Signing
Error handling: • Eliminate information-related error sources: avoid deficient, ambiguous, confusing, missing, misplaced, blocked, obscured, small, illegible, or inconspicuous displays (*3*).
Sign placement: • Spread out competing information sources by moving less important information upstream or downstream (*3*). • Structure driver expectations through advanced warning (*4*). • Repeat important information or do not provide interchange information so far upstream that it is forgotten by the time that the interchange is reached (*3*).
Sign content: • Provide appropriate signing to guide drivers (*2*). • Satisfy all driver information needs (*3*).
Sight Distance
• Avoid sightline restrictions (*1*). • Provide visibility that is proportional to feature criticality (*2*).

MAJOR WEAVE WITH LANE BALANCE AT EXIT GORE



Source: Transportation Research Board (*7*)

Discussion

Overall, there is little information available in the research literature that provides specific guidance related to supporting driver expectations at interchanges. The information provided in the guideline on the previous page is generally related to principles of geometry, signage, and sight distance to support elements of driver expectations at interchanges.

Geometric elements: Doctor, Merritt, and Moler (*6*) discuss driver expectations in reference to multiple elements of interchange design. Ramp spacing that is too close can lead to congestion and cluttered signage. The combination of system and service interchanges can lead to information overload, inconsistent sign design, and contradictory movements. Route continuity is provided by designing a roadway on which "changing lanes is not necessary to continue on the through route" (*5*). This principle "reduces lane changes, simplifies signing, delineates the through route, and reduces the driver's search for directional signing" (*5*). Additionally, drivers sometimes assume that at a split, the leg with the greater number of lanes carries the main route. To use lane balance, designers arrange the lanes on the freeway to require drivers to take the minimum number of lane shifts. This is done by using option and auxiliary lanes.

Signing: Advance guide signing that prepares drivers to make decisions and maneuvers is possibly the most important strategy for helping drivers navigate complex interchanges (*6*). Signing can spread out the amount of time that drivers can use to perform lane changes in advance of the decision points. Additionally, signs at the decision point confirm decisions that drivers made on the approach (*6*). Lunenfeld (*3*) stresses that the amount of information should not overwhelm the driver. When information sources compete, the less important sources should be moved upstream or downstream. However, information should not be provided so far upstream that it is forgotten by the time that the interchange is reached. If information is too far upstream, it may need to be repeated closer to the interchange.

Sight distance: Adequate sight distance is required due to the reliance on visual information and for complex decision making (*3*). Sightline obstructions that cover up important or critical information cues should be avoided.

Design Issues

In particular, driver expectations can be easily violated at transition sections where the roadway conditions change. Drivers anticipate the upcoming roadway characteristics based on features that are common to the road they are on (*4*). Roadway designers should look for possible expectancy violations where changes in roadway characteristics (e.g., geometrics, design, or operation) or changes in operating practices occur (e.g., speed zones, no passing zones, or signal timings; *1*). Features that are "first of a kind" on a particular roadway or those that drivers may find unusual or special are also important to examine (*1*). Additionally, adequate transitions should be provided (*2*).

Cross References

Sight Distance Guidelines, 5-1
Driver Expectations at Freeway Lane Drops and Reductions, 12-6
Signing Guidelines, 18-1

Key References

1. Lunenfeld, H., & Alexander, G.J. (1984). Human factors in highway design and operations. *Journal of Transportation Engineering, 110*(2), 149-158.
2. Messer, C.J., Mounce, J.M., & Brackett, R.Q. (1981). *Highway geometric design consistency related to driver expectancy: Vol. I, Executive summary.* (FHWA/RD-81/035). Washington, DC: FHWA.
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ARROW-PER-LANE SIGN DESIGN TO SUPPORT DRIVER NAVIGATION

Introduction

Arrow-per-lane (APL) signs are composed of primarily two parts: arrows that point to individual lanes, and the destination information listed above the arrows. They generally either are large signs or occur in groups, because every individual lane requires its own arrow. These signs provide clear direction for the destinations reached by each lane and have been shown to increase the number of correct lane choices by older drivers as compared to standard diagrammatic signs (*1*). The signs shown in the guideline vary slightly from those recommended by the MUTCD (*2*), because they are modeled after real sign examples. Therefore, this guideline is focused on troubleshooting driver issues rather than informing new sign design.

Design Guidelines

To effectively support driver navigation, the destination information and sign design must allow drivers to pair the destination information with an arrow, and consequently, an arrow with a travel lane.

PAIRING DESTINATION INFORMATION WITH ONE OR MORE ARROWS

Poorly Distinguished Information		Easily Associated Information	
Unsymmetrical centered text above split text:		*Text centered above one or more arrows:*	
	• 30 West shield can be interpreted to apply only to left lane.		• Centered text is easily matched to one or more arrows.
Hyphenated destinations:		*Stacked and centered text:*	
	• Hyphenated destinations may cause driver confusion.		• Stacked destinations are interpreted to go with both arrows.
"Exit Only" by one of multiple arrows:		*Exit placard centered above a panel:*	
	• "Exit Only" notation may be associated with the destination rather than the arrow.		• A centered exit placard is interpreted to apply to the entire sign.

PAIRING ARROWS WITH TRAVEL LANES

Causes of Driver Confusion	What to Do to Fix It
Arrows do not appear to be centered over the lanes.	On tangents, make sure that the arrows are centered over the lanes from the time when the sign is first legible until the driver passes the sign (for legibility distance calculations, see Tutorial 5). Avoid APL signs on sharp horizontal curves.
All of the destinations above an arrow are not reachable by using that lane.	Avoid positioning a destination above an arrow if it can't be reached by the indicated lane.
All of the destinations above an arrow are not able to be reached by following the same direction at a split or option lane.	Match the layout of the destination information to the roadway geometry.

Discussion

The drivers' reading goal is to associate destination information with an arrow which points to a particular lane. To accomplish this goal, the pertinent destination information must be able to be separated from adjacent information and clearly pertain to one or more arrows. The primary sign feature that accomplishes this is the centering of information above the applicable arrows. In essence, destinations are interpreted as being centered above the arrow(s) to which they apply. Design elements that cause inappropriate continuity or separation between elements make the navigation task more difficult. The figure on page 12-10 shows both good and bad examples of pairing destination information with arrows.

Poorly distinguished information: Sign layout can make destination information more difficult to associate with the relevant arrows. One way in which this may occur is when destination information that is meant to be shared by multiple arrows (i.e., more than one lane leads to the same destination or destinations) is interpreted by drivers to mean that each lane leads to a different destination. For example, with the 30 West notation in the guideline, the entire text segment is centered on the sign. Some drivers, however, may interpret the route shield as being more toward the left side of the sign and associate the route with only the left-hand arrow rather than both arrows because the route shield is much larger than the "west" notation. Another problem may occur when text and associated arrows that are meant to indicate different destinations are interpreted by drivers to indicate multiple lanes that lead to the same destination. Destination groupings that are separated by a hyphen may lead to this kind of confusion. The destinations can be interpreted as two areas on the same roadway, or two separate areas. The hyphen prevents association with a single arrow by creating continuity between destination names. Thus, it should be avoided.

In Richard and Lichty (*3*), a situation arose where the "Exit Only" indication was positioned above a single lane on a multiple-APL sign. Drivers interpreted this "Exit Only" text in a different way than the destination information when used above a single arrow; rather than applying this information to the arrow, and thus the travel lane, drivers assigned it to the destination(s). Therefore, this positioning may cause some drivers to believe that they need to be in the exit-only lane to reach the destination, causing unnecessary lane changes.

Easily associated information: In Richard and Lichty (*3*), destination information shown directly above an arrow was associated by all drivers with the lane below the arrow. Drivers thought that an arrow with multiple destinations meant that all of the listed destinations could be reached using that lane. Similarly, information that was centered above multiple arrows was generally seen as applying to all of the arrows that it was centered above. This applied to destination information above multiple arrows or smaller placards above larger guide signs that referred to the entire guide sign.

The signs included in the guideline section on the previous page are modeled after real sign examples. It should be noted that they vary slightly from those recommended in the MUTCD (*2*). For example, those included show downward pointing arrows, whereas the MUTCD recommends upward pointing arrows except in cases where the lane use is restricted to the listed destinations. The direction that the arrows point should not have an impact on the visual grouping performed by drivers. The MUTCD has additional guidance recommending using only one destination per movement; however, multiple destinations listed per movement are common on existing signs. This guideline does not seek to contradict the MUTCD with design guidance, but rather to discuss general interpretation patterns and provide guidance for troubleshooting problematic signs and prioritizing their replacement.

Design Issues

Separations between sign panels can also be used to distinguish between lanes or lane groupings. Destinations on different panels are typically not associated with one another (*3*). Splits between sign panels also show where "Exit" placards apply and do not apply. The MUTCD (*2*) describes the usage of a vertical white line to separate diverging route movements. This is likely comparable to the distinction between separate sign panels.

Cross References

General Principles for Sign Legends, 18-2
Driver Comprehension of Signs, 18-8

Key References

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2. FHWA (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, DC.
3. Richard, C. and Lichty, M.G. (2011). Driver expectations when navigating complex interchanges. Task 4: Gather feedback from drivers. Draft report (Federal Highway Administration Contract No. DTFH61-08-D-00032-T-10005). Seattle, WA: Battelle.

DRIVER BEHAVIORAL TRENDS BASED ON EXIT RAMP GEOMETRY

Introduction

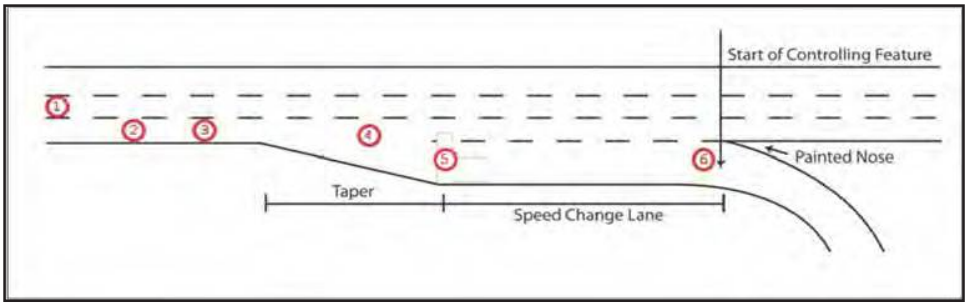
Exit ramps provide the means of accessing adjacent surface streets from a freeway. Well-designed exit ramps provide sufficient area for vehicles to depart from the main freeway lanes and sufficient distance for vehicles to decelerate comfortably from freeway speeds to a speed appropriate for the controlling feature of the ramp, which may be the first curve encountered along the ramp or it could be the crossroad terminal. Driver behavior at freeway exit ramps is based upon a variety of factors, including the operating conditions along the freeway and the geometry of the ramp.

Design Guidelines

To design exit ramps, it is important first to define the intended behaviors of an exiting driver (*1*). Ramps should be designed accordingly to support these safe driving behaviors. The figure highlights where key driver behaviors/decisions take place in the vicinity of an exit ramp. The numbers in the figure correspond to the driver behaviors listed in the first column of the table.

Driver Behaviors for Safe Exit	Design Features to Support Safe Driving Behaviors
1. The driver should maintain a relatively constant speed in the freeway lanes. 2. The driver should position his/her vehicle in the right lane of the freeway prior to the beginning of the deceleration lane. 3. The driver should signal to indicate his/her intended maneuver to other drivers in the traffic stream. 4. The driver should initiate the diverge maneuver shortly after the deceleration lane begins. 5. Deceleration should begin gradually, immediately after entering the deceleration lane. 6. The driver should reach ramp speed before the end of the deceleration lane.	1. Proper sequence and location of guide signs to allow drivers time to make proper route choice decisions. 2. Sufficient sight distance to allow drivers to perform appropriate maneuvers. 3. Pavement markings and roadside delineation to delineate the proper trajectory along the ramp. 4. Delineation to distinguish the features of the gore area. 5. For taper-type exits, sufficient divergence angle to provide a clear indication of the point of departure from the through lanes. A typical divergence angle is usually between 2 and 5 degrees. 6. For parallel-type exits, a taper area should be provided to indicate the general path to be followed by the exiting driver. Typical taper lengths are between 15:1 to 25:1 [longitudinal:transverse]. 7. Deceleration lane lengths sufficient for drivers to reduce their speed from the operating speed along the freeway to the average running speed of the controlling feature at the end of the speed-change lane. Minimum deceleration lane lengths are provided in Table 10-5 of the Green Book (*2*).

PLAN VIEW OF DRIVER BEHAVIORS AT EXIT RAMP*



*Numbers correspond to "Driver Behaviors" in the guideline above.

Design Guidance

On an exit ramp, deceleration is accomplished first as the driver removes his/her foot from the throttle and the vehicle coasts in gear for a period of time (typically) without the use of brakes, and then the driver applies the brakes and decelerates comfortably. A recent study (*3*) confirmed that drivers coast in gear an average of 3 s prior to applying the brakes to decelerate along a deceleration lane. Coasting time was defined to be the sum of the elapsed time between occurrence of peak speed and deactivation of throttle and the elapsed time between deactivation of throttle and activation of brake. Furthermore, drivers typically coast in gear approximately 2 s in the freeway lanes and approximately 1 s in the deceleration lane prior to applying the brakes.

Through further investigations of diverge locations and speeds and deceleration, Torbic et al. (*3*) concluded the minimum deceleration lane lengths provided in the 2004 Green Book (*4*) are conservative estimates, given the current vehicle fleet and driver population. Drivers decelerate at levels well within the capabilities of the vehicle fleet and driver preferences. This is, in part, due to some deceleration by drivers in the freeway prior to the diverge maneuver. Drivers typically diverge between 4 to 7 mi/h below average freeway speeds; however, it is prudent for designers to assume that all deceleration takes place in the speed-change lane when determining minimum deceleration lane length.

Although it seems intuitive that a relationship should exist between deceleration level and deceleration lane length, no relationship has been determined (*5*). It has been found that longer deceleration lanes lead to later deceleration at a higher level, perhaps because drivers relax thinking there is more time than there actually is to decelerate (*5*). Also, as deceleration lane length increases, the percentage of return maneuvers increases (*6*). On the other hand, shorter deceleration lanes lead to an increase in early exits (*6*) and deceleration along the taper to the lane. Torbic et al. (*3*) found similar results, indicating that providing deceleration lanes longer than the minimum values provided in the 2004 Green Book (*4*) may promote more casual deceleration by exiting drivers, particularly under uncongested or lightly congested conditions, but noted this is not necessarily a negative result. Simply, it changes the operational characteristics of the ramp.

Most drivers diverge from the freeway either within the taper or the first two-thirds of the speed-change lane (defined as the distance between the end of the taper to the painted nose). Few drivers diverge from the freeway in the final third of the speed-change lane or beyond the painted nose. Drivers that diverge earlier along the speed-change lane decelerate at a more casual level compared to drivers that diverge closer to the painted nose (*3*).

Design Issues

The current design criteria for exit ramps assume free-flow or uncongested conditions along the freeway and are based upon the vehicle capabilities of passenger cars and driver comfort levels. Several studies (*7, 8*) recommend longer deceleration lane lengths on the order of 15% to 50% longer than those required for passenger cars to better accommodate the reduced vehicle capabilities of heavy vehicles. However, when exiting the freeway, trucks decelerate at levels very comparable to those of passenger cars (*3*). In addition, truck drivers typically choose to diverge from the freeway at lower speeds than drivers in passenger cars and, during uncongested freeway conditions, the distribution of diverge locations for trucks is very similar to the distribution of diverge locations for passenger cars.

One of the goals in designing an exit ramp should be to minimize erratic behaviors near the ramp such as crossing gore paint, crossing gore area, stopping in gore, backing up, sudden slowing, lane changing (to exit), swerving, and stopping on shoulder. Erratic maneuvers occur most frequently after lunch, after rush hour, and during the first hour of darkness during mid-morning and mid-afternoon. These data suggest that most erratic maneuvers are made by motorists taking unfamiliar routes, as contrasted to shopping or commuting-to-work trips, which involve familiar and frequently used routes (*9*). Proper sequencing and location of overhead guide signs, good delineation of the exit ramp, and clearly distinguishing the taper, the beginning of the deceleration lane, and the gore area using pavement markings (e.g., raised pavement markers) and roadside delineation, in addition to geometrics, need to be considered to reduce driver confusion near exit ramps.

Cross References

Task Analysis of Driver Merging Behavior at Freeway Entrance Ramps, 12-2

Key References

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