Transportation is a fundamental support of society. Rail, road, water, and air networks provide the links for the movement of people and goods, delivering the food, fuel, housing materials and supplies, health care, and education essential to modern communities and economies.

Transportation systems generally operate under routine and predictable conditions, but incidents and events occasionally restrict capacity, generate sudden and wide-ranging surges in travel demand, and create unexpectedly hazardous travel. Although most commonly associated with disasters, evacuations, and other types of hazardous events, these disruptions more frequently occur as part of planned and unplanned events.

In the past, disasters and event conditions that brought unavoidable disruptions and that reduced transportation capacity were regarded as inevitable. Today, however, transportation professionals are taking a new view and are developing and applying policies, techniques, and technologies to increase the resilience and robustness of transportation networks.

**Resilience and Transportation**

The Special Committee on Transportation Security and Emergency Management of the American Association of State Highway and Transportation Officials and the Resilient America Roundtable of the National Academies of Sciences, Engineering, and Medicine have defined resilience as “the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events” (1).

Applied to transportation, resilience incorporates ways to work “smarter and more creatively” with

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improved knowledge, training, and communication, adapting innovative, yet safe and effective, methods to maintain mobility and to serve the needs of travelers during nonroutine incidents and events.

Evacuations are an integral part of transportation systems resilience, widely regarded as an emergency response measure that supports protective action and decision making by authorities during catastrophic life-and-death emergencies. Nevertheless, many of the tools, techniques, and philosophies for the planning and management of evacuation traffic are applicable to incidents and events that affect the movement of people and goods—whether the events are large or small, planned or unplanned, long or short in duration, or covering large or small areas.

Techniques rely on the management of demand, the enhancement of capacity, and the improvement of communication, coordination, and resource allocation.

**Evacuation and Resilience**

An evacuation moves people away from a high-risk area to a safer area for the protection of life. Evacuation typically is effective in response to an advance notice of hazardous conditions. Evacuations also can occur spontaneously or under direction after a hazardous event or when dangerous conditions threaten. Post-event evacuations may occur with or without notice.

Evacuation also may be an adaptation to changing conditions, such as a coming threat or post-impact hazards. These conditions differ from the everyday and redefine normal behavior. How individuals should behave and interact in these settings is emergent and differs from established norms (2; 3, p. 143).

Emergent norms of behavior have a parallel in the operation of transportation infrastructure. For large-scale evacuations and for some planned events, the roadway network can be operated in a different way from normal. One example is Evaculanes (see photos, below)—shoulders or center turn lanes that can be operated in the outbound direction to increase capacity (4).

Other temporary control and operational measures also can increase directional capacity away from a hazard. Each technique can be activated, terminated, and adjusted temporally and spatially in response to prevailing or anticipated conditions and can add resilience to the transportation network.

**Evacuation Behavior**

Evacuation is a way to preserve life and to reduce injuries from a hazard, protecting a community’s population and public health. The community plays a large role in the success of an evacuation and of the later recovery. Evacuation behavior affects a community’s resilience.

**Communication and Social Networks**

A warning or evacuation notice is key in encouraging people to evacuate (5). Warnings are a social process and involve the interaction of the warning sources—such as an agency or person crafting and delivering the message (6, 7)—with the message...
receivers, as well as the interaction of the receivers with each other, and of the receivers with their social networks—not necessarily via social media.

Individuals in an at-risk population may not receive the message directly from the source, but from social contacts. The source influences individuals’ responses to the warnings. Individuals must trust the source and believe that the information is credible to overcome any initial disbelief that a hazard is threatening their area (8, 9). Trusted sources may vary across the population; nonetheless, consistent messages from multiple sources may encourage the adoption of recommended actions.

People also seek confirmation of hazard information from their social connections, such as friends, relatives, and coworkers (9). Once individuals believe they are at risk and that evacuation is appropriate, they can begin making related preparations and decisions, such as whether to evacuate, where to go, when to go, and how to get there.

The ability to evacuate depends on several factors. People with access and functional needs may not be ready or able to self-evacuate, because of a lack of funds, appropriate accessible transportation, or accessible communication, or because of other issues.

Prearranged networks of established and diverse community-based official and unofficial service organizations, together with public and service agency transportation providers, can fill gaps of trust, communication, and transportation services to support the preparedness and response of the whole community (10). Transportation and transit agency websites and communications can provide information on transit and related transportation resources, as well as on general transportation conditions and options; the information should be reliable and up to date.

**Personal and Community Resources**

Evacuees require transportation, a place to stay, and basic necessities. Self-evacuees may use their own vehicles. People without access to personal vehicles may rely on extended family, friends, neighbors, coworkers, or other social connections for transportation. Emergency management or other agencies may request buses to help transport evacuees. All of these transportation options require energy or fuel, which in turn require financial resources.

Personal financial resources also may be required when an evacuee reaches accommodations, particularly for hotels or motels. The homes of family or friends are commonly preferred but require social resources or connections; public shelters generally are least preferred and may be close to the affected area or farther away. These accommodations generally are established in buildings such as schools and require the flexible use of community facilities.

Evacuees need water and basic life-sustaining food at the evacuation destination, and possibly en route. Some will require medicine and other items for health care. If these are not provided by a relief organization, personal financial resources are necessary. Coordination among transportation agencies and relief organizations can generate information about evacuees’ origins, destinations, and resource needs to ensure effective preparation and response.

**Evacuation Alternatives**

For some hazards, such as tornadoes and some radiological and chemical threats, sheltering in place may be the appropriate protective action. In other cases, people may choose to remain in their homes—they may not have received appropriate information in...
time, may lack personal resources, may face personal logistical challenges, or may believe that staying where they are is best. Staying behind does not necessarily mean doing nothing. “Stayers” may prepare their home—for example, by boarding windows—or may stock up on supplies, such as food and water.

Other people may shelter locally but not in their own homes—for instance, at the homes of friends or family at higher elevations or of better construction than their own home. Access to these sheltering options depends on local social connections.

Adapting the Concepts
Resilience concepts applicable to evacuation and large-scale disasters—such as transportation management techniques—can be adapted to more common, smaller-scale disruptions and vice versa. This offers the benefit of making some of these plans more routine and preparing agencies for larger-scale or more life-threatening events (11).

Transportation agencies have worked with law enforcement agencies to develop and implement a variety of traffic management strategies to accommodate the demand associated with evacuations. These approaches generally seek to increase system capacity or manage demand.

Techniques include a variety of methods, most of which are commonly used for controlling and managing traffic during a variety of routine planned and unplanned events. Methods to enhance capacity include control, geometric, and operational changes that favor critical movements, as well as suspending tolls during an evacuation to support faster travel. Demand management techniques seek to spread, limit, or eliminate vehicular traffic demand, temporally and spatially.

Operational Strategies
Following are commonly used operational strategies that have been adapted for emergency evacuations.

Contraflow
Contraflow is a form of reversible traffic operation that uses one or more travel lanes for the movement of traffic in the opposing direction (12). Every U.S. coastal state threatened by hurricanes has a variety of plans to implement contraflow.

Contraflow can increase the directional capacity of a roadway immediately and significantly without the time or cost required to plan, design, and construct additional lanes. Contraflow segments are most common and logical on freeways—that is, on the highest-capacity roadways designed to facilitate high-speed operation. Freeways do not incorporate at-grade intersections that interrupt flow and do not permit unrestricted access into the reversed segment. Contraflow on freeways also requires fewer manpower resources than on unrestricted highways.

On selected routes during contraflow, inbound capacity may be needed for heavy equipment, such as for utility repair and emergency response.

Route Closures
The closure of road segments can manage traffic during major emergency evacuations. During radiological releases, for example, closures can limit traveler exposure to a hazard or can limit the cut-through traffic into areas not equipped to accommodate increased demand. At the regional level, closures also have been used to limit traffic flow into a downstream section that has inadequate capacity to accommodate demand from multiple incoming routes.
No-notice evacuation strategies include timing traffic signals to facilitate the movement of vehicles away from the hazard.

Ramp Closures
Ramp closures can promote freeway traffic flow by decreasing the number of merge points that require reduced speed. Under regular, nonevacuation conditions, ramp closures have eliminated bottlenecks on mainline freeway lanes.

Although the effects can increase travel speed, ramp closures may not increase the total throughput and may lead to more delays on the arterials (13). Ramp closures therefore should be considered carefully.

As with route closures, ramp closures also can limit access to threatened areas. Access should be considered for responding personnel and emergency vehicles.

Turn Restrictions
Ramp closures are appropriate for freeways; for arterial roadways, turn restrictions can be applied at intersections—an evacuation strategy known as “crossing elimination.” The concept is to remove all or some conflicting interruptions of the traffic stream—such as left turns and minor street crossings—to provide continuous flow in the primary outbound direction. Police control or barricades are needed to implement these restrictions.

Signal Timing Modification
Traffic signals can facilitate evacuations in urban areas, particularly under no-notice conditions. Although a recent review of practice found no standards or recommended rules of operation for traffic signal control during evacuation emergencies, the primary goal is to facilitate the movement of traffic away from the hazard (14).

A simulation study examined the effects of varied traffic signal timings under evacuation conditions (15). Tests with cycle lengths of 180, 240, and 300 seconds, as well as all-yellow and all-red flashing modes, suggested that the best plan depended on what needed to be achieved.

Longer cycle lengths with longer green times for the outbound directions worked best in facilitating the movement of evacuation traffic. If volumes approached those of routine peak periods, however, typical nonemergency timing plans for the outbound peak period could be effective.

Manual Traffic Control
A common technique for addressing congestion in evacuation emergencies is to allocate police officers strategically to direct traffic at a few key, highly congested intersections. The police officers immediately observe and adapt to changing traffic patterns and can move traffic more effectively than with an actuated controller.

Recent research has suggested that manual traffic control is best suited for intersections immediately upstream of a bottleneck or for closely spaced, uncoordinated signals (16). Flashing yellow signals appear to work best for intersections with high, unbalanced demand and with low volumes on minor approaches.

Crossing elimination strategies, however, work most effectively when demand from nonconflicting directions is high and all other approach volumes are relatively low.

Modifying Demand
In addition to the measures described above, which focus on enhancing the capacity of travel networks during evacuations, a variety of methods can modify demand. The goal is not to prohibit or restrict evacuee departures but to influence the spatial and temporal departure of evacuees safely and shift them to other modes that reduce the total number of vehicles on
the evacuation routes. These demand management methods include transit, pretrip traveler information, incentives, and phased evacuation orders.

Traffic incident management resources, such as motorist service patrols and temporary signage, also can be used, along with traveler information and surveillance systems, such as highway advisory radio, changeable message signs, and closed-circuit television. Incident management techniques, such as emergency vehicle access into threat areas, event venues, and incident scenes, also can be useful.

**During Incidents**
Traffic incidents occur daily, causing delays and putting drivers at risk of secondary incidents. As in evacuations, ramp and route closures and turning restrictions can limit exposure to conditions; shoulders may be used to increase capacity near the incident; manual traffic control may be implemented; and information can be shared to manage travel demand.

**During Adverse Weather**
Adverse weather events have increased in frequency and intensity in the past decade. Many events, such as hurricanes, flooding, and wildfires, require evacuation. Advance warning for evacuation is usually longer for hurricanes—often multiple days of alerts are possible, with two or more days of warning once the path and intensity of the storm can be more accurately forecast.

Flooding from rain and snowmelt is usually well forecast, although additional circumstances, such as a potential dam breach, can create uncertainty. Wildfires usually occur after some warning, but the incidence and spread can be rapid.

The challenges with hurricanes, flooding, and wildfires include complacency—mostly from people who have survived previous incidents and do not acknowledge the increased risk from the current incident—and overreaction, when people not in direct danger create a “shadow evacuation” that can overwhelm roads, supplies, and shelters.

Authorities must be clear about who needs to evacuate. Tornadoes, hailstorms, and severe snow and ice storms are likely to require secure shelter. These events may require limited evacuation or relocation because of the potential or actual destruction of shelter—for example, in mobile home parks—or because of an extended loss of power and utilities.

**Infrastructure Enhancements**
Capital infrastructure improvements also can improve resilience and evacuation operations. For example, the Tampa Hillsborough Expressway Authority proposed an extension to link the Selmon Expressway directly to Gandy Bridge, one of three joining the Tampa and St. Petersburg peninsulas. Although the primary goal of the Gandy Connector was to reduce congestion on Gandy Boulevard, the surface arterial segment, the planning assessments showed that the connector would offer many resilience benefits—notably the ability to evacuate the region and to keep traffic flowing during incidents on the other bridges.

Models showed that the capacity-increasing
aspects of the bridge would offset losses in functionality during emergencies and incidents by permitting a more rapid recovery. Moreover, an incident or event did not have to occur within the Gandy Bridge–Gandy Boulevard corridor; incidents occurring elsewhere would have less of an impact because the effects could be dispersed.

Future Changes

More frequent natural events and a rise in sea level, combined with increases in coastal populations, necessitate careful planning for resilience and evacuations. As shared-ride transportation modes become more popular or as the co-ownership of vehicles becomes more common, fewer households may be able to self-evacuate, leading to a greater need for multimodal and publicly assisted evacuations.

Autonomous or “self-driving” vehicles may support assisted evacuations of carless and mobility-limited populations, as well as the movement of people into and out of threatened areas unsafe for human drivers. The capacity of evacuation routes may improve with currently available autonomous vehicle technologies like automatic speed control, braking, and lane keeping, which allow vehicles to travel safely in denser, higher-speed platoons (17).

The U.S. Department of Transportation has worked to apply connected vehicle communication technologies to assist evacuating travelers during emergencies. The Response, Emergency Staging and Communications, Uniform Management, and Evacuation applications, along with the Emergency Communications for Evacuation application, provide evacuees with en route information to locate shelters, fuel, food, water, cash machines, and other necessities. The technology also could provide route guidance under normal and incident conditions to alleviate congestion and communicate pickup times and location options for low-mobility and carless evacuees.

These expand the multifaceted approaches that make evacuations successful and that improve transportation and community resilience during threats.