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Urban rail systems are designed to carry large volumes of people into and out of major activity centers. As a result, the stations at these major activity centers are often crowded with boarding and alighting passengers, resulting in passenger inconvenience, delays, and at times danger. This study examines the planning and analysis of station passenger queuing and flows to offer rail transit station designers and transit system operators guidance on how to best accommodate and manage their rail passengers. The objectives of the study are to: 1) Understand the particular infrastructural, operational, behavioral, and spatial factors that affect and may constrain passenger queuing and flows in different types of rail transit stations; 2) Identify, compare, and evaluate practices for efficient, expedient, and safe passenger flows in different types of station environments and during typical (rush hour) and atypical (evacuations, station maintenance/ refurbishment) situations; and 3) Compile short-, medium-, and long-term recommendations for optimizing passenger flows in different station environments.

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Passenger Flows in Underground Railway Stations and Platforms

MTI Report 12-43

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REPORT 12-43

PASSENGER FLOWS IN UNDERGROUND RAILWAY STATIONS AND PLATFORMS

Anastasia Loukaitou-Sideris, Ph.D.
Brian D. Taylor, Ph.D.
Carole Turley Voulgaris

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16. Abstract

Urban rail systems are designed to carry large volumes of people into and out of major activity centers. As a result, the stations at these major activity centers are often crowded with boarding and alighting passengers, resulting in passenger inconvenience, delays, and at times danger. This study examines the planning and analysis of station passenger queuing and flows to offer rail transit station designers and transit system operators guidance on how to best accommodate and manage their rail passengers. The objectives of the study are to: 1) Understand the particular infrastructural, operational, behavioral, and spatial factors that affect and may constrain passenger queuing and flows in different types of rail transit stations; 2) Identify, compare, and evaluate practices for efficient, expedient, and safe passenger flows in different types of station environments and during typical (rush hour) and atypical (evacuations, station maintenance/ refurbishment) situations; and 3) Compile short-, medium-, and long-term recommendations for optimizing passenger flows in different station environments.

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Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu

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EXECUTIVE SUMMARY

Rapid, or heavy, rail transit is the highest capacity urban transit mode. Operating on exclusive rights of way, and grade-separated from motor vehicle traffic, rapid rail typically operates underground in subways or above ground on elevated lines. Unlike buses and light rail transit – which passengers can board or alight at relatively simple, austere stops or stations – subways and elevated lines stop only at grade-separated stations where passengers must move to and from track platforms, ticketing areas, and adjacent streets. These stations are frequently complex pieces of engineering and architectural design in their own rights, where tens of thousands of people move, wait, transfer, and sometimes shop in a single day. This report examines how the movement of people through these stations is analyzed and planned.

Because many subway and elevated transit stations have been in service for decades, they often must accommodate in the same physical space more passengers than they originally were designed to handle. Thus, transit station designers and transit operators not only must devise strategies to provide safe and comfortable movement of passengers through transit stations, they also must implement these strategies within an environment of physical and financial constraints. Therefore, an important goal of this report is to explain how transit system managers, planners, and designers provide optimal passenger flow.

RESEARCH SCOPE

Subway and elevated rail transit stations frequently experience high levels of pedestrian congestion. Underground stations are particularly vulnerable to pedestrian congestion because they comprise primarily enclosed areas with limited entrances and exits.

The researchers studied how North American subway/elevated rail transit operators analyze and design for passenger crowding, with a particular focus on below-grade rail transit stations. The specific objectives of this report are to:

1. Understand the particular infrastructural, operational, behavioral, and spatial factors that affect and possibly constrain passenger flows in different types of underground rail transit stations;

2. Identify, compare, and evaluate practices for efficient, expedient, and safe passenger flows in different types of station environments and during typical (rush hour) and atypical (evacuations, station maintenance/ refurbishment) situations; and

3. Compile short-, medium-, and long-term recommendations for optimizing passenger flows in different station environments.

RESEARCH METHODOLOGY

The researchers began by examining scholarly literature as well as manuals, standards, and codes on the management and analysis of pedestrian flows, with a particular emphasis on passenger flows in rail transit stations. This was followed by in-depth, semi-structured interviews with 16 experts in transit rail station design, including architects, engineers, and planners.

Drawing on the themes identified through the interviews, the research team prepared and administered an on-line survey to 18 transit professionals representing all 16 transit agencies in the United States and Canada with heavy rail transit stations. The survey asked respondents to indicate who within (or from outside) their respective agencies is responsible for particular station planning and design tasks; to identify specific strategies and methodologies that the agencies have employed or considered to manage passenger congestion within rail transit stations; and to give their personal opinions on whether these strategies and methodologies are effective.

Through review of the literature, interviews with experts, and the results of the online survey, the researchers made observations and developed recommendations in each of four topic areas: (1) agency planning for passenger flows; (2) data collection and forecasting; (3) analysis; and (4) design.

AGENCY PLANNING FOR PASSENGER FLOWS

The survey results indicate that one individual within a transit agency often has responsibilities for both planning/analyzing passenger flows and designing for passenger flows. To the extent that such integrated roles are common, one would expect this to support pedestrian-friendly station designs because designers with analysis experience are more likely to properly interpret and analyze their own designs. Conversely, analysts with design experience would appear more likely to generate information that is relevant and useful to designers.

Several interviewees indicated that there is more separation between station planners/designers and those responsible for construction, and also between station planners/designers and those who formulate emergency evacuation procedures. The former may result in a failure of planners to adequately account for construction needs, or in a failure of builders to fully implement the strategies that are intended by planners; the latter may result in evacuation procedures and routes that do not fully utilize the designed station capacity.

Recommendation: Encourage coordination and knowledge sharing among the various specialists responsible for aspects of the passenger experience, including construction and emergency evacuations.

DATA COLLECTION AND FORECASTING

Based on the results of the survey, collection of existing passenger volume data and, to a lesser extent, forecasting of future passenger volumes are more likely to be done by in-house transit agency staff than contracted to outside consultants.

Prior research suggests that ridership forecasts used to justify new rail transit projects are often inflated. One interviewee suggested that, in light of this bias, planners should use caution in applying such forecasts as the basis for station design decisions. However, other interviewees pointed out that, to facilitate passenger flows and passenger comfort, an overdesigned station is better than an under-designed one since it is difficult and expensive to add capacity to a station once it has been built. Thus, passenger volume forecasts used for station design should be as accurate as possible; however, budget allocation should err on the side of overestimating passenger volumes.

In addition to carefully evaluating the assumptions and methodologies used to estimate the number of passengers that will use a station, an agency should also occasionally collect data to confirm assumptions about passenger characteristics, such as space occupied per passenger and average desired walking speeds.

Recommendation: Routinely assess assumptions used to estimate pedestrian volumes and pedestrian characteristics.

ANALYSIS

Armed with appropriate estimations of pedestrian volumes and characteristics, a transit station planner can apply several different tools to determine pedestrian needs within the station environment. The deterministic models developed in the mid-twentieth century eventually led to the development of guidelines, standards, and codes that tended to standardize some aspects of transit station design. As modern computing allowed more complex computations, stochastic micro-simulation models were developed that allowed more detailed analysis and visualization of pedestrian movement. Each of these three tools – deterministic models, established standards, and micro-simulation models – is still used today. Each offers distinct advantages and disadvantages in particular situations. The appropriate tool may depend largely on the specific question the planner or analyst seeks to answer.

Recommendation: Select analysis tools and methodologies based on each particular question.

DESIGN

Most design strategies to optimize pedestrian flows through transit stations are implemented in a particular area of the station. Surveyed agencies were most likely to report crowded conditions on station platforms and at vertical circulation elements.

On station platforms, a short-term strategy to reduce passenger congestion might be to disperse passengers more evenly along the entire length of the platform through strategic placement of signage or other amenities. In the medium term, it may be possible to increase the capacity of the platform by removing obstacles such as columns or platform furniture. In the long term, it may be necessary to widen the platform, but this is often cost-prohibitive if it is even possible.

Capacity of vertical circulation elements can be increased by encouraging one-way flows, adjusting escalator speeds, or installing escalators that can move passengers in either direction. The most costly way to increase vertical circulation capacity is to construct additional vertical circulation benefits. Because of the costs associated with adding additional vertical circulation elements to existing stations, it is important to design new stations with adequate vertical circulation capacity from the beginning.

Although the design strategies described above are implemented at particular station elements, they can affect the entire station. To optimize passenger flows, it is important that designers consider the station as an entire system rather than only in terms of its individual parts.

Recommendation: Consider the impact that each design strategy implemented in one station area will have in other areas of the station and on the adjacent street environment.

I. INTRODUCTION

Why people choose to travel by private car rather than by public transit is of major concern to transportation planners and transit operators. For some reluctant would-be riders, the answer might be summed up by the words of Yogi Berra when asked why he no longer patronized a popular St. Louis nightspot: “Nobody goes there anymore. It’s too crowded.”[1]

Passenger crowding on rail transit and in stations may not only decrease the attractiveness of transit for potential riders, it can also create unsafe conditions in stations as passengers risk being pushed onto tracks. Passengers forced to occupy space intended as a buffer along the platform edge are placed in harm’s way. Moreover, excessive station crowding can also prevent passengers from entering and exiting transit vehicles quickly and safely. If passenger volumes are so high that flow through stations is significantly obstructed, emergency evacuations may be impeded as well, risking health and safety. Beyond safety, crowding in transit stations can also reduce average vehicle speeds (and hence system capacity) by increasing vehicle dwell times due to protracted passenger boarding and alighting.

Rail is the highest-capacity transit mode, and rail transit stations frequently experience high levels of pedestrian congestion, typically during the morning and afternoon rush hours, but also related to special events – such as festivals, parades, and sporting events – that attract large crowds of riders. Occasionally, extreme events such as natural or human-made disasters, such as an earthquake, fire, or terrorist attack that require the complete evacuation of transit facilities, may also result in high levels of pedestrian congestion.

In addition to walking and waiting, passengers also frequently purchase and validate their tickets, buy newspapers or food from concessions, ask for information at kiosks, or stop to consult maps. Thus, transit station congestion can take place in walking areas such as stairways, escalators, and elevators, but also in waiting areas such as platforms (especially during train boarding and alighting times). Point areas (Figure 1) such as station entrances and exits, ticketing machines, turnstiles/fare gates, and concessions may also experience congestion and queuing. Figure 1 does not and cannot reflect the variety of station configurations that exist in underground rail stations, but it does indicate an approximate sequence of events that passengers might experience.

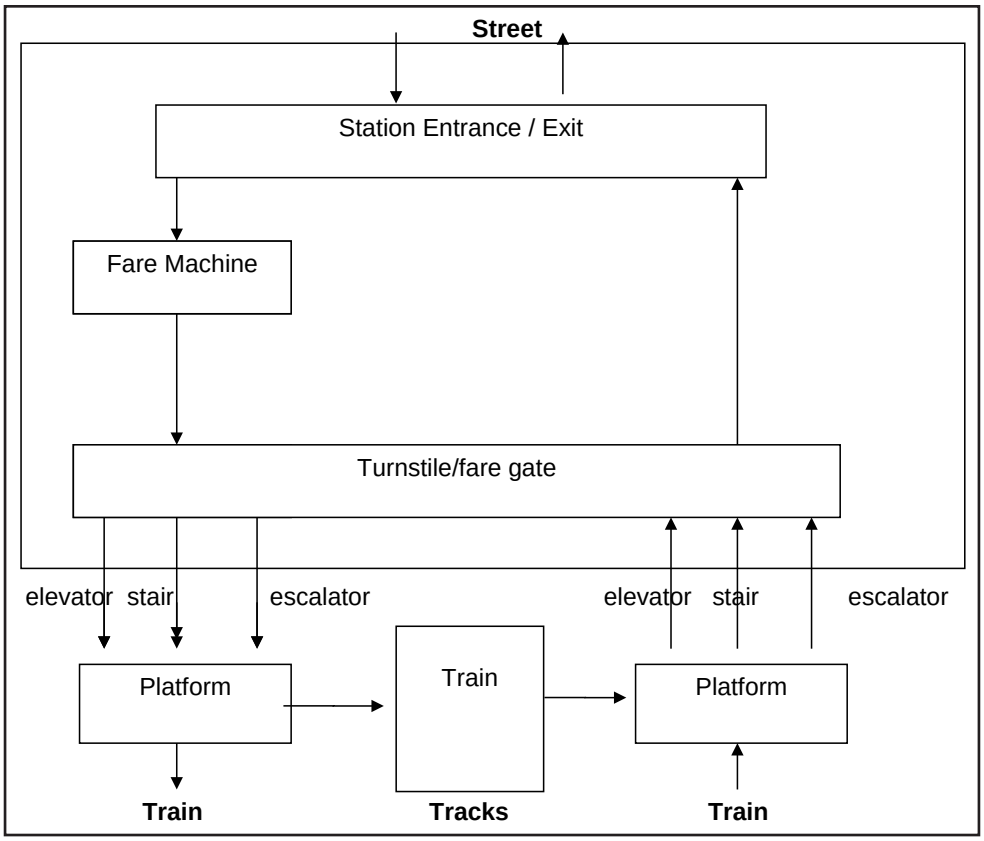

Figure 1. Conceptual Diagram of Rail Station Passenger Flow

While there is a substantial body of literature on solutions to the technical and computational problems associated with accurately portraying the movement of pedestrians,[2,3,4,5] very little has been written about how these increasingly sophisticated methods are applied in practice and the context in which they are used. Some scholars have written about the use of ridership forecasts to justify new rail transit service,[6,7,8] and a smaller number have written about institutional and political factors that influence transit fare policy and technology adoption,[9,10] but this work does not address how these phenomena affect station design. This report seeks to address these gaps in the literature.

Pedestrian flow is defined as the number of pedestrians who pass through a cross-section of an area during a given time period. (Refer to Section III for a more detailed discussion of the relationship between flow rates and related measures of speed and density.) Pedestrian flow in rail transit stations is affected by both the numbers of pedestrians sharing the space and the spatial layout of the station – including the size and location of different station areas, how these areas are connected to one another, and the number, size, and location of the vertical circulation elements (escalators, elevators, and stairs). The maximum rate of pedestrian flow is usually constrained by the acceptable levels of passenger comfort as well as by safety considerations.[11] How transit system managers design and operate rail transit stations for optimal passenger flow and comfort is the focus of this study.

RESEARCH SCOPE

In transit stations, platforms must accommodate flows of passengers (i) arriving and departing from the station, (ii) waiting for vehicles, (iii) boarding and alighting, and (iv) transferring between vehicles or lines. Many transit stations have been in service for decades, so in some cases they may accommodate in the same physical space more passengers than they were originally designed for. During station maintenance, repair, and refurbishment, some platform areas may be partially closed, further constraining the available space for passengers.

This research examines how North American heavy rail transit operators analyze and design for passenger crowding at below-grade rail transit stations in light of recent research and current best practices on analyzing and predicting passenger flows. More specifically, the objectives of this report are: 1) to understand the particular infrastructural, operational, behavioral, and spatial factors that affect and may constrain passenger flows in different types of underground rail transit stations; 2) to identify, compare, and evaluate practices for efficient, expedient, and safe passenger flows in different types of station environments and during typical (rush hour) and atypical (evacuations, station maintenance/ refurbishment) situations; and 3) to compile short-, medium-, and long-term recommendations for optimizing passenger flows in different station environments.

While many of the passenger queuing and flow issues in underground heavy rail transit stations are also found in other types of stations serving other transit modes (underground bus and light rail stations, surface-level and elevated stations, and commuter rail stations, for example), the scope of this study was limited to underground heavy rail stations.

RESEARCH METHODOLOGY

The authors began the research by examining scholarly literature as well as manuals, standards, and codes on the management and analysis of pedestrian flows, with a particular emphasis on passenger flows in rail transit stations.

This was followed by in-depth, semi-structured interviews with 16 experts in transit station design, including architects, engineers, and transit planners. (For a list of interviewees, see Appendix A. For the interview instrument, see Appendix B.) Experts were identified based on referrals from transportation professionals. The experts included private consultants and transit agency staff, and many had worked in both contexts. Interviews were conducted between November 12, 2013 and January 7, 2014 by telephone, and they were recorded and transcribed. In one instance, the expert was not available for a phone interview and answered the interview questions by email. After compiling the interview transcripts, the authors carefully reviewed them to identify recurring themes, issues, and considerations in transit station planning for pedestrians.

Based on the themes identified through the expert interviews, an online survey was prepared and administered to planners, designers, engineers, and managers of all 16 transit agencies in the United States and Canada that have underground heavy rail transit stations. (For a list of the responding transit agencies, see Appendix C.) The authors

contacted representatives from each transit agency by email to invite them to complete the survey. If a person initially contacted by the authors did not believe that he or she was the appropriate person to complete the survey, he or she was asked to identify a more appropriate individual within the organization. In the event of non-response, a follow-up telephone call asked the initial contacts to complete the survey or to identify another person within their agency who was well suited to complete it. In most cases, one respondent from each agency completed the survey. At two agencies, New York City Metropolitan Transportation Authority (NYCTA) and Bay Area Rapid Transit District (BART), two people from each agency completed the survey. While 18 respondents is a relatively small sample size for a survey, it is something of a census because every transit operator in the United States and Canada with heavy rail transit stations was represented in the survey. The survey included questions on specific strategies and methodologies that the agencies have employed or considered in order to manage passenger congestion within rail transit stations, as well as the respondents' personal opinions on whether these strategies and methodologies are effective. The survey also asked respondents whether particular tasks related to planning, managing, and designing for passenger flows were done primarily by in-house staff or by outside consultants. The survey instrument is shown in Appendix D.

REPORT ORGANIZATION

This report is organized by topic rather than by research task. Thus, the insights gained from the literature review, the semi-structured interviews, and the results of the online survey are presented throughout the report, based on the topics they address.

The first section of the report (after this introductory section) presents relevant background on the *who*, *why*, and *what* of analyzing and designing for passenger flows in underground rail transit stations. Specifically, *who* within (or outside) a transit agency is responsible for addressing the needs of passengers and pedestrians, and how are these responsibilities shared among departments within an agency, as well as with outside consultants? *Why* do agencies plan for passenger flows, and how do the motivations of passenger safety, passenger comfort, and system efficiency relate to one another? Finally, *what* types of pedestrian flows do transit agencies primarily consider, whether they occur in rare but dangerous emergency evacuations or in day-to-day commuting?

The next three sections of the report address the question of *how* transit operators accommodate passenger flows, each at a different stage of the planning and design process. First, the report discusses data collection and forecasting. Second, it discusses passenger flow analysis, including a history of some of the earliest methods of analyzing passenger flows (many of which are still in use today), as well as a discussion of more sophisticated tools that utilize modern computing technology. Third, the report discusses particular design strategies that agencies have used to manage passenger congestion in each part of an underground rail transit station.

The final section of the report summarizes a number of recommendations that transit planners, designers, and operators can implement in the short, medium, and long term. These include recommendations on policy and operations as well as on transit station design and physical station retrofits.

II. AGENCY PLANNING FOR PASSENGER FLOWS

Before addressing *how* transit operators design stations to accommodate passenger flows, it may be helpful to place these activities in context by addressing the *who*, *why*, and *what*. Specifically, *who* within (or working for) an agency is responsible for addressing the needs of passengers and pedestrians as they are moving through the station, waiting for, boarding or alighting a train; and how are these responsibilities shared among departments within an agency, as well as with outside consultants? *Why* do agencies plan for passenger flows, and how do the motivations of passenger safety, passenger comfort, and system efficiency relate to one another? Finally, *what* types of pedestrian flows do transit agencies primarily consider, and do they focus mostly on rare but dangerous emergency evacuations or on day-to-day commuting? The following sections address each of these questions in turn.

WHO PLANS FOR PASSENGER FLOWS?

Different departments within an agency may handle different aspects of the passenger experience. Responsibility for the passenger experience may vary at each stage of a transit station project, from conceptual design to operations and maintenance. At each of these stages, specialized knowledge of various types of analysis, standards, design considerations, and safety procedures is required. One consultant interviewed for this study noted that for large stations in particular, an agency might hire multiple consulting firms, each with expertise in a particular area, such as analysis, operations, or design.

> "I would say that there's probably a combination in multiple examples where the station is of any significant size or complexity, where we tend to see a combination of an architecture-oriented type of firm that really understands space planning and three-dimensional design and the associated structural and design side of that conversation. We typically tend to see coupled with that a civil engineering firm or multi-disciplinary engineering firm or any combination of specialty traffic engineering/transportation planning firms involved."[12]

Compartmentalization of specialized knowledge, whether within a transit agency, between in-house agency staff and outside consultants, or among consultants, might lead to sub-optimal station design or operations if there is insufficient communication among those conducting the analysis, those making operational and policy decisions, and those making design decisions. The survey results may offer some indication of the degree to which this compartmentalization may occur.

Division of Labor Within an Agency

Because the survey responses were anonymous, the researchers cannot identify the transit agency department within which each respondent works. However, the survey did ask respondents to identify their own roles in planning and designing for pedestrians, grouped into two categories: analysis and design. Respondents could select all applicable roles from a list of the following five:[13]

- Analysis
  - Conducting analysis such as passenger volume forecasts and level-of-service analysis
  - Managing analysis by others
  - Interpreting analysis as a basis for capital investment and operations decisions
- Design
  - Designing station areas to serve passengers, and
  - Managing design work by others

As Table 1 shows, over two-thirds of the survey respondents (13 out of 18) play two or more of the roles identified above. Of the five who identified only one role, two manage design work, one manages analysis work, one interprets analysis as a basis for capital investment and operations decisions, and one conducts analysis. Table 2 shows which of the five identified roles are most commonly played by the same survey respondent. The values along the diagonal (shown in bold) represent the total number of respondents who play a given role.[14] Roles were not paired in the survey question; pairs of roles in Table 2 indicate that the survey respondent selected multiple roles.

Table 1. Number of Roles Played by Survey Respondents

Number of roles played by the respondent	Number of survey respondents
1	5
2	2
3	6
4	5
5	0
Total	18

Source: Authors' Survey.

Table 2. Matrix Indicating Roles Fulfilled by the Same Survey Respondent

	Conducting analysis	Managing analysis	Interpreting analysis	Designing	Managing design
Conducting analysis	**6**	2	5	4	2
Managing analysis		**10**	6	5	7
Interpreting analysis			**11**	6	6
Designing				8	4
Managing design					11

Source: Authors' Survey.

Of the 11 survey respondents responsible for managing design work, seven (representing nearly two-thirds) also manage analysis work. Half of the survey respondents with design responsibilities also have analysis responsibilities. The average respondent had between two and three roles, and five of the 18 respondents reported having four roles. These results suggest that agency staff manage as well as conduct analysis and/or design work. A sample size of 18 agency employees cannot provide strong support for a claim about the degree to which these types of tasks that support pedestrian movement are compartmentalized among specialized departments. However, these results do suggest some degree of coordination among analysts, designers, and other decision-makers (i.e., those whose role is to interpret analysis as a basis for capital investment and/or operations decisions) because, in many cases, the same individual plays these roles. Based on statements from the expert interviews, however, there may be opportunities for improvement in the coordination among designers or planners, construction departments, and safety departments.

In an interview, a transit planner at one agency explained the danger that provisions intended to improve the pedestrian experience can be lost as a project is handed from one department to another.

> "So, if you don't lock provisions in, like in mitigations in an environmental review process, often there is a disconnect when a project is moved into being managed by construction departments of transit agencies. Those people or managers don't necessarily understand how the connectivity would exist and how to support good potential development through what they design and construct."[15]

When asked about planning for emergency evacuation, the same staff member noted that a separate department of the agency handled those considerations.

> "That's something that I'm not as well versed in. But I think that's managed by our corporate safety department, and we have a fire wise safety committee. They always look to adhering to standards."[16]

A consultant who works on transit station design also addressed the compartment-alizing between planning for day-to-day use by transit planners and planning for emergency evacuations by transit police departments.

> "The agency has all of that [emergency evacuation procedures] worked out through their own police department. The consultants typically would not manage or direct that kind of activity. Of course, it's always in the back of our mind in the design standpoint, but that question is one I can't answer because the agency is the one handling it."[17]

Division of Labor Between Agency Staff and Consultants

In addition to the division of labor among staff with particular specializations, there is also a division of labor between in-house staff and outside consultants. For each of four tasks (data collection, passenger forecasting, passenger flow analysis, and design), the survey asked respondents to identify the degree to which the work was done by in-house agency

staff or contracted out to consultants, based on a five-point scale. Their responses are summarized in Table 3. For instances in which there was more than one response from the same agency, those responses were averaged.

Based on the survey responses shown in Table 3, agencies are most likely to collect their own passenger volume data rather than outsourcing data collection to consultants. Twelve out of the 16 operators reported that in-house staff does all or most of such data collection. Analysis tasks such as volume forecasting and level of service analysis appear more likely to be contracted to outside consultants, but they still are most commonly done in-house. Design work appears to be slightly more likely to be done by consultants than by in-house staff.

Table 3. Division of Labor Between Consultants and Agency Staff

	All work done in-house	Most work done in-house, some by consultants	Evenly split between in-house staff and consultants	Most work done by consultants, some in-house	All work done by consultants	Total
Collecting data on existing passenger volumes and passenger crowding	8	4	1	2	1	**16**
Forecasting future passenger volumes	5	4	4	2	1	**16**
Analyzing existing or future passenger levels of service, queuing, or flows	7	2	4	2	1	**16**
Designing passenger-serving station areas	4	1	3	8	0	**16**

Source: Authors' Survey.

A number of interviewees mentioned that agency staff generally collect and maintain data on pedestrian volumes, and that they are more likely to hire outside consultants to use that data for pedestrian circulation analysis. As a staff member at a large agency explained:

> "We have a group that's focused specifically on ped flows and station operations, … specifically looking at those ped flows. That doesn't mean that they do it by themselves here. But the large majority of the data is definitely fed by them. … More than likely, the consultant is just going to believe the data that those people have created and that's that. They have no reason to challenge it. And I would say that for a couple reasons. One, obviously, you want to keep your client happy, so why would you challenge your client? … The second reason is, you get paid typically these lump-sum fees. And if the data is being provided by your client, you're not looking to add extra work at no fee. So a huge percentage of the data, we're handling it ourselves."[18]

A consultant working with a different large transit agency described a similar division of labor between agency staff and outside consultants.

> "It's a joint effort. …. I believe a lot of that had to do with the fact that [the agency] maintains the ridership numbers, but the consultant understood the lines that were being evaluated and the movement of people in a more microscopic way than [the agency] would."[19]

Another consultant explained that he had observed this dynamic – in which the agency provides data and the consultant conducts the analysis – at a number of different agencies.

> "They know what their projections are in terms of future ridership. So a lot of that information they'll provide or develop. … They can provide their rail rider numbers as well as their projections for growth. But a lot of the planning analysis, usually consultants are involved with."[20]

A third consultant echoed the same:

> "So typically, the agency planning groups have passenger flow counts for the particular lines, and then they get ridership data for each station, depending upon the forecast you are dealing for the station design, whether it's designing out 2020, 2030, or beyond. And then we work with them to model various scenarios, and the scenarios are often dependent upon what happens at some of the other stations in their system, and we can model that pretty accurately with passenger simulation modeling to give them some examples, area plans, plans themselves, based on that data."[21]

A fourth consultant described how his firm conducted analysis based on some of their own field observations, together with more comprehensive data collected and provided by their client transit agency.

> "In these efforts, we've been using a pedestrian model to look at pedestrian flows and basically pairing our own field observations with [the agency's] data. They can collect information anytime someone enters or exits a station, so in an aggregate that can show when the highest demand is at the station and where people are going. And then this can all be fed into a model that can be used to have a better picture of where people are going and where the pedestrian issues might be, and any other things that might be of interest."[22]

In general, the consultants interviewed appeared to believe that the division of labor, in which agencies collect data and then hire consultants to do the analysis, was more clear-cut than is suggested by the survey responses summarized in Table 3. One consultant noted that his impressions were likely biased because he had a better awareness of the work that was done by consulting firms than of the work that agencies do in-house.

> "Being on the consultant side, I probably see more of the work that comes to the consultant side. But I'm sure agencies do some analyses in-house as well."[23]

A staff member at a large agency also expressed her view that the division of labor between agencies and consultants may vary considerably from agency to agency, which is consistent with the findings from the survey.

> "You know, we have [a large number of] architects and engineers that work here. This makes us a very large AEC [architecture, engineering, and construction] company. Which I think in general is unusual, if you compare us to other transit systems. … They [other agencies] pretty much farm the large majority of their work out to consultants, whereas we have this tradition of doing things internally."[24]

In any discussion of current state-of-practice or recommended approaches to accommodating pedestrian flows at transit stations, it is important to recognize that these approaches are implemented by a network of specialists both within and from outside transit agencies. The ways in which tasks are divided among specialists may have important implications for the solutions that are ultimately implemented.

WHY PLAN FOR PASSENGER FLOWS?

The motivations behind planning and designing for passenger flows may also influence the approaches that planners and designers take to these tasks. In general, planning and design for pedestrian flows at transit stations most often takes place in connection with the design of new stations or the retrofit of old ones. Agencies may undertake station retrofits for a number of reasons, so the survey asked respondents to indicate the criteria typically used to determine the need for a station retrofit by selecting as many options as applicable from the following: passenger surveys; passenger complaints; passenger incident analysis; current or forecast passenger volumes; technical studies (including modeling and level-of-service analysis); and station centrality (e.g., key transfer stations).

The first three criteria are generally reactive in the sense that an agency determines the need for a retrofit as a reaction to past and existing problems. This is particularly true of passenger complaints and passenger incident analyses. The final three of the above criteria are more proactive in that the agency determines the need for a retrofit in anticipation of future problems.[25]

Table 4 indicates which criteria are most commonly considered, as well as which pairs of criteria are commonly used by the same agency. As in Table 2, criteria were not paired in the survey question; pairs of criteria in Table 4 indicate that the survey respondent selected multiple criteria. The values along the diagonal (shown in bold) represent the total number of agencies that use a given criterion to determine the need for a retrofit.[26]

Interestingly, as shown in Table 4, agencies seem to use proactive criteria such as station centrality, passenger forecasts, and other technical studies to a greater extent than reactive criteria such as passenger complaints and incident analyses. This suggests that planning and designing for pedestrians at rail transit stations are primarily aimed at preventing anticipated problems rather than solving existing ones.

Table 4. Pairs of Criteria for Station Retrofits Used by the Same Agency

	Passenger surveys	Passenger complaints	Passenger incident analysis	Current or forecast passenger volumes	Technical studies	Station centrality	Age and state of good repair	Accessibility for people with disabilities	Political considerations
Passenger surveys	**7**	5	3	7	7	5	3	0	0
Passenger complaints		**8**	4	6	6	5	1	0	1
Passenger incident analysis			**5**	5	4	4	1	0	0
Current or forecast passenger volumes				**11**	9	9	2	0	0
Technical studies					**11**	6	1	0	0
Station centrality						**11**	1	1	1
Age and state of good repair							**3**	0	0
Accessibility for people with disabilities								**1**	0
Political considerations									1

Source: Authors' Survey.

Table 5. Primary and Secondary Motivations for Recent Station Retrofits

		Additional *secondary* motivations and/or recognized benefits							
Primary motivation	**Total**	**Funding availability**	**Compliance with NFPA 130 or fire code requirements**	**Compliance with ADA requirements**	**Compliance with other standards and codes**	**Passenger congestion**	**Response to a particular incident**	**Litigation**	**Other structural condition**
Funding availability	**6**	NA	*2*	*4*	*2*	*2*	*1*	*1*	*0*
Compliance with NFPA 130 or fire code requirements	**3**	*3*	NA	*2*	2	2	2	1	0
Compliance with ADA requirements	**6**	*6*	*4*	NA	*5*	*3*	*3*	*2*	*0*
Compliance with other standards and codes	**2**	*2*	*1*	*2*	NA	*0*	*1*	*0*	*0*
Passenger congestion	**4**	*4*	*4*	*2*	*2*	NA	*2*	*0*	*0*
Response to a particular incident	**1**	*1*	*1*	*1*	*1*	*0*	NA	*1*	*0*
Litigation	**2**	*2*	*2*	*2*	*2*	*1*	*2*	NA	*0*
Structural condition	**1**	*0*	*0*	*1*	*0*	*0*	*0*	*0*	NA

Source: Authors' Survey.

Improvements to a transit station often serve multiple purposes, and in addition may provide other benefits that may not have motivated the improvement but are nonetheless recognized by agencies as positive outcomes. Respondents were asked to think about the most recent station retrofit in which they had been personally involved (Chapter V discusses in which station areas these retrofits took place) and to identify for each of seven possible motivations whether it was a primary motivation, a secondary motivation, or a recognized benefit that was not a motivation.[27] The seven motivations respondents were asked to consider were:

1. Funding availability

2. Compliance with NFPA[28] 130 or fire code requirements

3. Compliance with ADA[29] requirements

4. Compliance with other standards and codes

5. Passenger congestion

6. Response to a particular incident

7. Litigation

Table 5 summarizes the number of projects for which each motivation was identified by respondents as a primary motivation, and which benefits (including additional primary motivations, secondary motivations, and recognized benefits that were not motivations) most commonly accompany each primary motivation.

As Table 5 shows, the most common primary motivations for station retrofits are funding availability and compliance with the requirements of the Americans with Disabilities Act (ADA). The least common primary motivation was response to a particular incident, once again highlighting the priority agencies appear to place on preventing problems before they arise rather than reacting to incidents. However, non-compliance with current standards and codes can be an ongoing problem, particularly at older agencies with stations constructed prior to the establishment of the current standards.

The same factor might be seen as a primary motivation for one operator's retrofit but as a collateral benefit for another operator's retrofit. ADA compliance is an example of this. Of the six station retrofit projects that were motivated primarily by funding availability, four offered the additional benefit of bringing station elements into compliance with the ADA. For the six projects that were motivated primarily by compliance with the ADA, the most common additional benefits and motivations were funding availability and compliance with other standards and codes, including fire codes and guidelines by the National Fire Protection Association (NFPA). This emphasis on code compliance over criteria such as passenger congestion does not necessarily mean that day-to-day passenger comfort is neglected. Rather, the standards and guidelines created by ADA and the NFPA require designers to plan for extraordinary conditions, such as emergency evacuations or passengers with

severe disabilities. When the requirements for these extraordinary conditions are met, the requirements for typical conditions are often exceeded.

WHAT TYPES OF FLOWS DO AGENCIES CONSIDER?

Designers must account for many types of pedestrian flows when sizing, designing, or updating an underground transit platform. These include peak commuter conditions, evacuations, special events, and off-peak conditions that occur late at night or early in the morning. While the primary factor differentiating these conditions is passenger density, other important differences, such as passenger attitudes and route familiarity, also inform the design. Ideally, a station will meet the needs of passengers in each of these contexts.

Peak Commuter Conditions

Typical peak period passenger volumes at subway stations tend to occur at the beginning and end of each workday (weekdays from 6 a.m. to 9 a.m. and from 4 p.m. to 7 p.m.), when regular commuters dominate ridership during these periods. Peak period passengers often share certain characteristics:

1. They use the same stations to reach the same destinations day after day, and are thus highly familiar with their habitual routes. As a result, they may not pay attention to wayfinding signs and instructions, relying instead on experience, including precisely where to stand on the platforms while waiting for trains.

2. They appreciate the opportunity that transit offers them to multi-task during their commutes. Thus, they may be distracted from their surroundings because of their attention to reading materials or mobile devices.

3. Particularly during the morning peak, commuters in destination stations frequently move with more urgency in order to arrive at work on time.

4. Over time, they have formed expectations of typical commuting conditions and thus may be willing to tolerate a greater degree of crowding than occasional transit riders, if such crowding is typical. However, these same commuters may also experience more frustration with service delays or other disruptions than occasional riders experience.

One senior staff member at a large agency explained how planners and designers who are not frequent or long-time users of the transit system may over-estimate the needs of daily commuters, who in many cases represent the majority of transit patrons. Discussing an application that a group of students had developed to assist in wayfinding, she said:

> “I suspect that tourists would probably find that of interest, and it would most certainly impact their decisions, but the truth of the matter is … there are two types of commuters: There’s the type that they want to be where they want to be, and they don’t care if it’s jammed. And then there’s the commuter that knows that that’s where he really wants to be, but he’ll be damned to be a sardine, and so he’ll just go to the other end. Just so that

> he can breathe. So you know, the commuters most certainly know exactly where they need to be and either, they train themselves, or they decide to deal with it or not. So I don't know if the millions of people would really care about an app like that. And it was funny because the people that are coming up with this, these are students who are new to [the area], they came from wherever they came from, and so from their perspective, it was … a really brilliant thing."[30]

Evacuations

One senior staff member at a large transit agency described how increasing focus on terrorist-related emergencies not only increases the focus on the need to efficiently evacuate stations but, paradoxically, also leads to the creation of security-related barriers that may actually impede efficient movement in and out of the station.

> "Before, certain things were open, but now because of certain concerns for someone carrying a bag or a bomb, you've closed it up, which means you've constricted people. So any of the other social or political problems begin to change things."[31]

Any change to a station, including those intended to increase safety, can lead to unsafe situations if they impede the ability of passengers to quickly exit the station in the event of an emergency.

Station evacuations are extremely rare occurrences, and thus they have minimal impact on passengers' typical experience with transit. However, while failure to design for other types of pedestrian flows may result in passenger discomfort, confusion, or frustration, failure to adequately design for evacuations can result in serious injuries and deaths if crowds begin to panic. Helbing, Keltsch, and Vicsek list 63 major crowd disasters that have been documented over the past 150 years in which deaths and injuries resulted from crushing and trampling in panicked crowds.[32] The majority of these disasters occurred in entertainment venues such as stadiums and theaters.

The few documented cases of crowd disasters in subway stations have generally been associated with people rushing to enter the station (to seek shelter from weather or air raids, for example) rather than with emergency evacuations. This may be because most rail transit stations are well designed to accommodate evacuations, and/or because such evacuations are exceedingly rare. In a survey of rail passengers in Southern China, a majority claimed that they would behave calmly and follow instructions in case of an emergency,[33] though this finding is a better indication of how passengers believe they should behave than of how they would actually behave. Given the rarity of actual evacuation events at transit stations, empirical studies of passenger behavior under evacuation conditions are rare.[34] However, in a survey of the literature on crowd panic, Helbing, Keltsch, and Vicsek identify nine typical features of panicked crowds:[35]

1. Individuals become nervous and develop blind actionism;

2. People try to move faster than normal;

3. People engage in physical interactions such as pushing;

4. Crowd movement becomes uncoordinated, particularly at bottlenecks;

5. Exits become jammed;

6. Physical interactions can result in dangerously high pressures that can bend steel barriers and tear down brick walls;

7. Fallen and injured people become obstacles that impede escape;

8. People exhibit herding behavior, doing what the people around them are doing; and

9. People fail to notice alternative exits or fail to use them efficiently.

The National Fire Protection Association (NFPA) has created a model design standard for fixed-guideway transit and passenger rail systems, called NFPA 130, which includes requirements for transit station areas and platforms. Some jurisdictions have incorporated NFPA 130 into their local ordinances. Even in areas where it does not have the force of law, NFPA typically is a guide for the design of new transit stations.[36]

NFPA 130 requires station area designers to make conservative assumptions to determine the conditions under which people may need to be evacuated from a transit platform in the event of an emergency. The design evacuation event takes place during the peak 15 minutes of service, with trains in both directions running one headway behind schedule. Thus, each train would be carrying twice its normal load (but no more than a full load), and twice as many passengers would be waiting on the platform. Furthermore, designers are to assume one escalator would be out of service and unavailable, if they intend for passengers to use escalators to evacuate the platform. The remaining escalators are expected to provide no more than half the egress capacity from the platform.[37]

In many cases, NFPA requirements for the number and width of stairways and the maximum allowable distance from the most remote point on a platform to the nearest stairway or escalator are the controlling factors for determining the required platform size. The resulting required platform areas are typically more than adequate for maintaining pedestrian flow rates and providing passenger comfort under typical operating conditions.[38]

Special Events

Special events such as major concerts and sporting events can be an ideal opportunity to introduce new riders to public transit because traffic and parking congestion are often so onerous at these events that passengers are more open to trying unfamiliar alternative modes of transportation that may allow them to avoid these problems. Rail transit is particularly suited to serve heavy temporal, directional, and spatial peaking, which characterizes special events. However, the unusually high passenger volumes often associated with these events can result in highly unstable crowd conditions. Boisterous sports fans may be less likely to

follow or be aware of safety procedures and instructions, making the likelihood of a crowd disaster as described above an even greater threat. While most documented crowd disasters have occurred in stadiums and theaters,[39,40] when those same crowds exit the stadium and enter a transit platform, their behavior may be similarly volatile.

Design volumes for evacuations are often based on passenger volumes during the peak 15 minutes of a typical weekday. However, for stations that serve large stadiums and arenas, peak special event volumes should be considered as well, even when such volumes occur only a few times each year (as at many college and professional football stadiums).

As noted above, many passengers taking rail transit to special events may be first-time or occasional transit riders, meaning they are less familiar with station layouts, as well as with procedures for paying fares and boarding trains. Extra staff and/or signage are often necessary to assist such novice passengers to expedite crowd movements through stations.

Off-peak Conditions

In off-peak hours, particularly at night, the dangers associated with crowds become much less important than the dangers and perceived dangers associated with the lack of crowds: unmonitored spaces and the potential for crime. In a survey of transit passengers in Los Angeles, Iseki and Taylor found that transit riders tend to value a feeling of safety at night more highly than most other characteristics of the transit experience, such as convenience and reliability.[41] Women in particular are likely to feel less safe on empty train cars and platforms where there is no transit staff, regardless of the presence of security cameras and other automated surveillance systems.[42]

Elements that are intended to channel crowds and provide wayfinding, such as barrier walls, information signs, and stairways, may also obstruct the line of sight for passengers, security personnel, or cameras, making it more difficult to adequately surveil the entire platform and establishing places for potential assailants to hide. Fear of assault can be a significant source of passenger discomfort and a deterrent to transit use, regardless of whether the danger associated with such unobserved spaces is real or perceived.[43] While passengers' feelings of safety in unmonitored spaces are not directly related to the efficient movement of passenger flows, they are important to the passenger experience. Station improvements that increase sightlines and visibility, together with passenger flows, are thus preferred to those that may improve passenger flows at the expense of sightlines and visibility.

The discussion in this section of *who* plans for pedestrian flows, *why* pedestrian flows are considered, and *what* types of pedestrian flows are of interest provides helpful context to the next sections that discuss *how* transit planners and designers address pedestrian needs.

III. DATA COLLECTION AND FORECASTING

Designing for passenger flows requires data on three types of passenger peaking: directional, spatial, and temporal. Directional peaking refers to the degree to which passengers flow in one direction. One consultant interviewed described how a station with strong directional peaking operates more smoothly than it would if the directional flows were more balanced.

> "Part of the reason that the vertical circulation elements work okay is that the flows tend to be directional: inbound in the morning and outbound in the evening. And so you might have people walking up the stairs two abreast and one line walking down the stairs, and the width affords that. If those flows were more bidirectional, the degree of congestion starts to add up, and that makes a difference."[44]

Another type of peaking to be understood and managed is spatial peaking across stations within a system. Another consultant mentioned how some special events may be equally well-served by two different rail stations on the same line, and that passenger congestion could be managed by encouraging special event patrons to utilize both stations rather than only one.

> "I'm thinking about game-day kind of things and encouraging people to use two stations instead of one. So I think if all passengers were messaged to use the same station, you create undue loads on the load point, and you have pedestrian flow issues. But if you have two stations and you message your ticket materials, and on game day you have signage that says you can go to either of these locations and board, you have some ability to manage that flow, where you have multiple portals available."[45]

Spatial peaking may also occur inside a station. A designer may create multiple pathways through a station, but the additional capacity may not be utilized if passengers are not aware of them, or if they choose to ignore some pathways for other reasons. The same consultant related his experience as a transit passenger when he discovered that there were two paths through a station, one of which was much more congested than the other.

> "When I first started making the transfer, I went with the herd and turned right, and turned right again, and went down the stairs down to the [other] line. What I found over time was that it's really not markedly different to go to the other end of the portal and go down to the red line, but there was a lot less congestion in terms of pedestrian flow. Right now there's no real signage or wayfinding that says you can go either way here."[46]

Table 6. Level of Crowding Reported by Station Area

	Substantial crowding	Some crowding	Not much crowding	No crowding / don't know / no response	Total
Ticketing areas	5	6	5	0	16
Entrances and exits to paid areas	5	5	3	3	16
Vertical circulation elements	5	9	0	2	16
Station platforms	6	8	1	1	16

Source: Authors' Survey.

Table 6 shows that survey respondents were more likely to report substantial crowding on station platforms than in other areas of the station. In some cases, a platform may have adequate space to accommodate all the passengers who use it, but passengers may still experience congestion because they do not spread out across the entire length of the platform, sometimes because of passengers' "preboarding," based on knowledge of where the train doors will open once the train stops and even what part of the destination station passengers wish to exit into. One consultant described this practice:

> "One term that we tend to use is 'pre-boarding,' where if you're in a ten-car train and you know where you're getting off the train should be towards the front of the train, you can walk to the front so that when you get out you are close to the exit that's near your destination. So people can position themselves better and spread themselves out over the platform knowing that at the destination station, these train doors will be closer to their exit. 'If I get myself in the right spot, I'll be close to my exit at the destination station and ready to go when the train arrives.'"[47]

The same interviewee explained how changes to the design of the platform might not be effective in dispersing pedestrians along the platform length if the land uses surrounding the station are such that most passengers are coming from and going to one end of the station or the other.

> "You can design a station so that you have sufficient vertical circulation, stairs, and escalators to the platform, but it might be that the way the station is aligned or located, that everyone wants to go to the north end of the station because that's where their office is. They don't want to exit to the south end of the station. So sometimes one of the things that really needs to be identified is people's travel patterns. You could have a well-designed station, and people are not using the station in a balanced, equal way. All people will remember is waiting in line, trying to get up a staircase closest to where they work or want to go shopping, and not using other stair elements. You don't want to create situations like that. You want to either accommodate knowing ahead of time that they have a preference for one end over the other and create more vertical circulation at that end. … If everyone wants to be at the same spot at the same time, you can't do that. You try the best you can to accommodate them for the direction of travel they prefer to go to."[48]

One consultant mentioned that strategic placement of vertical circulation elements, train stopping locations, or other amenities could potentially encourage passengers to use the available space on the platform more efficiently.

> "We should be thinking actively about the placement of elevators and escalators within a station and maybe varying the placement across a set of stations, and maybe even varying where the trains stop within stations. So this would allow a train to distribute the passengers throughout a [platform]. … If one train tended to collect all the passengers at one end of the [platform], then at the next station you might encourage the passenger flow where pedestrians might cluster in the front or the back of the train."[49]

Another interviewee mentioned that if vertical circulation elements load all passengers onto the same end of the platform, they are unlikely to use the entire platform length.

> "Both ends of the station are designed to have access, but typically as the stations have been built, only one side has actually opened. So a few of them could be expanded, but for the time being they are kind of loaded only on one end."[50]

In addition to directional and spatial peaking, planners must also be aware of temporal peaking. While all types of traffic flows – pedestrian, non-motorized, and motorized – tend to vary over the course of the day, the week, and the seasons, pedestrian volumes within transit stations may also display temporal variability over much shorter time scales, depending on train operations and arrival patterns. Stations with trains that run at very high frequencies require passengers to wait in the station for very short amounts of time, reducing the number of people on the platform at any particular moment. One consultant mentioned that one possible way to reduce platform congestion is to increase train frequencies.

> "Another [issue] is whether you're running more vehicles with smaller capacities or fewer vehicles with higher capacities. So imagine a four-car train every five minutes or every six minutes as opposed to a two-car train every three minutes. You have the ability to disperse some of those pedestrian flows, but the operating costs of the transit agency may be much higher in the more vehicles/more frequency example."[51]

In addition to train frequency, service reliability may also affect passenger flows and station design. When trains run infrequently but predictably, passengers may still have short waiting times (resulting in fewer pedestrians on the platform at one time) if they plan their travel so they arrive at the platform shortly before the train does. However, when train arrival times are unpredictable, perhaps because of delays associated with high passenger volumes at other stations in the system, passengers may arrive at random intervals, and larger queues accumulate occasionally. Likewise, when headways are shorter than about 12 minutes, passengers are much less likely to time their arrivals based on scheduled stops, and they tend to arrive at more or less random intervals.[52]

EXISTING AND FUTURE PASSENGER VOLUME DATA

In-house transit agency employees are more likely than outside consultants to collect data on existing passenger volumes. As shown in Table 7, half of those surveyed report that their agencies collect all passenger volume data in-house, and 13 out of 16 agencies undertake at least half the data collection work in-house. Table 7 also shows that transit agencies are more likely to contract out at least some passenger volume forecasting work to outside consultants than they are to contract out data collection on existing passenger

volumes. However, the proportion of agencies that do at least half their forecasting work in-house is the same as the proportion that do at least half their data collection in-house.

Table 7. Division of Labor Between Consultants and Agency Staff

	All work done in-house	Most work done in-house, some by consultants	Evenly split between in-house staff and consultants	Most work done by consultants, some in-house	All work done by consultants	Total
Collecting data on existing passenger volumes and passenger crowding	8	4	1	2	1	**16**
Forecasting future passenger volumes	5	4	4	2	1	**16**
Analyzing existing or future passenger levels of service, queuing, or flows	7	2	4	2	1	**16**
Designing passenger-serving station areas	4	1	3	8	0	**16**

Source: Authors' Survey.

The accuracy of passenger volume forecasts depends importantly, if not exclusively, on accuracy of the data on existing passenger volumes. In turn, the accuracy of analyses to determine design needs depends on the accuracy of passenger volume forecasts. This study did not address specific data collection methodologies. Given the importance of accurate data, the question of how agencies typically collect passenger volume data warrants further research. One agency staff member described how skepticism about the output of a forecasting model might have as much to do with uncertainty about the passenger volume inputs to the model as it does with the validity of the model itself.

> "I went to a meeting this morning where we were reviewing [microsimulation] models and, the bottom line is, the [microsimulation] model is only as good as the information that's being put in there. And you know, if the person with the data is saying that the data that he or she gave them is accurate, then they're standing firm on that. It's not about the model. The model is as subjective as the data of the actual person who's in there saying the data is accurate. And that's somewhat frustrating if you really need some sort of an objective analysis."[53]

A consultant described how ridership forecasts could be particularly challenging for new rail systems, as opposed to existing stations or new stations in existing systems. In these cases, an analyst must be particularly cautious about the assumptions used to generate the forecasts.

> "When you have a brand new system, clearly you have to have ridership forecasts. So LA has them. In that particular case, ridership forecasts are frighteningly large because high-speed rail is meant to be [a competitor to air travel]. Instead of going up in the air, you have this high-speed rail going from LA to San Francisco in no time flat. So the ridership forecasts in that case are very large. So you have to be careful when you do these

> things that you don't over-design, you don't say, 'OK, 20,000 people are going to get off this station per day,' when you know there's no parking there, for example."[54]

Inaccurate rail forecasts occasionally may be the result of deliberate misrepresentation. Some researchers have noted that rail projects seem to be particularly prone to intentionally optimistic ridership forecasts to justify project approval.[55,56] Flyvberg, Skamris, Holm, and Buhl conducted a survey including 27 rail projects from around the world that were completed between 1969 and 1998. Two-thirds of surveyed rail projects (representing about 18 projects) were based on forecasts that overestimated ridership by about two-thirds. Based on statements by project managers and researchers about the causes of inaccuracies in ridership forecasts, the authors estimated that inaccurate ridership forecasts for about one-quarter of surveyed rail projects (representing about seven projects) were attributable to unrealistic, optimistic forecasts. They noted that there is often pressure on analysts to inflate ridership projections and to underestimate costs in order for a politically desirable project to be approved even when the likely benefits of the project do not justify the costs.[57]

One consultant referred to the fact that inflated ridership forecasts may be used to justify a rail project and emphasized the importance of verifying all assumptions used for ridership forecasts before applying those forecasts to station design.

> "Sometimes ridership forecasts are high just to justify the pursuit of the project. … But I know when I see some numbers, and the numbers look high, I can tell that's going to be a problem before I run any analysis. So ridership forecasts have to be as exact as possible. And these guys, whatever formula or factor they use, I trust them, but when I see those that are really high, I say, 'Well, let's get into the numbers a little bit.' So it's important, it's important to do it right."[58]

The Flyvberg, Skamris, Holm, and Buhl study was based on comparisons between opening-year ridership forecasts and observed ridership in the opening year.[59] However, design decisions are typically not based on opening-year forecasts because rail infrastructure is generally expected to serve passengers for much longer time periods. One consultant explained that a 20-25 year horizon was generally typical, in part because that is the longest time period over which analysts can have reasonable confidence in their forecasting assumptions.

> "So generally 20 to 25 years out is the time frame we tend to be analyzing for because it's a reasonable time in terms of projecting ridership. When you count further than that, you don't really know what type of dynamics you have hitting an area or even people's travelling preferences at that time."[60]

Another consultant mentioned that many rail transit stations in older systems that are congested today were sized appropriately when they were first constructed over a century ago.

> "The original planning for a hundred years out, I think was very successful, but planning for the next hundred years is the challenge."[61]

In contrast to widespread concerns over inflated forecasts, one staff member at a large transit agency pointed out the particular danger of relying on ridership forecasts that are too low.

> "Any successful system fails because of [higher than anticipated ridership], which means it wasn't designed for this. So when we confront these large crowds, you say. "Why didn't we plan better?' We really didn't expect [to experience] one of the highest light-rail riderships in the nation."[62]

Although reliance on overly optimistic forecasts may result in over-built stations that are more costly to construct than necessary, reliance on low forecasts can result in under-designed stations that do not meet passenger needs. Compared with the financial and political costs of trying to expand a recently constructed station that has already exceeded its capacity, designing a station with excess pedestrian capacity may be the prudently risk-averse alternative in some cases. As one consultant described, current software allows designers to conduct sensitivity analyses to determine how inaccurate ridership projections may influence station design.

> "Ridership forecasting is prevalent now in these simulation packages. So before you could say, 'Well, there may be 20,000 riders at [a particular station].' And I'd say, "Fine. That's your number. Let's run some static spreadsheets.' But with the advent of simulations, I can take that further and test out the validity of such a ridership projection way before design goes into the advanced stages. So that's really the power of these software packages – the ability to look at a system well before it gets built so that it doesn't get over-designed."[63]

By using ranges of possible passenger volumes rather than point estimates, designers can balance the risk of possibly too-small stations against the additional costs of building in more capacity in an informed way.

DATA ON PASSENGER CHARACTERISTICS

Although data collection for a particular project is often limited to the number of passengers currently using or anticipated to use a transit station, a number of assumptions are built into subsequent analyses that occasionally should be verified by direct observation. One of these assumptions is the amount of space each pedestrian occupies. One agency staff member noted that her agency typically assumes that pedestrians are wider than the industry standard would suggest, and she joked that perhaps people in her city were, on average, just plain larger than in other places.

> "We know a ped width is, you know, whatever it is. We say 28 to 36 inches, which is more, probably, than what FTA calls for it to be. But you know – people are fat in [this city]. I don't know."[64]

A consultant mentioned that assuming that pedestrians occupy more space could have as much to do with the things they could be carrying as it does with the actual dimensions of their bodies.

> "People are bigger or they're carrying more stuff. How many people do you see carrying a backpack now? I'm saying the footprint of people is getting bigger. I'm not saying they're fatter. I'm just saying they just seem to be carrying more. Or those bags with wheels, or where now I'm seeing a lot of people in commuting situations with strollers. Some have work, and they have to take their kids to daycare before they go to work. Backpacks, rolling bags – they have changed the size of a person to something more difficult to deal with."[65]

In addition to the amount of space pedestrians occupy (whether as a result of their physical dimensions or of the loads they might be carrying), pedestrians might also vary with respect to the amount of distance they wish to maintain from other pedestrians. One consultant noted that this could vary from culture to culture.

> "I think, in terms of the basics of what pedestrian density acceptance levels are, walking speeds, and flow, they're for the most part set, and they vary slightly between nationalities. So maybe in the US, they want more spacing between travelers, while other countries' travelers may be able to accept closer personal spacing."[66]

A study in Singapore by Tanaboriboon, Hwa, and Chor found that although free-flow walking speeds in Singapore appeared to be, on average, slower than those observed in previous studies of North American pedestrians, the maximum observed flow rate was higher. They suggest that this is a result of a greater Asian tolerance for higher pedestrian densities.[67] Later studies in Hong Kong and Bangkok yielded similar results.[68,69]

Walking speeds could also vary from culture to culture and across socio-demographic characteristics such as gender or age. Henderson and Lyons found that the average walking speed of women in Australia is slightly slower than that of men, and women are more likely than men to change their paths due to disturbances or outside influences such as vehicular traffic.[70]

In the study in Singapore by Tanaboriboon and colleagues, the authors found that secondary school children had similar free-flow walking speeds to those of adults, but that elderly pedestrians (where classification as elderly was based on subjective observation) had a free flow walking speed that was about 30% slower than that of younger adults.[71]

Pushkarev compiled and compared data from a number of prior studies to comment on differences in free-flow walking speeds and maximum pedestrian flow rates by trip purpose. He found that pedestrians walking in close military drill formation achieve the highest flow rates, followed by commuters, then shoppers, and then students.[72]

Passenger characteristics, such as system familiarity, size, tolerance for crowding, and average walking speeds, are less likely to change from year to year than passenger volumes. However, when the same assumptions regarding these passenger characteristics are used for multiple decades, prudence suggests that such assumptions be revisited from time to time to confirm that they are still valid for the local context.

Once transit agencies have collected or predicted the necessary data to describe the flow of passengers through a transit station, these data can be used as inputs into analyses to determine pedestrian needs, as will be discussed in the next section.

IV. ANALYSIS

Engineers have sought to apply quantitative analysis to understanding the needs of pedestrians at transit stations for more than a half-century. The deterministic models developed in the mid-twentieth century eventually led to the development of guidelines, standards, and codes that tended to standardize some aspects of transit station design. As modern computing allowed for more complex computations, stochastic microsimulation models were developed that allowed for more detailed analysis and visualization of pedestrian movement. In this section, we will discuss each of these three tools: deterministic models, established standards, and microsimulation models.

The chief civil engineer of the London Transport Executive requested one of the first empirical studies of pedestrian flows at transit stations in 1958, noting:

> "Our present rough and ready yardsticks for measuring the capacity of subways underground pedestrian passageways] and deciding widths are reasonably satisfactory but it might be desirable to have some additional work done so as to arrive at a more logically founded theory."[73]

In response, Hankin and Wright performed a series of experiments and observations to determine an empirical relationship among pedestrian speeds, densities, and flow rates. They arrived at three primary conclusions that laid the groundwork for deterministic models of pedestrian flows:[74]

1. The maximum pedestrian flow rate through a passage wider than about four feet (1.2 meters) is directly proportional to the width of the passage. For narrower passages, capacity increases only by multiples of pedestrian shoulder width. Obstructions such as center handrails reduce the effective width of a passage.

2. Movement on stairs is slower than movement through a level passageway, and movement up stairs is slower than movement down stairs. Thus, stairways are commonly bottlenecks in pedestrian circulation systems.

3. As a passageway becomes crowded, pedestrians slow down to avoid touching one another or stepping on the heels of the person in front of them. As a result, there is a maximum pedestrian flow rate beyond which the reduced speed from additional crowding reduces pedestrian throughput (while greatly increasing pedestrian discomfort).

From the first of Hankin and Wright's conclusions, one can derive two equations that govern passenger flow through passageways. Equation 1 describes pedestrian flow in terms of speed and density, while Equation 2 describes it in terms of speed and space, which is the reciprocal of density.

$$v = S \times D \qquad (1)$$

where v = pedestrian flow per foot width (p/ft/min),

S = walking speed (ft/min), and

D = pedestrian density (p/ft^2)

v = S/M (2)

where v = pedestrian flow per foot width (p/ft/min),

S = walking speed (ft/min), and

M = pedestrian space (ft^2/p).

These two equations imply that maximizing both walking speeds and pedestrian density would maximize pedestrian flows. However, the third of Hankin and Wright's conclusions shows that it is impossible to simultaneously maximize speed and density because increasing densities tend to decrease speeds. This relationship and the resulting relationship between pedestrian density and pedestrian flow rates are illustrated in Figure 2.

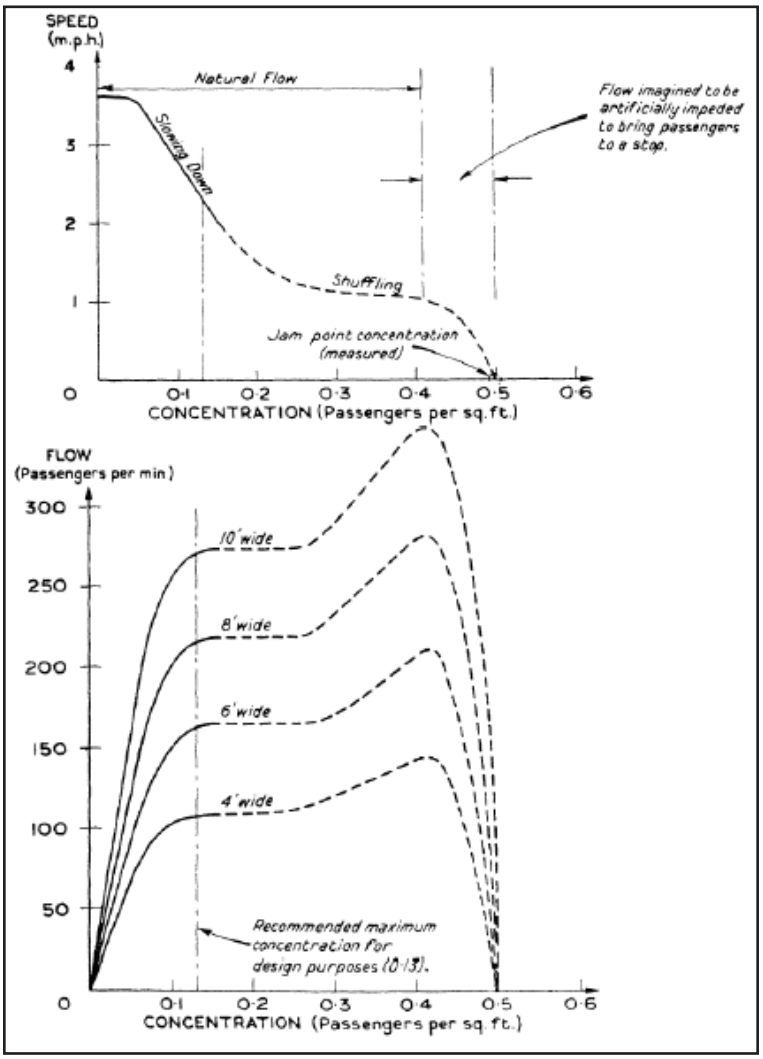

Figure 2. Speed-Density and Flow-Density Relationships

Source: Hankin and Wright, 1958.

In the half-century since Hankin and Wright's initial work on this topic, several other researchers have observed a similar relationship between pedestrian speeds and pedestrian density, although they each observed different maximum pedestrian densities, as summarized in a review and meta-analysis by Weidmann.[75] The most influential of these studies, in the United States at least, was conducted by John Fruin and incorporated into his highly cited manual, *Pedestrian Planning and Design*.[76]

The simple relationships described by Equations 1 and 2 and illustrated in Figure 1 can be applied to determine the appropriate widths of transit station elements such as passageways, doorways, stairways, and platforms. The second edition of the *Transit Capacity and Quality of Service Manual*, also referred to as *TCRP 100*, recommends such a design methodology, in which the designer may consider the station area as comprising distinct elements (as illustrated in Figure 3) and determine the appropriate sizes for each element, based on anticipaed passenger volumes.[77]

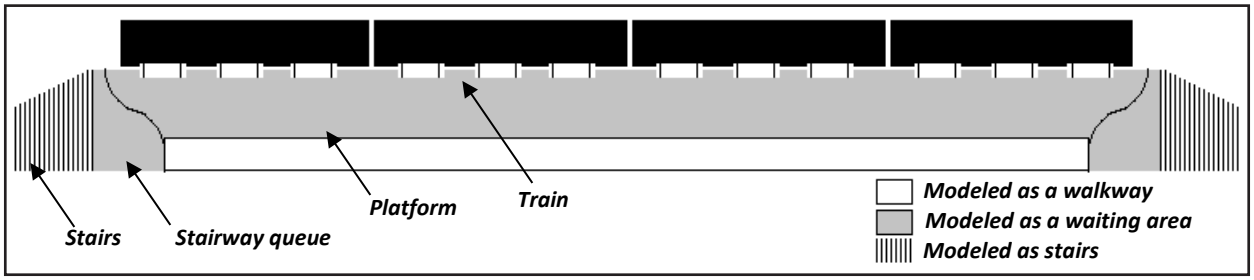

Figure 3. Elements of a Transit Platform Area for Deterministic Analysis (Based on Kittleson & Associates, Inc. et al. 2003) (Not To Scale)

The deterministic methodology described in TCRP 100 is relatively straightforward to implement – the analysis can be done using simple spreadsheet calculations – and adequately describes pedestrian flows in simple stations under non-congested conditions. However, its applicability to more complex and crowded conditions may be problematic.

Beginning in the late 1980s, researchers began to explore the application of increasingly powerful computing technology to simulate the movement of crowds of individual pedestrians without aggregating them into average flows.[78] As computers have become more powerful and widespread, microsimulation has become a more feasible way to evaluate pedestrian (and motor vehicle traffic) flows in complex environments and to understand crowd dynamics.

Over the past several decades, researchers have developed several models to simulate pedestrian movement at the microscopic (or individual pedestrian) level.[79,80,81,82] These models are the basis for commercially available pedestrian modeling software packages such as VISSIM[83] and Legion.[84]

STANDARDS AND CODES

While pedestrian flow analysis – whether deterministic and macroscopic, or stochastic and microscopic – can guide the design of transit stations, established standards and codes may play a more important role in station design because they often require designers to allow more space for pedestrians than would be required for anticipated passenger flows.[85] Two sets of standards particularly relevant to station design are the Americans with Disabilities Act (ADA)[86] and the *Standard for Fixed Guideway Transit Systems* published by the National Fire Protection Association, also referred to as *NFPA 130*.[87]

The ADA was passed by the United States Congress in 1990. It requires that public transit agencies design their systems in such a way that they can provide the same level of service to people with disabilities, including those using wheelchairs, that they provide to people without disabilities.

NFPA 130 contains guidelines for station designs that facilitate safe evacuation of transit stations in the event of an emergency. Some jurisdictions have incorporated *NFPA 130* into their local ordinances. Even in areas where it does not have the force of law, *NFPA* typically serves as a guide for designing new transit stations.[88]

As explained in the previous chapter, *NFPA 130* requires station area designers to make conservative assumptions to determine the conditions under which people may require evacuation from a transit platform in the event of an emergency. The design evacuation event takes place during the peak 15 minutes of service, with trains in both directions, each running one headway behind schedule. Thus, each train would be carrying twice its normal load (but no more than a full load), and twice as many passengers would be waiting on the platform. Furthermore, designers are to assume that one escalator would be out of service and unavailable, if they intend for passengers to use escalators to evacuate the platform. The remaining escalators are assumed to provide no more than half of the egress capacity from the platform.

In many cases, NFPA requirements for the number and width of stairways and the maximum allowable distance from the most remote point on a platform to the nearest stairway or escalator are the controlling factors for determining the required platform size. The resulting required platform areas are typically more than adequate for maintaining pedestrian flow rates and providing passenger comfort under typical conditions.[89]

But while sizing transit stations to meet the needs of disabled passengers and evacuations under peak conditions frequently determines platform and station size, such standards do not define maximums in all cases, nor do they define all aspects of platforms, queueing areas, and stairs. In such cases, other standards, rules of thumb, and deterministic and microsimulation models come into play. The researchers examined which of these tools and techniques apply in which situations.

The experts interviewed for this study frequently referred to the role of published standards as well as deterministic and microsimulation models as tools in the analysis of pedestrian flows at transit stations.

PUBLISHED STANDARDS

Both consultants and agency staff mentioned the conservative nature of existing standards and codes, noting that adherence to existing standards can render detailed analyses of pedestrian flows moot because the circulation spaces resulting from the standards are more than adequate for anticipated passenger volumes. As a staff member at one transit operator put it,

> "A lot of that kind of technical work is embedded in standards …. So as long as you follow the standards, typically you have enough entrance capacity to satisfy safety requirements associated with transit stations. So whether you have enough entrances and exits to satisfy the pedestrian flow and circulation space, those are typically handled through the standards we have in place."[90]

A consultant also explained that station design depends on many criteria other than passenger volumes, and that when these other criteria are met, the design will often be more than adequate to accommodate anticipated passenger volumes.

> "It depends on the level of passenger volumes, but there are typically many other factors that will govern the size and number of the facilities. For example, many transit agencies require a minimum of two escalators – one for each direction. However, they may require a third so capacity can be maintained when one is taken out of service for maintenance, which is a fairly regular occurrence. … You will often have more capacity than dictated strictly by passenger volumes, normal operations, and expected growth just by the fact of redundancy and maintenance requirements."[91]

This idea of standards serving a dual purpose – for example, that standards intended to allow smooth emergency evacuation also provide adequate circulation space for comfortable day-to-day passenger flows – is also reflected in the attitudes toward ADA standards. The same consultant said:

> "A lot of the things you do for ADA actually help all passengers or a large percentage of passengers such as those with bikes, luggage, or carriages."[92]

In discussing ways in which the practice of designing transit stations has changed over the years, several of the consultants interviewed referred to an increasing reliance on – and stringency of – standards and codes. One referred specifically to the increasing role of ADA standards.

> "ADA has changed the way we handle pedestrians over the last 20 years. So we're a lot more cognizant of pedestrian safety and needs of access than we were just 20 years ago."[93]

Another mentioned that emergency evacuation standards have become more stringent and received more emphasis since the threat of terrorism has become a greater concern in the US.

> "We've gotten more focused on emergency evacuation… The emergency evacuation and smoke/heat ventilations standards have gotten more stringent, especially since 9/11. So they are often dictating the capacity of vertical and corridor elements."[94]

A third consultant referred to the nearly universal adoption of NFPA 130 as a positive development that would improve station safety, although its requirements might be unnecessarily conservative in some cases.

> "NFPA 130 is being embraced as the guideline. I don't think just in this country … Systems all around the world are following these guidelines, which I think is good. A little bit over-designed, but people will be safe."[95]

On the other hand, some experts expressed concern that the generic, one-size-fits-all nature of some standards could fail to account for station-specific contexts.

> "Pretty much everyone follows the NFPA 130 standards, which deal with emergency evacuation for passenger stations and terminal facilities. The challenge is that NFPA establishes a standard, and they provide examples of how you apply it, but the examples are by their nature generic. You often have situations that are different or unique, which requires a rather sophisticated knowledge and experience in applying NFPA 130. … The standards for the most part examine the station from a two-dimensional floor plan basis and don't really take into account the volumetric or three-dimensional design of the station box. Smoke and heat will behave very differently along a platform that has a low ceiling, as opposed to a very open, higher-ceiling design. The time required for getting people safely out of a station area will vary depending on such design considerations."[96]

As discussed previously, adherence to standards such as ADA and NFPA 130 may have added benefits beyond the purposes those standards are intended to serve. However, they are written to serve particular purposes, and the adoption of standards to meet these goals may also result in the neglect of other goals. For example, one expert mentioned that the lack of a specific standard for passenger comfort might lead to neglect of this consideration or to confusion regarding how to address it through station design.

> "There tends to be a gap between the fire and life-safety egress standards that might tell you one thing about what the minimum design safety factor might be and at the other end of the spectrum for the comfortable and desirable walking and vertical circulation environment. I think there's still a fair bit of murkiness for what tools are appropriate – what level of analysis is needed."[97]

The same expert also explained that, in the absence of standards for passenger comfort, improvements in this area often come as a response to passenger complaints and users' perceptions.

> "If complaints about the degree of crowding or the degree of congestion are sufficient to warrant the change, it hasn't been a particular standard or level of service calculation that's been driving those decisions; it's been more about the users' perception of comfort and high-quality service that's driving more of those conversations."[98]

As a staff member at a transit agency succinctly put it:

> "The problem, technically speaking, is that when you've met the engineering requirements, you may not have met a quality human experience."[99]

DETERMINISTIC MODELS

Experts also discussed the use of deterministic analysis, which can be done using spreadsheets, and microsimulation analysis, which requires specialized software. Such models ensure that designs meet adopted standards and/or address design issues not accounted for in standards.

Some experts mentioned that the methodologies for much of the pedestrian flow analyses for transit stations have changed very little over the past decades. One referenced the continuing relevance of John Fruin's guidelines.[100]

> "Surprisingly, a lot of what we do right now with pedestrian flow, the basic theory is from John Fruin. His book is called *Pedestrian Planning and Design*. He was a New York City Port Authority employee. This book was published … in the 70s … and most of the findings and guidelines are still used today. … All his guidelines for level of service in pedestrian corridors, stairs, escalators, are still used as a basis."[101]

Another expert highlighted the importance of Fruin's work in influencing later research.

> "There's been a lot of research on this topic in the last 20 years. ... But the vast majority did start with Jack Fruin. And I'm sure your readers know that history – the level of service standards that are based on the highway standards. … That remains the primary basis for almost all the transit station planning since the mid-70s."[102]

One consultant argued that the deterministic methods he had used early in his career are still appropriate for many transit planning applications, despite being supplanted by more sophisticated tools.

> "Everything then was done by hand, which was fine. In fact, it is still fine, using spreadsheets to get through your work."[103]

A major advantage of spreadsheet models is their simplicity and cost-effectiveness compared with microsimulation models. While an agency may need to hire consultants to conduct microsimulation analysis, deterministic models can be created in-house.

> "Usually consultants are involved with a lot of the planning analysis. Consultants tend to have the resources to model facilities, but a lot of the more basic spreadsheet type analyses for normal operations or emergency egress analyses, they can probably do those also in-house because those are Excel spreadsheet kind of work."[104]

However, one consultant gave an example to emphasize that deterministic models can be adapted to be as complex as circumstances require. If used appropriately, he argued, they can be as informative as microsimulation models.

> "We did a large survey of route choice in a major commuter terminal and found that about 95% of people use the same route day in and day out. This will be the case for many terminal facilities whose populations consist of regular users. And route choice can be easily observed and modeled without the need for relatively sophisticated route choice algorithms in simulation models that add complexity and cost in developing them and applying them to projects. We found that using relatively easy-to-develop-and-apply spreadsheet models, which were deterministic as opposed to stochastic, were very effective tools. A station designer could determine pretty confidently the paths that the vast majority of the users would take through the facility. You don't design a facility for a typical day anyway. You are designing it for the normal disruptions that occur with enough regularity that you have to plan for that as the design condition. So there are a lot of safety factors and contingencies built into a design that obviate the precision that more sophisticated models appear to produce."[105]

MICROSIMULATION MODELS

As discussed above, many experts find deterministic spreadsheet analysis of passenger flows to be sufficient for station design. Some were skeptical that microsimulation added much value beyond what could be gained through deterministic analysis. A staff member at one agency explained that she saw the value of microsimulation primarily in terms of visualization and communication.

> "We do have a license of Legion modeling here, although we don't use it a whole lot. And I think most people here have been doing without it for so many years, they don't see what it offers. It offers a lot as a communication tool, if you want to present the data to those who maybe don't get it in terms of numbers. And so maybe if it's a real key location, and there are key political people potentially, then you might want to use it. But for our purposes, it's not used as widely as one might expect."[106]

A consultant expressed concern that reliance on sophisticated software packages could supplant, and even inhibit, the development of an analyst's or designer's intuition and expertise.

> "The models really help you quantify what you probably already know, assuming you've had enough experience dealing with these issues, and you have a real solid understanding of how things work. There are a couple of new generation models, which I'm afraid have become too much of a black box for some appliers. Some of the models have some features that are very sophisticated, but they also dumbed down some other components like the appropriate use of different pedestrian level of service standards for various types of station components and the time duration for which certain conditions exist. Some of the people that are applying these models are mechanically adept at running the program but don't know how to interpret the output. My concern is that, as the models have become more technically and graphically sophisticated, that the people operating them don't really understand what's going on inside them and don't have a good underlying understanding of what the output is telling them. So they are just relying on the raw output that the simulation spits out. … I'm finding that the lack of understanding of the fundamental principles of pedestrian

> flow in the interpretation of the results is a real problem and results in overdesign and unnecessary capital and operating and maintenance costs."[107]

A number of experts interviewed referred to the high cost of microsimulation models. One consultant explained why microsimulation was not typically used for station retrofits.

> "There are very sophisticated pedestrian flow modeling and pedestrian simulation modeling tools that are available, but they're going to be quite costly in the context of a retrofit to a station."[108]

Another consultant further explained that the costs of running a microsimulation model go beyond simply the software license or the consultant fee, and that these costs may be justified only in particular situations:

> "It can be quite labor intensive as far as field observations, and then you need special software packages, and you need people that are trained and know how to use them. All of that up-front cost can be a little bit of a barrier. So there are really going to be specific situations where there's crowding or particular issues that need to be looked at maybe when there are alternatives being proposed. And they need to be evaluated from the perspective of what's going to have the greatest benefit for pedestrians – then you want to do the model."[109]

Despite these drawbacks, experts mentioned that microsimulation models allow analysts to test a variety of different designs under a variety of different conditions. As one consultant explained:

> "You can test all types of scenarios, all kinds of changes in the terminal infrastructure, where the fare gates might be and the type of fare gates. ... And then we can do that for emergency cases as well as for normal conditions."[110]

He also described how the ability to test a variety of scenarios could be particularly important when planning for emergency situations:

> "We took those plumes and moved them to different locations that seemed to be more critical than others, meaning where more people are, that they could likely target. So we had to be sure that if something happens there, we can still get people out. And how do you do that? You do it with the simulation model, which we did, and we tested five or six or seven locations."[111]

Experts also appreciated the ways in which microsimulation allowed analysts to more easily visualize and explain how alternative designs or conditions might affect pedestrian flows. One consultant described how her firm had used microsimulation to reassure a client that adequate operations could be maintained during the construction phase of a proposed project.

> "We … built the model … so that we could run scheduling to show how passengers could flow, how our TO [train operator] could run the trains, how you had a safe condition, and

we would run these models over and over again depending on which stakeholder was represented at a meeting. And, we really did make the case that you could."[112]

Table 8 shows the pros and cons of deterministic analyses and microsimulation models. Deterministic models reduce complex pedestrian movements into straightforward equations that a transit planner or transportation engineer can easily apply to analyze the performance of typical platform elements under normal conditions. They provide useful rules of thumb that practitioners frequently find satisfactory for planning purposes or use as a starting point for further analysis. An advantage of deterministic models is their simplicity: they can be analyzed through manual calculations or simple spreadsheet tools rather than requiring transit operators to purchase expensive software or hire consultants with expertise in more sophisticated methods.

Table 8. Pros and Cons of Deterministic Analysis and Microsimulation Model

Deterministic Analysis	Microsimulation Models
Pros • Simple, easy to use • Can be easily conducted in-house • Less costly	Pros • Can account for movements and characteristics of diverse pedestrians • Greater ability to test different scenarios • Better visualization capacity • Better opportunity for communication with clients
Cons • Ignores interaction among station elements • Less appropriate for very crowded, complex conditions at stations	Cons • Labor intensive • Cannot be often performed in-house; require specialized expertise • Costly

But deterministic methods are less appropriate for evaluating very crowded conditions, such as evacuations or special events, when pedestrian flows become unstable. Under such conditions, the analogy of pedestrian flow with fluid flow breaks down, and pedestrian flows begin to take on characteristics of granular flows.[113] Furthermore, deterministic methods require that analysts consider elements of the platform separately, which requires artificially dividing the platform into a walkway area and one or more queuing areas for the purposes of analysis (Figure 2). While this simplification may yield a rough estimation of required space for desired levels of pedestrian comfort, it ignores interaction among station elements. Such interactions may become significant under crowded conditions, when boundaries between walkways and waiting areas on the platform are not clearly delineated, and people who are standing to wait for the train act as barriers to those wishing to traverse the platform.

This is not to suggest that deterministic methods are necessarily overly simple. An analyst may make a number of adjustments to account for lost space due to buffers next to platform edges, walls, or other obstructions, and for unique pedestrian characteristics that may change pedestrians' preferred walking speed or required space. Nevertheless, even with these adjustments, the analogy with fluid flow implies that pedestrian characteristics are more or less evenly distributed throughout the pedestrian stream. For example, adjustments may be made for a high proportion of elderly pedestrians, which may reduce

the average pedestrian speed by 5-10%. However, this adjustment would be equivalent to reducing the speed of every pedestrian by that amount and would not account for the effect of having some pedestrians travelling much slower than the rest of the stream. For such complex calculations that adequately represent the random distribution of diverse individual characteristics throughout the pedestrian population, the employment of stochastic microsimulation models is usually required.

Thus, the primary advantage of microsimulation models over deterministic models is their ability to account for the movements and characteristics of individual pedestrians. This ability becomes particularly important when pedestrian flows are unstable due to heavily congested conditions and emergency evacuations. Microsimulations are also more able than deterministic models to explain pedestrian behavior at bottlenecks such as fare gates. They also allow experimentation so planners can determine the optimal placement of doorways and barriers to organize rather than impede pedestrian flows.[114]

On the other hand, compared to deterministic models, microsimulation models require significant resources, including the money to purchase necessary software and maintain staff with the required expertise, or to hire external consultants to perform the analysis, which is also costly. In many cases, the level of detail that a microsimulation model provides is not necessary to answer the questions a transit operator seeks to address. In such cases, a deterministic model may be able to satisfactorily meet the transit operator's needs at a fraction of the cost. However, one consultant described how the use of microsimulation models could ultimately save money by providing a more precise estimate of pedestrian needs, thus reducing the risk that a station will be overdesigned.

> "With the advent of simulations I can … test out the validity of … a ridership projection way before design goes into the advanced stages. So that's really the power of these software packages, the ability to look at a system well before it gets built so that it doesn't get over-designed."[115]

Ultimately, whether a particular tool will meet the operator's needs depends on the question the operator seeks to answer. Table 9 gives examples of the types of questions for which each of the three tools discussed here – standards, deterministic analyses, or microsimulation analyses – is most relevant.

Table 9. Appropriate Analytical Tools to Answer Particular Questions

Question	Analysis
Does the proposed design meet code requirements?	Analysis described in the relevant code
How much space is needed to accommodate at a particular station element (e.g., width of platforms or corridors, number of doorways or fare gates)?	Deterministic spreadsheet analysis
How and where do passenger flows transition from one element to another, and how do individual elements interact with one another?	Microsimulation analysis
How do streams of pedestrians in opposing directions interact with one another?	Microsimulation analysis

PRACTICAL APPLICATION

How are rail transit agencies using the three types of tools – standards, deterministic analyses, or microsimulation analyses – they have at their disposal? The expert interviews provide insights into the types of considerations that come into play as transit agencies make decisions about which analytical tools to use and how to account for pedestrian flows when designing underground transit stations. Survey responses can further contribute to an understanding of how these decisions play out in actual practice.

Table 10 shows that 12 of the 16 surveyed agencies reported that at least some aspects of the design for the most recently designed station in their system were based on published standards and codes. One of the 16 respondents skipped the question because he was not personally involved in the design of any recent stations. Of the three remaining agencies that did not report any of their design tasks to have been carried out based on published standards and codes, two reported using deterministic spreadsheet analysis as a basis for design. One did not report using any type of quantitative analysis as a basis for design, indicating instead that all design tasks were based on consistency with existing stations in the system.

Table 10. Transit Agencies' Reported Use of Station Design Approaches, by Design Task

Design task	Method or tool applied to design: Design based on published standards and codes	Deterministic spreadsheet analysis	Microsimulation software
Determining the number of fare collection machines and gates:	9 (60%)	5 (33%)	3 (20%)
Selecting locations of fare collection machines and gates:	7 (47%)	2 (13%)	2 (13%)
Selecting type of fare collection machines and gates:	4 (27%)	1 (7%)	1 (7%)
Determining the number of vertical circulation elements:	9 (60%)	3 (20%)	4 (27%)
Selecting locations for vertical circulation elements:	11 (73%)	4 (27%)	4 (27%)
Selecting the type of vertical circulation elements:	10 (67%)	3 (20%)	3 (20%)
Determining sizes for waiting and walking areas:	11 (73%)	3 (20%)	4 (27%)
Total:	61 (58%)	21 (20%)	21 (20%)
Any design task:	12 (80%)	5 (33%)	6 (40%)

Source: Authors' Survey.

A closer analysis of the survey responses allows us to answer whether reliance on published standards obviates the perceived need for further quantitative analysis, whether by deterministic spreadsheet models or microsimulation models. As Table 11 shows, this does not appear to be the case. The first two sections of Table 11 show how often each type of analysis is used when a design task is and is not guided by the use of standards and codes. The third section in Table 11 describes the use of each type of analysis overall (i.e., it sums the first two sections). Agencies that use standards and codes as the basis for a design task are about as likely to use microsimulation and/or deterministic analysis

for that task as those that do not use standards and codes as a basis – though neither is employed routinely.

Table 11. Transit Agencies' Reported Use of Approaches to Station Design Tasks, by Use (or Not) of Published Standards and Codes

Design Task	Microsimulation software analysis	Deterministic spreadsheet analysis	Both	Neither	TOTAL
When published standards or codes are used					
Determining the number of fare collection machines and gates:	1	1	1	6	9
Selecting locations of fare collection machines and gates:	0	0	1	6	7
Selecting type of fare collection machines and gates:	1	0	0	3	4
Determining the number of vertical circulation elements:	1	0	1	7	9
Selecting locations for vertical circulation elements:	1	0	3	7	11
Selecting the type of vertical circulation elements:	0	0	2	8	10
Determining sizes for waiting and walking areas:	1	1	1	8	11
TOTAL	5	2	9	45	61
Percent	8%	3%	15%	74%	100%
*When published standards or codes are **not** used*					
Determining the number of fare collection machines and gates:	0	2	1	3	6
Selecting locations of fare collection machines and gates:	1	1	0	6	8
Selecting type of fare collection machines and gates:	0	0	0	11	11
Determining the number of vertical circulation elements:	0	0	2	4	6
Selecting locations for vertical circulation elements:	0	1	0	3	4
Selecting the type of vertical circulation elements:	0	1	0	4	5
Determining sizes for waiting and walking areas:	0	0	1	3	4
TOTAL	1	5	4	34	44
Percent	2%	12%	9%	77%	100%
Regardless of use of standards and codes					
Determining the number of fare collection machines and gates:	1	3	2	9	15
Selecting locations of fare collection machines and gates:	1	1	1	12	15
Selecting type of fare collection machines and gates:	1	0	0	14	15
Determining the number of vertical circulation elements:	1	0	3	11	15
Selecting locations for vertical circulation elements:	1	1	3	10	15
Selecting the type of vertical circulation elements:	0	1	2	12	15
Determining sizes for waiting and walking areas:	1	1	2	11	15
TOTAL	6	7	13	79	105
Percent	6%	7%	12%	75%	100%

Source: Authors' Survey.

Based on interviews, in which transit station design experts explained the advantages and disadvantages of deterministic vis-à-vis microsimulation analyses, one might expect these two types of analysis to be substitutes for one another. However, Table 11 does not suggest that this is the case. Note that most design decisions are not based on analysis of pedestrian flows but rather on other factors such as compliance with standards and codes, consistency with other stations, or acknowledged best practices. However, for a given design task, when agencies do base their design decisions on passenger flow analysis, they are about as likely to use both microsimulation and deterministic analysis than either type of analysis alone. This suggests that microsimulation analysis and deterministic analysis are used as complements as often as substitutes.

The results of expert interviews and subsequent survey of transit operators suggest that the application of published standards and codes, deterministic spreadsheet models, and microsimulation models interact in complex ways to inform planning for pedestrian flows in the design of underground rail transit stations. As bases for station design, they are as likely to complement as to substitute for one another.

This research cannot recommend what approach agencies *ought* to take in analyzing pedestrian flows; rather, it describes the approaches that rail transit agency report having taken in their own recent station design efforts. A better understanding of how these types of analyses operate and interact in practice, and why pedestrian flow models of all types are employed so sparingly, is necessary to inform ongoing research in pedestrian flow analysis. To the extent that an analytical tool is selected based on factors such as cost or inertia alone, operators should be encouraged to also consider which tool is most appropriate to address the design task at hand.

As government agencies and professional organizations continue to develop and refine standards and codes, they should do it in ways that encourage the use of available and appropriate analytical tools to adapt guidelines to the appropriate local context. There may also be opportunities to use microsimulation models to verify and refine deterministic models and vice versa.

As future research responds to the realities of professional practice, one can expect to see both incremental and innovative improvements in transit station design that will create a safe and comfortable environment for all passengers.

V. DESIGN

This section draws from the research interviews with station design experts, the survey with staff from transit agencies, and relevant literature to consider design strategies to meet the needs of pedestrians waiting in and moving through rail transit stations. This section first discusses constraints that may limit the options that designers have to accommodate pedestrian needs. Next, this section discusses the importance of considering the station as a complete system rather than simply as a collection of constituent parts. The section then discuss individual station elements in greater detail, including particular issues that may arise in various areas and facilities of a transit station and offer specific strategies that designers may use to address them.

DESIGN CONSTRAINTS

Even if a designer understands the needs of pedestrians in a station and the appropriate design strategies to meet those needs, several constraints can prevent otherwise workable strategies from being implemented.

Table 12 summarizes survey responses regarding the issues that agencies experience at existing underground rail transit stations and which of these issues they have tried to address in their design of new stations. In general, agencies are slightly more likely to identify a particular shortcoming at existing stations than to correct for that shortcoming in the design of planned new stations. This may indicate that, in some cases, operators do not necessarily assume that issues identified at existing stations will also occur at planned stations until the stations become operational and there is evidence to suggest that this is the case.

Table 12. Issues Identified at Existing Stations

Issue	Number of agencies identifying the issue at existing stations	Number of agencies attempting to correct for the issue at new stations
Passenger confusion due to inadequate wayfinding	10	9
Bottlenecks at vertical circulation elements	8	6
Overcrowding at station platform	8	6
Bottlenecks at fare collection gates	7	7
None	2	3
Climate control	1	1

Source: Authors' survey of transit agencies.

Retrofits of existing stations to meet changing passenger needs can be even more costly than designing stations to optimize passenger flows from the beginning. Ten of the 16 agencies surveyed indicated that they had to defer or cancel one or more planned station retrofits in the past decade. Of those, nine indicated that budget constraints or funding limitations had necessitated the cancelation or deferral of a retrofit. The tenth did not specify a reason. As additional reasons for canceling or deferring planned retrofits, one agency identified a lack of necessary staff or other resources, and two identified failure to obtain required permits and approvals.

One transit agency staff member explained how some features that may improve the passenger experience ultimately must be set aside to conserve limited financial resources.

> "Well, the hard engineering is what drives most of it, and to do it right actually costs money. That means you have most of your amenities and other things that you need. And as a cost-conscious group – and most working groups are – the person making the decisions is looking for the minimum standard and lower cost to meet the design requirements. And in reality, what you're looking for from an economic side is a much more robust exiting for the purposes of some economic advantage or kind of quality customer experience. You have to be cost-conscious, and the trade-off between what's considered to be a quality amenity is not seen as essential to meet the objective of the project, which is just kind of a cut-and-dry capacity issue."[116]

Another mentioned that a published standard for passenger convenience and comfort might help to preserve some design elements that would otherwise be eliminated.

> "I think that's really a result of value engineering in both cases. And the lack of a pedestrian standard along those lines for flow and access, I think, contributes to that being an option that's removable as opposed to an option that's considered. Since it isn't considered a standard option for pedestrian access, it's an option that can be removed, and I think just as a practitioner, I think it would be helpful to see guidance from APTA or other industry-type sources in terms of requiring access in multiple directions to multiple destinations to minimize pedestrian conflicts, either with intersections or with crossing."[117]

Physical characteristics of the area around a transit station may also be a constraint, as designers may be limited in how deep, long, or wide an underground transit station can be. As one respondent reasoned:

> "Site conditions and the physical environment in which a station is being placed can be the primary determinant of the physical configuration of the station. Depending on what type of transit mode you are dealing with, finding a sufficient tangent length and width for the guideway and platforms and space for the users' access and ancillary facilities is a challenge and will often have major influences on the sizes and configuration of station components. Structural systems, especially column locations and sizes, will also have a strong influence."[118]

STATIONS AS SYSTEMS

Transit station designers face not only external constraints, such as budget and physical characteristics of the area around the station; they also must consider the ways in which their design in one part of a station affects or is affected by the other parts.

A passenger's experience with a transit station might begin on the street adjacent to the station, which she may have to cross or otherwise navigate to reach the entrance to the station. The station entrance may be a simple portal or stairway to the street, or at more elaborate main stations, it may contain escalators, ticket vending machines, and/or ticket

agents. Ticket vending machines and ticket agents also may be located on a below-ground mezzanine level or on the platform level. Vertical circulation elements, such as stairways, escalators, and elevators, allow passengers to move from one level to another. Signage and other messaging throughout the station can direct passengers where to go, thus improving pedestrian flows by reducing passenger confusion. Fare collection gates typically provide a transition into the paid areas of the station, such as the station platform. The platform functions as both a waiting area and a walkway as passengers traverse from one end to the other. Finally, the operation of the train may have a tremendous impact on the flow of passengers through the rest of the station. For example, short headways may not require as much platform queueing space. When trains stop at consistent or predictable locations (perhaps as indicated by markings on the platform), this can cause travelers to queue at regular intervals where the doors will open. Rapid deceleration into and acceleration from stations can cause passengers to stand further from the platform edge, away from fast moving trains.

The level of crowding that a passenger experiences may vary substantially at each part of her journey through the station. Table 13 summarizes how survey respondents perceive the level of crowding in various areas of the transit stations in their respective systems. Respondents reported the greatest degree of crowding on station platforms and at vertical circulation elements, like stairs and escalators. However, the best solutions to passenger congestion in those areas may involve changes to other areas. For example, the placement of entrances and exits may influence where on the platform passengers arrive and wait for the train, as well as the degree to which they are spread out evenly along the length of the platform or cluster together at one or a few places.

Table 13. Level of Crowding Reported by Station Area

	Substantial crowding	Some crowding	Not much crowding	No crowding/ don't know/ no response	Total
Ticketing areas	5	6	5	0	16
Entrances and exits to paid areas	5	5	3	3	16
Vertical circulation elements	5	9	0	2	16
Station platforms	6	8	1	1	16

Source: Authors' survey of transit agencies.

Thoughtful design of one station element can improve operations throughout the station. Of course, the reverse is also true. One consultant emphasized that if one part of a transit station operates poorly, it can affect operations throughout the station.

> "You have to really look at the complex, the total, and not just the train; I mean the [movement from the] train out to the street. I always like to tell people that if any one of those key elements fails, then everything back from there could also fail. It'll feel like dominos falling backwards. So you have to look at the whole system, individually, and then as a system. … You really have to look at the terminal completely, not just one stair or one element, which you still have to do, but you really have to look at the whole system and how the system works. I can't emphasize that enough."[119]

Because of the ways in which each station element interacts with the rest of the station, station retrofit projects rarely involve only one part of the station. Survey respondents described 14 different retrofit projects with which they had had recent experience. None of these were limited to a single station element. All but one involved station entrances and exits. Eleven included changes to ticketing areas; ten included the mezzanine; nine involved the station platform; and eight involved ticketing areas.

System planning is important not only in thinking about the various physical components of a transit station, but also in thinking about the multiple purposes a transit station serves. In addition to its role as part of the transportation system, a station also may be a place of business, a meeting place, or even a gathering place that adds to the vibrancy and identity of a neighborhood.

> "There's kind of this inherent tension at a transit station where you want to create a place, so you want the station to be right where the activity is, and you want to have the transit bringing vitality to the area by bringing people there, and then also the transit benefiting from the vitality of a vibrant place. But then that's kind of at odds with the idea of the transit station being a node, where it intercepts and allows transfers with other nodes. So on the one hand, you are trying to make a pleasant place to be in and a place where people would enjoy spending a few minutes for a break at a street café or whatever. And then on the other hand, you need a place where buses are stopping and people are getting off buses, and you need a place to park bikes, and if you are in a more suburban setting, you have park-and-ride. And when you have buses and parking and all of that. That really makes it difficult to make it a nice place for people to just hang out."[120]

While transit planners and engineers may be aware of these additional roles a transit station may play, they may be frustrated when these roles conflict with one another. Said one interviewee:

> "Let me give you the one that's always an issue for me; it is the issue of retail and the placement of retail kiosks where the people are traveling. Meaning, you want to put these things where people are going to stop to get their food or their newspapers, yet at the same time I don't want them there because I want people to move freely."[121]

ENTRANCES AND ADJACENT STREETS

The adjacent street environment is the aspect of a transit station that is most often neglected, if planners think of the station as a closed system that accommodates only part of passengers' entire journeys. One consultant mentioned that designing a station to consider passenger safety should also include consideration of the entire passenger experience, including the journey from a pedestrian's origin to the station entrance.

> "Station safety and safety in the adjacent walking environment, those are not typically thought of concurrently. But the typical transit station, that's all part of the transit access experience. You are either traveling from your park-and-ride location to the platform and the loading zone, or walking from your origin to that connection point.

> And I think good planning and design respects that experience throughout the journey. But the standards currently relate only to the station architecture itself, or the standard the local jurisdiction has for their urban environment."[122]

Another consultant referred to the added expense associated with including convenient pedestrian access from the adjacent streets.

> "Some people might have a more difficult route because instead of having access right close to them on one block, they have to walk a block out of their way to get access coming back the other direction. So my feeling is that as many access points you can have coming out of the station the better. But of course, each time you do that it adds expense. And then there are security concerns where there needs to be some sort of passive, or present security, so that any entrance or passage way is a safe and attractive place for people to use. So there's a lot of balancing to do with the design."[123]

Nevertheless, as one consultant expressed it, planners do have a responsibility for the safety of transit passengers, even after they have left the transit property.

> "The bottom line is, once they get off that train, they're still my responsibility. I've got to be able to get them to their destination in a safe way. A lot of times with light rail in particular, … the stations [are] in the middle of an intersection or in the middle of a roadway, so I still need to get [passengers] across that road in some way, shape or form."[124]

Carefully considering the location of station entrances with respect to the adjacent streets allows planners and designers to anticipate which entrances will be most heavily used, and thus, which parts of the station may have the highest pedestrian volumes.

> "Even if you get the platform and the station area designed correctly, the interface of the street immediately adjacent to the site or the crossing location onto the viaduct crossing may have no relationship to what's actually happening from the perspective of the transit agency's architect or the transit agency's platform design-level attention to what's needed to actually bring folks across the street to that location."[125]

With regard to optimizing passenger flows, one consultant expressed the idea that the most convenient design for pedestrians is one that has multiple entrances connecting the station to the adjacent street.

> "I would say a lot of the older systems like New York City have – when you just compare a typical Metrorail station in Los Angeles to a typical New York City subway station – [in Los Angeles] you have maybe one portal, possibly two. New York City will have at least four. … I'm thinking of really high capacity transit systems like Hong Kong or Tokyo. You probably have ten or 12 portals. …. And I think generally, those types of systems, they maximize the options for pedestrians, they can go in and out in any number of locations. … And I think it's not necessarily anything innovative or new, but I think functionally it works much better. In a lot of the --- stations, there's one option… There's really one way you can get in and out. Both from a ped flow perspective and user experience and convenience, more is generally better than less."[126]

However, each additional entrance represents an additional cost, and possibly also additional project delays as the transit agency coordinates with other local agencies. More than other aspects of the station design, correctly accounting for the interface between the transit station and adjacent streets requires interagency coordination that may be more difficult in some jurisdictions than in others.

> "Some [stations] are really well integrated, and there's a good synergy between the transit agency and the city or the jurisdiction that's controlling a lot of the access and the relationship to the surrounding parking and/or street network."[127]

One consultant mentioned that city staff could be hesitant or simply disinterested in supporting improvements that promote safety and convenience for transit patrons while negatively impacting vehicular flow.

> "If we started talking [about] mid-block signals just for pedestrian movement, the city, being more centric on vehicular flow over pedestrian flow, would be inclined to resist, and say, you know, that's going to really mess up my vehicular flow in the major thoroughfares. As a result, it was a constant challenge to try and convince all of the entities, city, county, state, whoever it may be, that a mid-block signal was necessary."[128]

On the other hand, another consultant argued that a well-placed and well-designed transit station might also bring benefits to non-transit users on adjacent streets, such as pedestrians and cyclists, making proper integration of the station to its surroundings a matter of interest not only for transit agencies but also city departments of transportation or planning.

> "I think things have become more multi-modal, and where in the past agencies or cities may have strictly looked at 'what's the need for access for this station in a particular location,' well, there could also be other benefits to people who are maybe just trying to cross the street, or people with bikes. With time, people have taken more of a multi-modal approach of looking at what the overall benefits could be, not just benefits to ridership on the transit system itself."[129]

Although coordinating among agencies to facilitate convenient and safe access to new stations from the street may be time-consuming and difficult, it is generally much less costly than going back to retrofit stations to add entrances or move existing ones. As one interviewee put it:

> "That access project was something that was conducted after the station was already completed. And obviously there's a real challenge there because you have this big transit infrastructure that can't be tweaked, and one of the most important elements, of course, is the portal location."[130]

SIGNAGE AND MESSAGING

Once pedestrians have successfully entered a station from an adjacent street, they may not know where to go within the station or how to reach their desired destination. Throughout the

station, signage, messaging, and other wayfinding aids are critical to directing passengers so they can safely, efficiently, and comfortably reach their destinations.

The importance of wayfinding is not lost on transit operators. One hundred percent of survey respondents indicated that their agencies had improved signage, messaging, and/or other forms of wayfinding assistance at rail stations over the past decade.

Table 14. Use and Perceptions of Dynamic Messaging for Train Arrival Times

	Believe that they are effective in improving passenger flows or station operations *Agencies (Respondents)*	**Don't know if they are effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Believe that they are *not* effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Total**
Already implemented	11 (13)	1 (1)	1 (1)	**13 (15)**
Planned or under discussion	3 (3)	0 (0)	0 (0)	**3 (3)**
Total	**14 (16)**	**1 (1)**	**1 (1)**	**16 (18)**

Source: Authors' survey of transit agencies.

One of the more popular rail station innovations involves dynamic signs to indicate arrival times for trains. Such real-time information has repeatedly shown that passengers' perceived burden of transit travel can be substantially reduced by providing accurate real-time information,[131,132,133] although inaccurate information can be worse, from the traveler's perspective, than no information at all.[134] As shown in Table 14, 13 of the 16 surveyed transit operators indicated that they had real-time displays with information about train arrivals currently implemented in one or more transit stations. The remaining three indicated that the addition of dynamic messaging was planned or under discussion. The three survey respondents at agencies that were planning or discussing real-time displays with train arrival times indicated that they believed such signs would be effective in improving passenger flows or station operations. Of the 15 respondents at agencies that have already implemented dynamic signs indicating train arrivals, only one was of the opinion that they were not effective in improving passenger flows or operations. The survey did not ask respondents to indicate why this was the case.

The most direct benefit of dynamic messaging for train arrival times, as noted by two consultants, is that passengers know when they can expect their trains to arrive.

> "There are dynamic signs that are now available that give you a message of immediacy, so you know when trains are arriving right away."[135]

> "We've come a long way with [real-time information] through GPS, the ability to know where trains and buses are relative to arrival and departure times, and being able to provide that information to riders."[136]

Another consultant noted how this information could improve the passenger experience by relieving passenger anxiety.

> "With dynamic signing you can provide people real-time information. And it helps passengers because you can tell them when their next train or bus is coming, to relieve their anxiety, because they can at least know if the service is running. The provision of passenger information is improving and will continue to get much better."[137]

One agency staff member mentioned that public response to dynamic messaging for train arrival times has been very positive.

> "Most recently, we've put in the count-down clocks. And on the whole, the feedback of the users is everybody loves them."[138]

Dynamic messaging can also affect passenger flows by influencing how quickly passengers move through a station because research has shown that passengers who know a train is about to arrive are likely to move more quickly.[139]

> "They are using electronic signage all along the passageways to provide information and keep the flow going … to give information about where you are going, or where your connection is, or when it is leaving."[140]

Similarly, dynamic messaging may improve congestion on the platform, as passengers may tend to stand near the signs to have a continuous view of information updates displayed there. Thus, proper placement of dynamic signs can serve to spread passengers more evenly along the length of a platform.

> "Those count-down clocks have definitely impacted to a certain extent how people flow and where they stand because they're curious to see what's going on in terms of that messaging. And their locations were put in as a way of presenting information. They were not put in as wayfinding at all. That was maybe an added benefit. I haven't heard anyone complaining that they're bringing people to wrong locations, so I guess that's a good thing."[141]

However, retrofitting trains, signals, and signage in large, older systems to accurately estimate train arrival times can be particularly difficult and costly. One staff member at an older system described how her organization had developed a work-around using sensors and triggers, but that a true system that could continuously and reliably track train locations would need to be rolled out over a period of more than 30 years.

> "Part of the problem is – well part of the challenge is that we have signals, and many of our signals are from the original system. You know, [older] signals, so they're operated the same way. So we have a program – a 30-plus year program, which we're in the middle of changing out our signals. To do true count-down clocks, to know where the trains are in the system. So for automatic knowledge of where the trains are, you have to have those updated signals out there. So you can have sensors and triggers, but it's not a true system that always knows where the trains are at all times. There's a way to do it, and that's what we've kind of put together out there; we've got it on [some] lines and we're now working on it for other lines. But it's not the full-fledged thing. That can't happen until the signals are changed out. So that's a 30-plus year – we'll be changing this over as the system changes over as well."[142]

Although dynamic messaging has most commonly been used to inform passengers of train arrival times, the potential of dynamic messages and electronic displays can extend beyond that. As one respondent argued:

> "I know one thing that is being implemented more and more even through the New York City subway system is just a digital display for passenger information, not only in terms of when the next train will be arriving, but also in terms of emergency directions on the best way to exit a facility. … But really the messaging has helped not just with normal operations but even in emergency conditions, giving people guidance so that if there is a train line out of service, they know ahead of time where to go to take either another route or a bus line to get to where they're going."[143]

Wayfinding and station-related signage are not confined only within the station but also in the station-adjacent area. As noted by a designer of transit stations:

> "In the last decade, there's been a very strong move for the dispersal of information throughout the transit environment and even into surrounding streets. Displays at varying scales that increasingly utilize dynamic technologies have allowed information to become effectively as mobile as passengers and customers. The net result being that the boundaries between the 'station,' its transit function, and other more amenity-driven spaces is less distinct, rendering more of the real estate in and around the station visible to users. So where historically, commuters tended to aggregate in one place around a large sign board, today they are freer to move about and occupy the station in ever more diverse and complementary ways. Pedestrian movements can be more fluid, more aligned to desired paths of travel, and from a commercial perspective, spaces that were formerly thought unattractive and too remote can be now attractive to retailers. Increased dispersal has provided the impetus for significant behavioral changes and, as a consequence, has improved the integration of stations into their neighborhoods."[144]

Table 15 shows that only eight out of 16 agencies use dynamic message signs for passenger information other than train arrival times. Three reported that additional uses for dynamic message signs were planned or under consideration. One agency that currently uses dynamic message signs to indicate train arrival times indicated that the use of dynamic signs for other passenger information had been considered and rejected. One agency currently planning or discussing dynamic signage for train arrival times has not considered its use for other passenger information. In general, however, most survey respondents expressed the opinion that dynamic messaging for other passenger information is or would be effective in improving passenger flows.

Table 15. Use and Perceptions of Dynamic Messaging for Other Passenger Information

	Believe that they are effective in improving passenger flows or station operations *Agencies (Respondents)*	**Don't know if they are effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Believe that they are *not* effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Total**
Already implemented	8 (9)	0 (0)	1 (2)	**9 (11)**
Planned or under discussion	2 (2)	1 (1)	0 (0)	**3 (3)**
Considered and rejected	0 (0)	0 (0)	1 (1)	**1 (1)**
Never considered	1 (1)	0 (0)	0 (0)	**1 (1)**
Don't know/no response	1 (1)	1 (1)	0 (0)	**2 (2)**
Total	**12 (13)**	**2 (2)**	**2 (3)**	**16 (18)**

Source: Authors' survey of transit agencies.

In many cases, static signage (that does not change in real time) may play a greater role than dynamic signage in improving passenger flows, and it is generally far less costly to implement. Permanent, static signage is appropriate to convey information that may change rarely, if at all, but not for regularly changing information. Examples of the former include transit system maps, maps of the surrounding street environment, directions to major buildings on the surface, and transit schedules.

Static signage can be particularly useful in conveying visual instructions to improve boarding and alighting. Table 16 summarizes the prevalence of visual instructions to improve boarding and alighting, as well as survey respondents' perceptions of their effectiveness. Nine survey respondents, representing eight different agencies, indicated that their agencies currently use visual instructions to improve boarding and alighting. In general, respondents at agencies where visual instructions are being used tended to believe that they are effective in improving passenger flows or station operations. Fewer respondents at agencies that had not considered this use of visual instructions believed that they would not be effective than at agencies that had considered it.

Table 16. Use and Perceptions of Visual Instructions to Improve Boarding and Alighting

	Believe that they are effective in improving passenger flows or station operations *Agencies (Respondents)*	**Don't know if they are effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Believe that they are *not* effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Total**
Already implemented	7 (8)	1 (1)	1 (1)	**8 (10)**
Planned or under discussion	0 (0)	2 (2)	0 (0)	**2 (2)**
Never considered	0 (0)	1 (1)	2 (2)	**3 (3)**
Don't know/no response	2 (2)	1 (1)	0 (0)	**3 (4)**
Total	**9 (10)**	**4.5 (5)**	**2.5 (3)**	**16 (18)**

Source: Authors' survey of transit agencies.

Figure 4. Dynamic, Interactive Digital Signage at St. Paul's Union Depot

Source: DigitalavMagazine.com

One disadvantage of visual messaging, whether static or dynamic, is that it can add to passengers' sense of visual clutter within the station. If a station becomes overloaded with signs and messages, passengers may become overwhelmed and fail to recognize which messages are important. To wit:

> "The more technology I bring in, the more stuff that has to come in as well, the more cluttered the station becomes. And when the station becomes cluttered, then way-finding becomes a challenge. And drawing that balance is important. We depend on advertising revenue to make our bottom line. Some look at that as clutter, obviously. It would be interesting to really hear from the users in an unfettered sense, where does information overload come in, if they went through the system and were picking and choosing, what's really helping, and what's disturbing them? It would be interesting."[145]

Particularly in emergency situations and evacuations, passengers may panic and ignore messages such as exit signs that are intended to help them find the quickest and safest route out of the station. One interviewee referred to studies that demonstrate that, in an emergency, people try to leave a station the same way they entered, rather than looking for signs to indicate emergency exits.

> "We provide exiting that is a door with an exit sign on it that may never be used. It is supposed to be made available for an emergency, but all of our studies in the industry have now shown that people won't go find an exit nearby in an emergency; they'll try and return the way they came in. ... We can go back and find out how people tried to get out, and they didn't find the exit door because it's not intuitive, and it's not something that you tend to look for."[146]

The same interviewee listed a few visual characteristics of stations that can improve wayfinding in a station simply by reducing the complexity of the visual environment.

> "One is the directness or indirectness of it. One is the openness. One is the color and texture – we call it environmental complexity. Lighting, intuitive and non-intuitive designs. There are really a thousand characteristics that you want to look at when you're dealing with that."[147]

Another consultant mentioned how column-free designs not only reduce visual clutter, but also eliminate blind spots. This can improve wayfinding, as passengers have a clear view of signs, doors, and stairways. It can also improve passengers' feelings of security because they have a clear view of the presence and location of other people on the platform.[148]

> "One key thing in station design is trying to keep it as clean and as simple as possible. Sort of, I don't want to say streamlined, but less columns, a more column-free design, so that not just from a pedestrian movement standpoint can you easily or more freely move from where you want to in a station to the concourse areas, but that there's even more of an awareness in terms of safety. With the columns, you have blind spots, or you can have people hidden behind columns, but it affects your line of sight, so you can't see too far ahead in terms of where you may want to go or you may be missing a corridor or an exit because of the columns. In terms of a more column-free design, it definitely helps movement, safety, and even access through stations."[149]

Ideally, signage goes hand-in-hand with other aspects of the visual design of the station. However, agency staff with responsibility for signage may work in a separate department than those who design the rest of the station. Some agencies reported that coordination between signage designers and station designers can be a challenge. One agency staff member suggested that coordination would be more straightforward if there were a published set of standards or guidelines for the integration of wayfinding signs with the rest of the station design.

> "Signage is not under my jurisdiction here, and there are a lot of jurisdictional issues. And it wouldn't surprise me if that's the case with other systems as well. I think we can – I think it would be great – a definitive best-practices out here if you will, that spoke to a definitive, intuitive signage in underground systems…. Something like that can then guide, it sort of circumvents the whole jurisdiction thing. It's not coming from me – there's something that's been approved, by whether it's APTA or an organization like that, or TRB or whatever. Those kinds of things, I think, could help make a difference."[150]

Audible instructions can communicate important information to transit passengers without adding to the visual complexity of the station design. Eleven of the 16 transit operators use audible instructions during boarding and alighting, and survey respondents at ten of those agencies indicated that they believed audible instructions were effective in improving passenger flows.

Table 17. Use and Perceptions of Audible Instructions During Boarding and Alighting

	Believe that they are effective in improving passenger flows or station operations *Agencies (Respondents)*	**Don't know if they are effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Believe that they are *not* effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Total**
Already implemented	10 (11)	1.5 (2)	1.5 (2)	**13 (15)**
Planned or under discussion	0 (0)	0 (0)	1 (1)	**1 (1)**
Never considered	0 (0)	1 (1)	0 (0)	**1 (1)**
Don't know/ no response	1 (1)	0 (0)	0 (0)	**1 (1)**
Total	**11 (12)**	**2.5 (3)**	**2.5 (3)**	**16 (18)**

Source: Authors' survey of transit agencies.

FARE COLLECTION GATES

As shown in Table 12, nearly half (seven out of 16) of the surveyed transit operators reported problems with bottlenecks at the fare collection gates of their existing transit stations. Table 13 indicates that five reported substantial crowding at the entrances and exits to paid areas, and an additional five reported some crowding at these locations. One consultant described how delays at fare collection gates can be the primary constraint to passenger flows at transit stations.

> "This is one of the most constraining factors during rush hour … the bottleneck at the fare collection/control barriers. When riders don't have tickets or whose tickets don't have enough money on them, then queuing up for the gates interrupts the smooth flow of movement. Exiting is freewheeling except in those systems that are distance-based."[151]

The expert interviewed also noted that distance-based fares, which require passengers to pass through a gate as they exit the station as well as when they enter, might further impede passenger flows. This is particularly the case with fare payment systems that require patrons to physically run their tickets through a reader (which still constitutes the majority of systems); queuing problems at fare gates should diminish over time as systems transition to smart card media that do not have to be removed from one's purse or wallet while passing through the fare gates.

> "BART and Washington Metro are what are called fare-based systems, distance-based. So you have to go through a gate or exit. LA Metro is an entrance-only system, and the agency knows … that they're going to have to go to a distance-based system, which means you then have to use … your smart card or whatever for exiting also. So you see, everything's kind of slowing down until we get into the EZ pass world for transit riders."[152]

As mentioned in the passage above, smart cards can greatly improve the ability of transit operators to vary fares by distance and time of day, which may exacerbate queuing in

payment areas, while the next generation of so-called "contactless" smart cards may reduce queuing. A survey of transit operators found that pedestrian flows out of stations were not considered by the transit agency staff surveyed as a major concern for the adoption of smart card fare collection systems, possibly because the departments that establish fare systems and policies are not typically those responsible for station design.[153]

One consultant pointed out that the movement away from turnstiles to other fare collection mechanisms represents a major improvement in moving passengers into stations; he described the sort of "semi-contactless" systems that have recently been installed in Los Angeles Metro Rail stations, among others.

> "There are new fare collection techniques. I talked about the touch node system. There's literally going to be a little kiosk to the side, or maybe even a little way back, and you'll take out your wallet, you don't even need to take your ticket out, and you just tap it and your fare is paid and you proceed to get on the train. That's going to be a big thing in terms of moving people through the system. The turnstile is always one of those locations where people get stuck. And just think if there is an emergency, and you didn't have a turnstile bank, how much faster people can move."[154]

Another consultant described a spectrum of fare collection technologies, in which turnstiles are the slowest means of processing passengers, swipe cards are faster, and tap cards are, for now at least, the fastest.

> "In some locations, and in Washington DC recently, you have to insert your ticket, wait for it to pop out, and then the turnstile would open. It's a slightly slower processing time. [New York has] a swipe card in terms of entering into the subway system, but then you also have a tap system in some areas, which improve pedestrian flow through the system. It makes them easier to access since you're not backing up people at the turnstiles. … One area that still is looking for improvement is the fare collection system, both with the commuter railroads and the local subways. Definitely within the next decade, the reader card system is going to be phased out for a new system that might be a tap system or something else we're not aware of. That will probably be a new innovation that will help definitely with the flow of people in and out of the system."[155]

Two consultants mentioned the experience of the Los Angeles Metro Rail system with a "barrier-free" system, which has been implemented with success on several northern European rail transit systems. Such systems have no fare gates but instead clearly identify "paid areas" of the station that require all to be in possession of a receipt or other evidence of fare payment. In such systems, most passengers' fare payments are never verified. To discourage scofflaws, transit police periodically verify that passengers had paid, and those who hadn't would be charged a fine. This proof-of-payment system is very efficient in terms of passenger flows because passengers do not have to stop at a gate when entering or exiting. However, the consultants mentioned a number of reasons why Los Angeles eventually abandoned the system and installed fare collection gates. First, fare collection gates can reduce the use of the station by non-transit riders, who might use the station for other purposes such as shelter.

> "But then you have security concerns. In Los Angeles, in particular, even though they didn't have turnstiles in their underground stations, they are putting turnstiles in as a means of reducing people who shouldn't be there, whether it is people who are loiterers, or trying to spend the night in the tunnel. So technology is changing so fast, it can completely change in three years."[156]

Second, the agency was losing revenue under the proof-of-payment system, as it turned out that a larger share of LA transit passengers were willing to risk a fine for non-payment than riders on similar systems in northern Europe. To keep the number of fare scofflaws at a reasonable level required very large expenditures on security personnel to collect fares, which cost more than the additional fare revenue collected and hurt passenger morale as many passengers – even those who had paid – found being publicly challenged regarding their fare payment a stressful experience. As a consultant further explained:

> "One of my pet topics is fare collection and control. As stated by other consultants, the entire heavy and light rail system in Los Angeles until about three or four years ago had a totally open honor system. They installed the gates at all subway stations and ticket vending but didn't lock down the gates. They realized that with increasing ridership, they still had a pretty substantial revenue loss. So they've now gone through a major retrofit of the whole system, including many of the light rail stations where entry control could be achieved, installed and locked down the gates. [I can] see the use of smart phone technology, which is already widely used in Asian and some European transit systems, being implemented here. Transit properties will be taking advantage of this proximity system and getting closer to a barrier-free, easy-pass system where patrons just walk in and out of stations using an overhead or pylon-mounted reader. We should eventually see the elimination of the fare gates altogether and the reduction of extensive fare vending and add fare machines that are costly to install and maintain over time."[157]

The Los Angeles Metro system currently uses a TAP card system, which makes it possible to efficiently move passengers into the station while still collecting fares.

> "With the development of electronic TAP cards and other means of automated cash-free fare payment such as used in the LA Metro system, passenger flow at fare collection barriers seems to move more smoothly."[158]

Figure 5. TAP Card Machine at LA Metro

Source: Metro.net

MEZZANINE

Not every underground rail transit station has a mezzanine level, and not every station needs one. In heavily utilized stations where multiple lines come together, a full mezzanine level can provide more opportunities for passengers to quickly get from one line or one part of a station to another. As noted:

> "Other times you may have a full mezzanine level, I'm thinking of really high capacity transit systems like Hong Kong or Tokyo, you have a pretty huge mezzanine level. And I think generally, those types of systems, they maximize the options for pedestrians. There's quite a large, extensive mixing area where they can cross, get through the turnstiles, and find their train. And I think it's not necessarily anything innovative or new, but I think functionally it works much better. … Obviously our ridership is much, much lower, so in many cases, it's not such a big deal."[159]

Including a mezzanine in new, heavily patronized stations and improving mezzanine-level passenger flows can have important, positive impacts on passenger flows. More than two-thirds (ten out of 14) of the station retrofit projects described by survey respondents involved the mezzanine level of the station. (Respondents were not asked to identify the specific type of retrofit improvements that were made to the mezzanine level.) Regarding these retrofit projects, respondents were asked to rate the extent to which the retrofit improved passenger flows, where a score of 5 indicated a major improvement, and a score of 1 indicated no improvement. Of the ten projects that involved a station mezzanine, nine were rated as a 4 or a 5, and one was rated as a 3. Of the four projects that did not involve the mezzanine level, one was rated as a 5, two were rated as 3s, and one was rated as a 2.

VERTICAL CIRCULATION ELEMENTS

Vertical circulation elements are the mechanisms by which passengers move from one level of a station to another. Survey respondents at half of the surveyed transit agencies (eight out of 16) indicated that bottlenecks at vertical circulation elements are an issue

at existing stations. Previous research has found that appropriate location of the vertical circulation elements can help smooth pedestrian flows. In particular, stairs and escalators should not be positioned in ways that force passengers moving in different directions to cross one another to reach them, and they should have adequate free space (at least 6.5 to 8 feet, or 2 to 2.4 meters) at both ends for queuing.[160]

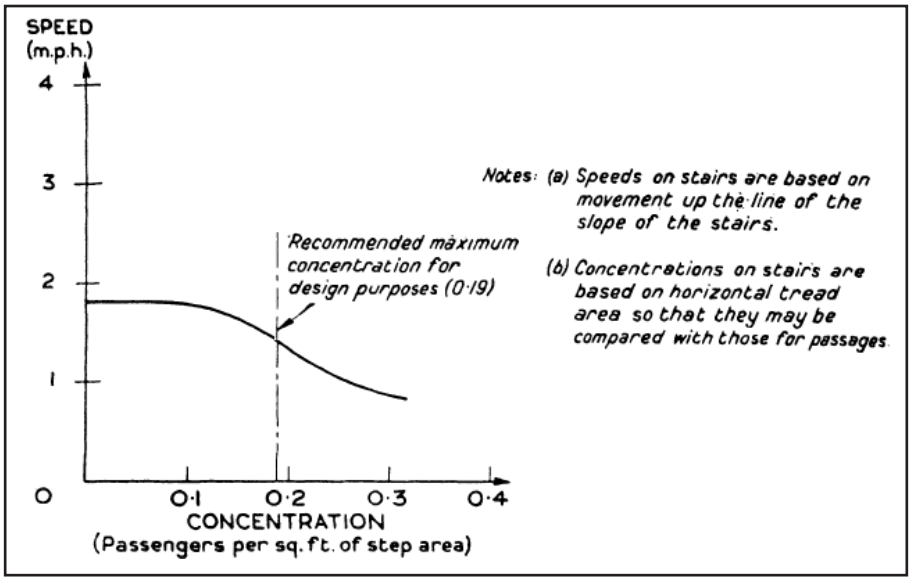

Figure 6. Relationship between Pedestrian Density and Speed Up Stairs

Source: Hankin and Wright 1958.

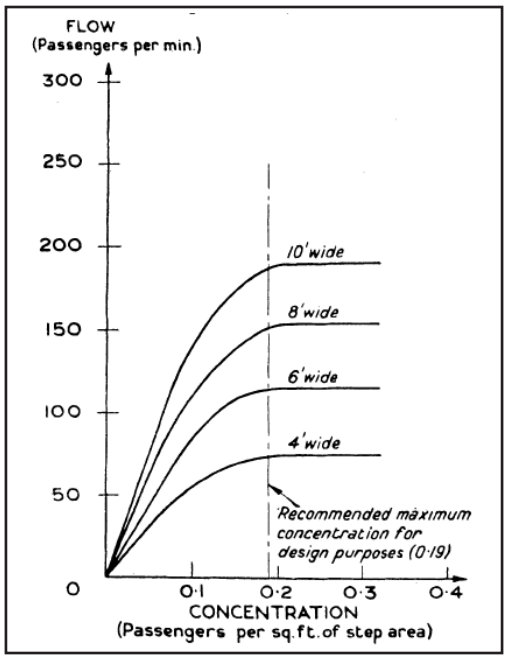

Figure 7. Relationship between Pedestrian Density and Flow Rates Up Stairs

Source: Hankin and Wright 1958.

In one of the earliest published empirical studies of pedestrian flows, Hankin and Wright arrived at three primary conclusions, one of which related to the movement of pedestrians on staircases. They found that pedestrians move more slowly up and down stairs than in level passages, and that they move more slowly up stairs than down.[161] Fruin describes this difference as well,[162] and both Hankin and Wright and Fruin present separate speed-density curves for pedestrian flows ascending stairways. Figures 6 and 7 show the observed relationships between pedestrian density, walking speeds, and pedestrian flow rates on stairs, from the study of Hankin and Wright. Figures 8 and 9 show Fruin's observed relationships between pedestrian space, walking speeds, and pedestrian flow rates.

Figure 8. Relationship between Pedestrian Space and Speed on Stairs

Source: Fruin 1971.

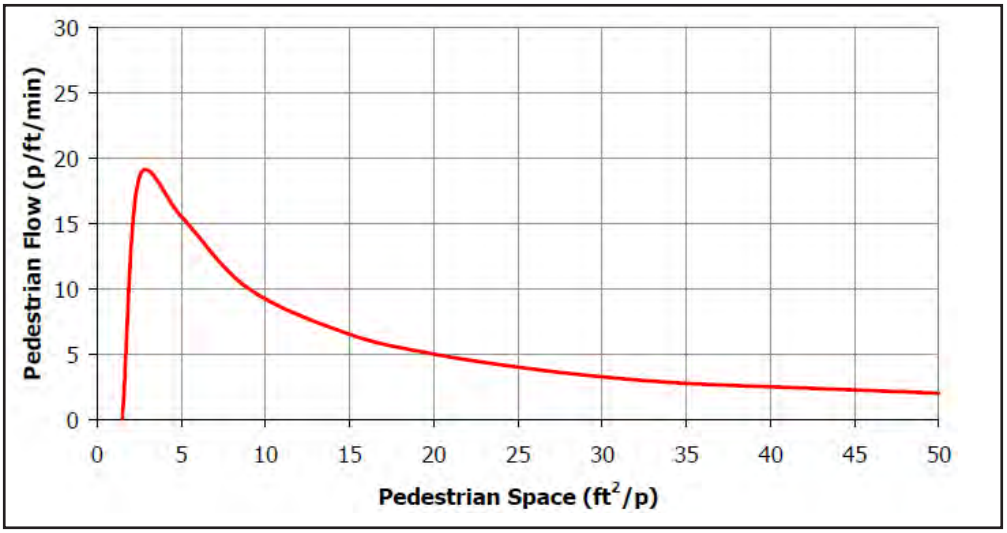

Figure 9. Relationship between Pedestrian Space and Flow Rate Up Stairs

Source: Fruin 1971.

Both of these important early studies report a maximum flow rate of about 19 people per linear foot per minute at a density of about 0.3 people per square foot (0.3 sq. m.), or 3.3 square feet (1 sq. m.) per person, although Fruin observed this maximum at a lower speed and higher density than did Hankin and Wright. Based on this maximum, Fruin suggests a separate level of service classification for stairways,[163] shown in Table 18, which has also been adopted by the *Transit Capacity and Quality of Service Manual*.

Table 18. Level of Service Classification for Stairways

LOS	Average pedestrian space (ft^2/p)	Flow per unit width (p/ft/min)	Description
A	≥ 20	≤ 5	Sufficient area to freely select speed and to pass slower-moving pedestrians. Reverse flows cause limited conflicts.
B	15-20	5-7	Sufficient area to freely select speed with some difficulty in passing slower-moving pedestrians. Reverse flows cause minor conflicts.
C	10-15	7-10	Speeds slightly restricted due to inability to pass slower-moving pedestrians. Reverse flows cause some conflicts.
D	7-10	10-13	Speeds restricted due to inability to pass slower-moving pedestrians. Reverse flows cause significant conflicts.
E	4-7	13-17	Speeds of all pedestrians reduced. Intermittent stoppages likely to occur. Reverse flows cause serious conflicts.
F	≤ 4	*Variable*	Complete breakdown in pedestrian flow with many stoppages. Forward progress depends on slowest moving pedestrians.

Source: Fruin 1971.

One consultant noted that stairways represent a capacity constraint in many transit stations, and that vertical circulation can be a particular challenge when planning for the needs of passengers with disabilities.

> "I think it is the vertical circulation elements [that are the most frequent bottleneck]; how do you get people [to] elevators to connect [them] to the various levels? … I think existing stair capacities is a constraint that you find in a lot of projects."[164]

In newer stations, escalators may be more common than stairways. One consultant mentioned how sensors can be used to vary the direction of escalators depending on the presence of passengers at the top or the bottom of the escalator. In these cases, the escalator would only move when pedestrians are present, which also has the advantage of conserving power.

> "Also, a way of dealing with the vertical circulation is escalators that are basically only turned on when people activate them by stepping on the plate, either at the bottom or the top. And then depending on which end of the escalator is activated on, it will start operating in that direction. So the benefit is that you can program them to be operating continuously during a peak period. But then in the off-peak when there's not a lot of traffic, instead of having the escalator running continuously and with the energy being wasted with that, you can [have] the escalator only running when someone is actually there, and have it only go in the direction someone wants to go instead only in one direction. So that's kind of an innovation in both energy savings and customer service."[165]

Table 19 summarizes the prevalence of variable escalator directions at the 16 surveyed transit operators and survey respondents' perceptions of their effectiveness in improving passenger flows.[166] Just over half the respondents at agencies using variable-direction escalators indicated that they were effective in improving passenger flows or station operations.

Table 19. Use and Perceptions of Variable Escalator Directions

	Believe that they are effective in improving passenger flows or station operations *Agencies (Respondents)*	**Don't know if they are effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Believe that they are *not* effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Total**
Already implemented	3.5 (4)	2 (2)	1 (1)	**6.5 (7)**
Planned or under discussion	1 (2)	0 (0)	0 (0)	**1 (2)**
Considered and rejected	1 (1)	1 (1)	1 (1)	**3 (3)**
Never considered	0 (0)	2.5 (3)	1 (1)	**3.5 (4)**
Don't know/no response	0 (0)	2 (2)	0 (0)	**2 (2)**
Total	**5.5 (7)**	**7.5 (8)**	**3 (3)**	**16 (18)**

Source: Authors' survey of transit agencies.

Escalator speeds can also affect pedestrian flows. One consultant described how escalator speeds in the United States are slower than in most other countries and suggested that safety concerns and fear of litigation prevented transit operators from experimenting with higher-speed escalators.

> "This continues to be a hot topic among transit planning professionals. The US uses the slowest speeds of any country for escalators due to safety concerns. Washington Metro has a lot of deep stations compared to most other legacy transit systems. The escalators travel at 90 feet [27 m] per minute, even though most of the newer equipment could be programmed for higher speeds. In Europe and in Asia, they run routinely at 120 or 150 feet [37 or 46 m] per minute. This has a dramatic effect on capacity for major urban stations. Travel times are almost cut in half using the higher speed escalators. … Safety concerns … are overcome in other systems through the use of a greater number of flat treads at the top and bottom of the escalator runs to allow for a transition time to adjust to the speed. [Nevertheless], our transit systems continue to use the slow speed equipment."[167]

However, even at the relatively low speeds at which escalators operate in the United States, they still move people more quickly than stairs, which have been observed to have a maximum flow rate of about 19 people per foot (0.3 m) per minute.[168,169]

Table 20. Use and Perceptions of Variable Escalator Flow Rates

	Believe that they are effective in improving passenger flows or station operations *Agencies (Respondents)*	**Don't know if they are effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Believe that they are *not* effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Total**
Already implemented	1 (1)	0 (0)	0 (0)	**1 (1)**
Planned or under discussion	0.5 (1)	0.5 (1)	0 (0)	**1 (2)**
Considered and rejected	1.5 (2)	0 (0)	1 (1)	**2.5 (3)**
Never considered	0 (0)	3.5 (4)	3 (3)	**6.5 (7)**
Don't know/no response	2 (2)	3 (3)	0 (0)	**5 (5)**
Total	**5 (6)**	**7 (8)**	**4 (4)**	**16 (18)**

Source: Authors' survey of transit agencies.

As summarized in Table 20, the use of variable escalator flow rates has not been considered by most transit agencies. About half the survey respondents had no opinion on whether variable escalator flow rates would improve passenger flows. Those who did have an opinion were almost as likely to believe that they would not be effective as to believe that they would be effective.

STATION PLATFORM

Station platforms serve as walkways, as passengers walk across the platform to get to and from train doors and vertical circulation elements, and as waiting areas, as passengers wait for their trains to arrive. There are two types of platform configurations: center platforms with the tracks on either side of the platform, and side platforms with the tracks in the middle of the station and one platform on either side. Center platforms must accommodate passengers boarding, alighting, and queuing for trains running in two directions. Thus, they are typically wider than side platforms. Center platform stations are also usually more expensive to construct because any money saved on few escalators and elevators is obviated by the need for larger escalators and elevators and, more importantly, the wider rail tunnels required at either end of the station to bring the tracks (and trains) around the center platform.

Fruin presents a level of service classification for pedestrian queuing and waiting areas,[170] which has also been adopted by the 2010 *Highway Capacity Manual* (for street corners at crosswalks) and by the *Transit Capacity and Level of Service Manual* (for waiting areas in transit stations). Similar to the level of service criteria for walkways and stairways, the criteria for queuing and waiting area levels of service are based on average space per person. Because flow rates are less relevant to queuing and waiting areas, thresholds are based on personal comfort and the ability of pedestrians to move through the crowd. They are shown in Table 21.

As conditions on a platform approach those described in Table 21 as levels of service E and F, not only can passenger comfort degrade, but so can passenger safety, as it becomes possible for passengers to inadvertently push one another onto the track.

Increasingly common on airport rail shuttle systems, platform screen doors, such as those shown in Figure 10, can mitigate this risk by creating a physical barrier between the platform and the track. Table 22 summarizes the prevalence of platform screen doors at North American transit agencies and the attitudes of survey respondents toward them.

Table 21. Level of Service Classification for Queuing and Waiting Areas

LOS	Average pedestrian space (ft^2/p)	Average inter-person space (ft)	Description	Illustration
A	≥ 13	≥ 4.0	Standing and free circulation through the queuing area possible without disturbing others within the queue.	
B	10-13	3.5-4.0	Standing and partially restricted circulation to avoid disturbing others within the queue is possible.	
C	7-10	3.0-3.5	Standing and restricted circulation through the queuing area by disturbing others is possible; this density is within the range of personal comfort.	
D	7-10	2.0-3.0	Standing without touching is impossible; circulation is severely restricted within the queue, and forward movement is possible only as a group; long-term waiting at this density is discomforting.	
E	3-7	< 2.0	Standing in physical contact with others is unavoidable; circulation within the queue is not possible; queuing at this density can be sustained only for a short period without serious discomfort.	
F	< 2	*Variable*	Virtually all people within the queue are standing in direct physical contact with others; this density is extremely discomforting; no movement is possible within the queue; the potential for pushing and panic exists.	

Source: Fruin 1971.

While platform screen doors are increasingly common in Europe and Asia, no North American transit operators currently use them, but four were planning (in 2014) to do so or considering the possibility. Five have considered the strategy but ultimately rejected it. In general, survey respondents appeared ambivalent about whether platform screen doors could improve passenger flows. Enthusiasm for platform screen doors as a means of improving safety may have cooled somewhat after a well-publicized incident in Hong Kong in 2007, in which a passenger trying to board a crowded train got caught between the platform screen and the train doors, fell onto the track, and became fatally injured as the train pulled away.[171] This is the only known incident of its kind, however, and platform screen doors are still far more likely to prevent people from falling onto train tracks than to cause such falls.

Figure 10. Platform Screen Doors and Platform Markings in Hong Kong (Left) and Paris (Right)

Source: Wikipedia Commons Users: Mailer Diablo and Greekski.

Table 22. Use and Perceptions of Platform Screen Doors

	Believe that they are effective in improving passenger flows or station operations *Agencies (Respondents)*	**Don't know if they are effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Believe that they are *not* effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Total**
Planned or under discussion	3 (4)	1 (2)	0 (0)	**4 (6)**
Considered and rejected	1 (1)	3 (3)	1 (1)	**5 (5)**
Never considered	0 (0)	2 (2)	0 (0)	**2 (2)**
Don't know/no response	0 (0)	5 (5)	0 (0)	**5 (5)**
Total	**4 (5)**	**11 (12)**	**1 (1)**	**16 (18)**

Source: Authors' survey of transit agencies.

One consultant suggested that some agencies hesitate to install platform screen doors at any location because they worry that they will improve safety so much that they will be forced to install them at all stations, which would be costly for large systems.

> "There's a lot of discussion in the US about the benefits of installing 'train screens.' The most common use of train screens (horizontal elevator doors is the best analogy) are in airport people-mover systems like San Francisco, Washington Dulles, Seattle, or Atlanta. So far in the United States, there's not a single transit system that has installed such devices. A number of the European systems such as Paris are retrofitting high-density stations with them. In London, the Jubilee line and new lines in Paris are using them. They are now standard practice in Hong Kong and Seoul, Korea for all new stations as well as retrofitting all other stations in their very highly utilized systems. They provide a safety barrier to the trainway as well as reduce the underground volume of the station itself for air conditioning. So you're improving the safety as well as comfort aspect, which probably gives you more capacity. New York City looked at

> using train screens on the new Second Avenue Subway Line but chose not to install them. Washington Metro has looked at such installations at very crowded stations such as Gallery Place. One of the major obstacles for the transit authorities is that if you install them in one or more stations, you've established a level of safety for a very small number of the total number of stations in their systems. New York has around 420 stations, with Washington Metro, [the number is] over 100. If somebody gets pushed into one of those other stations, 'Well why didn't you give us train screens?' The litigious issues come back once again to the US transit properties."[172]

Although platform screen doors may be costly, another consultant pointed out that they allow an operator to add effective capacity to a platform (by safely allowing more crowding and queueing of passengers near the platform edge) without increasing the actual width of the platform, which would be even more costly than adding platform screen doors (if widening the platform is even possible, which it often is not).

> "There are things like platform screen doors that can add capacity without having to expand the platform. So a lot of the new metro systems are built with those from the beginning."[173]

A third consultant went into more detail about how platform screen doors expand the capacity of a platform by eliminating the need for a wide platform edge strip that cannot be used as part of the passenger waiting area.

> "Systems that use platform screen doors (PSD) seem to improve both security and passenger flow. These are used in many places in Europe and here, mostly with automated people mover systems. This system may perhaps improve operating times by ensuring that the trainway remains clear at all times, and it allows passengers to queue up closer to the platform edge, which is a better use of constrained space, which in turn may allow passengers to board faster than the standard two-foot [0.6 m] detectable platform edge strip, which is space that cannot be used for boarding or circulation."[174]

Platform screen doors may be accompanied by platform markings to instruct passengers on the platform to stand to the side as passengers on the train alight, as shown in Figure 10. Even without platform screen doors, such markings can be helpful to indicate to passengers where on the platform the train doors will stop once the train arrives, in addition to indicating how to board and alight efficiently.

Although no North American transit operators currently use platform screen doors, six of the 16 surveyed agencies reported using platform markings to indicate the locations of train door entrances (Figure 11). Three more have considered installing such platform markings but eventually rejected the strategy. One indicated that platform markings are not feasible due to varying train car lengths and configurations within the agency's current rolling stock.

Table 23. Use and Perceptions of Platform Markings to Indicate Train Door Location

	Believe that they are effective in improving passenger flows or station operations *Agencies (Respondents)*	Don't know if they are effective in improving passenger flows or station operations *Agencies (Respondents)*	Believe that they are *not* effective in improving passenger flows or station operations *Agencies (Respondents)*	**Total**
Already implemented	6 (8)	0 (0)	0 (0)	**6 (8)**
Considered and rejected	0 (0)	1 (1)	2 (2)	**3 (3)**
Never considered	0 (0)	1 (1)	2 (2)	**3 (3)**
Don't know/no response	1 (1)	3 (3)	0 (0)	**4 (4)**
Total	**7 (9)**	**5 (5)**	**4 (4)**	**16 (18)**

Source: Authors' survey of transit agencies.

Figure 11. Platform Marking

Source: Washington Metropolitan Area Transit Authority.

It is important that passengers arriving at the platform have good visibility to aid wayfinding. Platform capacity can also be improved if platforms are designed with few obstacles, such as columns and staircases.

> "Column locations can be a constraint, especially for safe passage of riders in wheelchairs along the platform lengths."[175]

On the other hand, columns and staircases are necessary for overall station operations and for the structural integrity of the station. As noted:

> "You can't take away vertical circulation or basic structure. Most of the new stations have been designed to eliminate the need for columns. The Los Angeles subway system has columns in the existing stations, but [they] have eliminated them in the new extensions now in design and construction. Patrons have a greater sense of open space and free movement to and from the trains, escalators, stairs, and elevators, unconstrained by columns."[176]

TRAINS AND TRACKS

Passenger congestion on station platforms can be managed by either by increasing the capacity of the platform – possibly by increasing the platform width, removing obstacles, installing platform screen doors – or reducing the number of passengers who wait on a platform at a given time. One way to reduce the number of passengers on a platform is to reduce passenger wait times by decreasing train headways. On very busy rail lines, new forms of automatic train control can reduce headways beyond what would otherwise be possible, providing a perhaps overlooked opportunity to reduce passenger congestion on the platform through operations. On the other hand, however, research has shown that shorter headways are among the most effective ways to increase the attractiveness of public transit and attract more passengers,[177] which could cause crowding problems. One consultant described automatic train control as a relatively low-cost, short-term solution to platform congestion, compared with actually increasing the platform width.

> "Automatic train control allows for shorter segue, so they can run more trains more frequently in and out of the station, so they can bring great capacity onto the lines. Some of our clients are beginning to look at that, into the future, as a way to mitigate some of the delays that they are beginning to see in their forecasts because they won't have the ability to add more trains. So especially when you are looking at underground stations, it is costly to add additional platform capacity. So one way to vacate them is potentially shorter-term mitigation strategies, to look at [automatic train control] to get more riders on the line in the existing infrastructure that they have in terms of platform space."[178]

Another consultant used this as an example of the importance of considering the station as an entire system rather than as a collection of individual elements.

> "Trains can get closer to each other because the signal systems are improving, which means more people can move through the system. Then we are thinking about the whole system, so what does that mean for my platform? Does it need to be wider? Do I need more elements to get out of there? I think this whole system approach to each station, I'm seeing more and more being considered. It's how does the whole building operate, how does the whole station operate?"[179]

As summarized in Table 24, a respondent from only one rail system reported that his or her agency has not considered implementing automatic train control, and no survey respondents reported believing that automatic train control would not be effective in improving passenger flows (although four reported that they did not know).

Table 24. Use and Perceptions of Variable Automatic Train Control

	Believe that they are effective in improving passenger flows or station operations *Agencies (Respondents)*	**Don't know if they are effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Believe that they are *not* effective in improving passenger flows or station operations** *Agencies (Respondents)*	**Total**
Already implemented	9 (10)	2 (2)	0 (0)	**11 (12)**
Planned or under discussion	3 (4)	1 (1)	0 (0)	**4 (5)**
Never considered	0 (0)	1 (1)	0 (0)	**1 (1)**
Total	**12 (14)**	**4 (4)**	**0 (0)**	**16 (18)**

Source: Authors' survey of transit agencies.

The layout of train cars themselves can also improve passenger flows by allowing passengers to find a seat more quickly, facilitating faster boarding and alighting times, reducing train dwell times, and allowing agencies to reduce train headways.

Kogler and colleagues have used simulation models to demonstrate how longitudinal seating arrangements can improve boarding and alighting times relative to transverse seating, and how even simple modifications to a train layout can have an appreciable impact on the ability of passengers to quickly reach a seat.[180] Chicago Transit Authority staff have also found that longitudinal seating arrangements can reduce train dwell times, although they have questioned whether these arrangements increase the capacity of individual train cars.[181] The number of doors on each car can also significantly affect boarding and alighting times, with three- (or even four-) door cars typically having shorter dwell times than two-door cars. Decisions over the arrangement of seating and the number of doors, however, depends on a wide array of factors related to the desired ratio of standing to seated passengers, which in turn depends on average trip length of passengers and the average distance between stations: On systems with longer average trip lengths and longer station spacings, the higher proportion of seats on cars with transverse seating can substantially enhance passenger comfort and satisfaction, if at the cost of longer station dwell times.

Table 25 summarizes the aforementioned design recommendations for the different station components indicating if these can be enacted during a station retrofit. As discussed at the outset of this chapter, the choice of appropriate design strategies described in this section requires awareness of the external (particularly financial) constraints on the station design and should target the integration of each station element with the overall operations of the entire station.

Table 25. Design Recommendations for Better Passenger Flows

Station components	Design recommendations	New station design	Station retrofit
Overall station	- System design; good integration, connections with surrounding streets and parking lots	X	
Entrances	- Location of entrances in relation to surrounding streets and parking structures	X	
	- Multiple entrances	X	
Signage/ messaging	- Real-time electronic displays of train arrivals	X	X
	- Location and distribution of signs on platform to facilitate visibility and avoid crowding	X	X
	- Signage for emergency directions and indicating exit routes	X	X
	- Visual displays and audible instructions for boarding and alighting	X	X
Fare gates	- Replacement of turnstiles with smart cards or tap cards	X	X
Vertical circulation elements	- Appropriate location	X	X
	- Variable escalator flow rates		
	- Escalator sensors		
Platform	- Appropriate platform width	X	
	- Good platform visibility; elimination of obstacles, blind spots		X
	- Column-free design	X	
	- Platform screen doors		X
Mezzanine	- Arrangement of surface and track vertical circulation elements	X	
	- Sufficient space for purchasing tickets and processing passengers to and from the trains	X	
	- Retail, restrooms, and other passenger-serving amenities	X	X
Transit vehicle	- Longitudinal versus transverse seating arrangements		
	- Number of doors on each car		

VI. CONCLUSIONS AND RECOMMENDATIONS

The preceding sections of this report have presented observations and findings from the research team's review of scholarly and technical literature related to passenger flows at underground rail transit stations, the interviews with practitioners who have expertise in planning and designing for passenger flows in stations, and the results of the online survey conducted among railway transit operators in the US and Canada that operate heavy-rail transit stations. Across these three sources of information, the researchers identified three consistent themes regarding the planning of passenger movements and queueing in rail transit stations:

1. The importance of considering transit stations as complete systems rather than reductively in terms of individual station components;

2. The importance of cooperation and coordination among analysts, planners, and designers with responsibility for different aspects of station design and operations; and

3. The importance of the contexts in which passengers experience a transit station. For instance, the same transit station may be for many a transfer hub for day-to-day travel, for some a destination for social or economic activity, and for others, occasionally a source of shelter from unpleasant weather. Moreover, passenger flows and queueing often occur as a result of routine commuting but may also present different characteristics and challenges during special events or emergency evacuations.

The purpose of this closing section is to suggest specific strategies that may be useful to transit analysts, planners, and designers seeking to accommodate passenger flows and queuing in their rail transit stations. The recommendations are categorized as relating to analysis, operations, messaging and wayfinding, and station design. Within these four categories, strategies are further classified as short term, medium term, and long term. This latter classification may stem from one or more reasons. A strategy may be classified as short term because it provides only temporary relief from ongoing issues, because it can be implemented quickly and at a low cost, or because it must be carried out repeatedly to be effective. A strategy may be classified as long term because, once implemented, it may be difficult to modify, or because it is costly enough that it may require several years of planning and budgeting to fully implement.

The contextual characteristics of each station are also very important. Not every strategy described in this section is appropriate for every station or at every agency. Transit operators are urged to carefully consider local context as they select appropriate strategies to accommodate passenger flows within their respective systems.

ANALYSIS STRATEGIES

The purpose of quantitative analysis of passenger flows is to identify pedestrian needs, under observed and anticipated conditions. This analysis is not the only means of identifying such needs and should be used in concert with other methods, such as gathering passenger comments and complaints and responding appropriately to incidents.

Short Term

In the short term, agencies can begin each analytical exercise by clearly defining the question that the analysis seeks to address and selecting a modeling or analytical approach that can appropriately answer that question. Table 9 in Chapter IV lists some potential questions that may be associated with a particular design, as well as the most appropriate analysis tool to answer each question.

As discussed above, stations are components of larger systems that interact and are influenced by both the rail network and the neighborhood surrounding each station. Therefore, an additional short-term practice that can improve pedestrian queueing and flow analysis is to use information about current and anticipated land uses and travel flow patterns adjacent to the station to determine the most common origins and destinations of pedestrian flows within the station at different times of the day and week.

Medium Term

In the medium term, transit operators can establish processes and systems that encourage coordination and knowledge sharing between consultants and agency staff as well as among analysts, planners, and designers. Such coordination can improve the relevance of the analysis by giving analysts a better understanding of the questions being asked, and empowering them to select the most appropriate tools to answer them. It can also help designers to ask analysts the right questions. To the extent designers and decision-makers see analysis as a “black box,” they are less able to apply the information it can provide to their decision-making.

Long Term

Transit agencies should occasionally examine the requirements published in various standards and codes to determine how well they apply to the extant circumstances. In cases in which existing standards are very conservative, such that they result in stations that are consistently over-designed with respect to all other passenger queuing and flow parameters, transit agency staff may do one of three things. They can accept the additional margin of safety that the codes provide, or they can argue that the standards and codes need not be adhered to (where they are not bound into regulatory code), or they can request that the standards and codes ought to be relaxed in light of changing circumstances (where they are bound into administrative law).

On the other hand, in cases in which existing standards and codes are found to be inadequate with respect to passenger comfort or safety, transit agency staff may choose to codify their own, more demanding standards to ensure that passenger needs and safety will be consistently met.

Transit staff should also occasionally reexamine the assumptions that are routinely used for passenger queuing and flow analyses to determine whether they continue to adequately describe the characteristics of the pedestrians using the system. These assumptions may not change significantly from year to year, but they may drift enough over decades to require occasional adjustment. One such assumption might be the average space required by each pedestrian, whether due to physical dimensions, objects being carried, or tolerance for proximity to other pedestrians. Another is the average walking speed of a pedestrian. Both of these characteristics may vary enough by age, gender, and disability that it would be appropriate to collect data separately for different categories of passengers patronizing the transit system and their distribution within the passenger population.

OPERATIONS STRATEGIES

Agency staff members responsible for planning and designing rail transit stations are typically not responsible for decisions about train operations. However, train operations and station design both influence the flow of passengers through the station. The physical design of the station influences how quickly pedestrians are able to move through the station. Train headways in conjunction with passenger arrivals at the platform combine to affect the number of people who are in a station, particularly on the platform, at a given time. When trains arrive and depart more frequently, there is less time for crowds of passengers to accumulate on a platform. Headways may also influence how quickly passengers prefer to move through the station. For example, at a station serving a line with longer headways, passengers may rush to get on to a departing train rather than waiting for the next one. When headways are shorter, they may feel less urgency to run for the next train.

Fare policies and fare collection technologies may be similarly beyond the control of physical station designers, but they too have a major influence on passenger crowding by alleviating or exacerbating bottlenecks in ticket purchase areas and at the fare collection gates.

Short Term

In the short term, agencies can improve coordination between operations and design staff so that changes in the physical station environment can trigger the consideration of changes to train operations, and vice versa. For example, if a platform area is temporarily reduced during a construction or renovation project, it may be appropriate to address the resulting passenger crowding by temporarily increasing train headways. If, on the other hand, train headways must be reduced due to limited agency resources, planners and designers might anticipate increased platform crowding and consider steps to increase capacity at stations with already congested platforms, or to use existing capacity more efficiently.

Transit agency planners may also seek to temporarily relieve bottlenecks at fare collection gates by changing fare collection policies. For instance, human ticket checkers may supplement fare gates before and after major sporting and public events to more quickly clear large platoons of passengers moving out of or into certain stations. In Los Angeles, for example, this strategy is employed for University of Southern California football games hosted at the Coliseum.

Medium Term

When station platforms are consistently crowded due to ongoing circumstances (as opposed to temporary capacity reductions due to construction), it may be appropriate for an agency to consider the costs and benefits of investing in additional rolling stock and train operators to allow more frequent service to congested stations vis-à-vis the cost of adding platform capacity to an already constructed station.

The adoption of new fare collection technology can also improve station operations by alleviating bottlenecks at fare gates. In general, gates that require passengers to swipe a card through a card reader can process passengers more quickly than those in which passengers must insert a ticket. Tap cards can generally process passengers more quickly than traditional magnetic stripe cards. Radio-frequency identification (RFID) technology currently used for open-road tolling on some highways can be employed in transit fare collection to process passengers even more quickly than tap cards. This would allow passengers to simply move through ticket gantries without removing their tickets or TAP cards at all.

Turnstiles can prevent most passengers from entering the station without paying a fare, but they can significantly impede passenger flows in and out of loading areas. A proof-of-payment system in which agency personnel make random checks to ensure that all passengers in a station have paid a fare may reduce bottlenecks, but it results in both lost revenue and increased inspector costs. In deciding between the use of turnstiles and a proof-of-payment system, an agency must determine whether congestion relief or revenue capture and inspection costs is the more pressing concern.

Long Term

On very busy transit lines, headways are limited not by the number of available trains, but by the required distance that must be maintained between human-operated trains in order to prevent collisions. In these cases, automatic train control (ATC) systems can allow agencies to operate at very short headways, reducing the need for passengers to wait on the platform for more than a few minutes.

MESSAGING AND WAYFINDING STRATEGIES

Many passenger congestion issues may not be the result of insufficient platform or station capacity, but rather of passengers not using the available capacity as efficiently as they might. Signage and messaging may encourage more efficient use of available passenger capacity. This may be done either by explicitly directing passengers or by otherwise making more efficient use of space.

As with operations decisions, signage and messaging decisions may be handled by individuals within a transit agency other than the station planners and designers. Close coordination between signage and messaging designers and the planners and designers of the physical station area increases the likelihood that pedestrians will be able to navigate through stations intuitively and efficiently.

Short Term

In some cases, passengers may move more slowly because they are unsure about how to navigate the station. A short-term solution to this type of passenger confusion may be to place visible and approachable transit personnel at passenger decision points during times of highest demand. These individuals can answer passenger questions and direct them to the most appropriate path toward their destinations. Information personnel can also be a valuable means of determining what type of signage and messaging is necessary because they can report on common questions and sources of passenger confusion.

Audible instructions to passengers can be as important as visual messaging to encourage efficient use of station capacity. Audible instructions should supplement and complement visual instructions. At a minimum, care should be taken to ensure that audible instructions do not contradict visual instructions or overwhelm patrons with a cacophony of instructions.

Permanent, static signage is appropriate to convey information that may change rarely if at all, but not for regularly changing information. Examples of the former include transit system maps, maps of the surrounding street environment, directions to major buildings on the surface, and transit schedules. Static signage may also be helpful to communicate emergency evacuation routes and procedures. Such signage should be as simple and understandable as possible because panicking passengers are unlikely to take the time to read, or possibly even notice, complicated instructions during an evacuation.

Signs should be placed in locations that are clearly visible from passenger decision points, but they should be away from bottleneck locations, such as at fare collection gates or in the areas immediately at the tops or bottoms of staircases and escalators. On platforms, both static and dynamic signs may be placed in underutilized areas of the platform to encourage passengers to disperse along the entire platform length. Signs might also explicitly direct passengers to underutilized portals, pathways, areas of the platform, or even to underutilized stations that serve the same destinations as more congested stations.

Medium Term

Guo has found that the design of transit system maps can affect the path choices of transit patrons by making some routes look more direct than others or by making transfers between transit lines appear to be more or less difficult.[182] When a particular station in a system becomes very congested, an agency may redesign its transit system maps to make other, less congested stations in the system appear more convenient.

Dynamic signage to indicate upcoming train arrival times has become very popular with passengers. When placed on the mezzanine level or outside station portals, these messages

might reduce congestion on the platform by signaling to pedestrians that they do not need to enter a crowded platform until just before their train arrives. Dynamic messaging based on real-time train locations may be costly to implement, however. As an interim strategy, dynamic signs could be used to communicate scheduled train arrival times. At stations where arrival times are very reliable, this could be a relatively low-cost solution that offers most of the same benefits as true real-time arrival messaging. However, when train arrival times are not predictable or reliable, such signs would be consistently inaccurate, possibly leading to greater passenger frustration than if no such messaging were provided.

Dynamic signage can also be used to convey information other than train arrival times, such as boarding and alighting instructions, temporary schedule changes, suggested routes to popular destinations and special events, and even emergency evacuation instructions. Additionally, many transit agencies are developing applications that their passengers use to get real-time information about bus and train schedules; in the case of emergency evacuations, passengers may visit these applications to receive special instructions from the transit operator.

Long Term

Dynamic signs that display train arrival times based on their real-time locations are even more useful to passengers than those that simply convey scheduled arrival times. Particularly in larger, older systems, this may require significant, costly retrofits to train vehicles and train signals.

STATION DESIGN STRATEGIES

Design strategies to manage passenger congestion tend to be implemented within a particular station area, although their effect may propagate throughout the station. Below, the report describes strategies that can be implemented at station portals and entrances, vertical circulation elements, and the station platform itself. As in the preceding subsections, strategies are classified as short-term, medium-term, and long-term.

Short Term

The short-term design strategies discussed below might apply best to existing stations in which passenger congestion has become a problem but where immediate changes to the physical design of the station are not feasible.

Portals and Entrances

When portals and station entrances become congested, signage and messaging strategies discussed in the preceding subsection can delay the need for more costly medium- and long-term interventions. For example, when a station has multiple portals but only one portal is congested, signs can direct passengers to use the less congested portal.

As discussed in the subsection on signage and messaging, wayfinding signs should be placed so they are visible from the station entrance but not in areas that would create or exacerbate bottlenecks when passengers stop to read them.

Vertical Circulation

When stairways and escalators become congested, adding additional capacity by widening them or constructing additional vertical circulation elements may not be feasible in the short term. Stairways can accommodate higher pedestrian flow rates when passenger flows are unidirectional rather than bidirectional. When a platform is served by multiple stairways that have become congested with bidirectional pedestrian flows, restricting stairway traffic to a single direction might increase vertical circulation capacity (though at the cost of increasing the average level of on-platform passenger movements). For example, one staircase could be restricted to flows upstairs while the other is restricted to flows downstairs; while such restrictions are easy to enforce with escalators, enforcement on stairs can be more problematic when hurrying passengers ignore the restrictions.

Platforms

When platforms become crowded, it may be a result of passengers failing to disperse evenly along the length of the platform. In such cases, it may be possible to induce passengers to fully utilize the existing platform capacity rather than creating additional capacity. One low-cost way to disperse passengers along the platform length is to alert them when longer train sets are running, making it clear that they do not risk missing a train by waiting at either end of the platform. Another is to place amenities such as coffee carts or information kiosks at locations that are underutilized. On the other hand, these amenities take up space on the platform and could reduce overall platform capacity. Individual circumstances will determine whether the trade-off will result in a net improvement in platform crowding.

Another way to encourage passengers to disperse more evenly along the platform length is to vary the stopping locations of trains so some trains stop at one end the platform while others stop at the other end. This may be especially appropriate if a platform serves multiple train lines so trains from the same line continue to stop in a consistent location. If the trains' stopping locations are unpredictable, this could slow the boarding process and increase train dwell times, which could in turn reduce the minimum achievable headway and negatively affect schedule reliability.

Markings on the station platform can indicate to passengers where train doors will be situated when the train arrives, and they also would instruct them to allow alighting passengers to exit the train before they board. This is increasingly common on US rail transit systems, as it is thought to reduce the time required for boarding and alighting, allowing shorter headways, which can in turn relieve platform crowding. In the absence of platform screen doors, which separate passengers on the platform from the rail bed, raised strips are usually used to warn passengers (even sight-impaired passengers) not to stand too close to the platform edge.

Medium Term

The following strategies require more time and resources than the short-term strategies discussed above, but they could represent cost-effective retrofits to existing stations experiencing passenger congestion.

Portals and Entrances

Pedestrian flows through portals and entrances can be improved by creating clear lines of sight to all signs and messages, allowing pedestrians to quickly proceed to their destinations without missing important messages. At the same time, visual clutter such as station artwork or advertising can be minimized in areas where passengers may need to move more quickly without slowing to observe visual distractions.

Vertical Circulation

The maximum allowable flow rate on an escalator is controlled in part by the speed at which the escalator operates. Transit operators could seek to improve passenger flows through a station by varying escalator speeds according to their needs. For example, if the escalator itself is a bottleneck, an operator might increase escalator speeds to move passengers more quickly, though this can prove problematic for older riders. If a station platform is extremely crowded even with very short train headways, an operator may store some passengers on the mezzanine level rather than the station platform by slowing down the escalators, intentionally creating a bottleneck. In concept, this strategy would be similar to ramp metering strategies that are used on some highway onramps during peak periods.

Platforms

Platform capacity can be expanded in the medium term by removing platform furniture (such as seating), free-standing signage, or columns (if this can be done without compromising the structural integrity of the station). The removal of seating and messaging can increase platform capacity at the expense of passenger comfort and wayfinding, however. Station designers should carefully consider whether such trade-offs would be worthwhile, considering current and anticipated passenger needs.

Another way to expand platform capacity is through the use of platform screen doors. Train platforms typically require a two-foot buffer to prevent passengers from standing too close to the platform edge and potentially falling onto the track. Platform screen doors eliminate the need for such a buffer, expanding the effective width of the platform by about two feet (0.6 m).

Long Term

The strategies discussed below would be appropriate for incorporation into the construction of new stations as a solution to anticipated passenger congestion. They might also be considered as long-term retrofits for existing stations.

Portals and Entrances

When all portals providing access to a station become congested or are poorly integrated into the adjacent street environment, it may be advisable to construct additional portals to the street or substantially reconstruct existing ones. This can be very costly at existing stations, and in some cases it may not be possible or feasible at all. When new stations

are constructed, care must be taken to include enough portals and to place them to serve the surrounding land uses as well as possible. After construction has been completed, the number and location of portals and entrances are the most difficult aspects of the station design to correct after-the-fact.

Vertical Circulation

At stations where vertical circulation exhibits strong directional peaking, bidirectional escalators can increase vertical circulation capacity in one direction. For example, if a station is served by two escalators and a stairway, and most passengers are entering a platform during the morning peak period and exiting a platform during the evening peak, escalator capacity can be doubled by running both escalators in the same direction during peak periods (down in the morning, up in the evening), compared with the case in which one escalator runs up and the other runs down.

Escalators with sensors can also be used, so the escalator does not move when it is unoccupied. If a passenger approaches the top of an escalator that is not moving, the escalator begins to move in a downward direction. When a pedestrian approaches the bottom of an escalator that is not moving, the escalator begins to move in an upward direction. Because the escalator can move only in one direction at a time, if passengers approach the escalator from the top and bottom simultaneously, the direction of movement will be determined by whichever passenger is detected first. This design can reduce power consumption in addition to potentially allowing more efficient use of vertical circulation capacity.

In the long-term, some operators may find it necessary to construct additional staircases, escalators, or elevators. These changes may be costly after station construction. When possible, stations should be constructed with adequate vertical circulation from the beginning.

Platforms

When stations are still in the planning and design stages, the simplest way to alleviate anticipated passenger congestion in the platform areas may be to design the station with wider or longer platforms than might initially be required. In circumstances in which track geometry, geological factors, or surrounding buildings do not allow as much platform area as would otherwise be desirable, some of the short- and medium-term strategies discussed above may be used to maximize available capacity.

Widening platforms that have already been constructed may be cost prohibitive or infeasible from a practical perspective. However, if the other strategies are ineffective in maximizing platform capacity within existing geometric constraints, agencies may consider platform widening as a long-term solution to ongoing station congestion.

Table 26. Short-, Medium-, and Long-Term Strategies for Managing Passenger Flows

	Short-term	Medium-term	Long-term
Analysis	• Select tools and methodologies based on the question to be answered • Use surrounding land use and pedestrian traffic patterns as an input to analysis	• Encourage coordination and knowledge sharing among the various specialists responsible for aspects of the passenger experience	• Reevaluate requirements of standards and codes • Reevaluate assumptions about pedestrian characteristics
Operations	• Establish processes by which changes in train headways trigger evaluation of platform crowding, and vice versa • Consider fare policy changes	• Consider reduced train headways • Consider more efficient fare collection	• Initiate automatic train control
Messaging and wayfinding	• Ensure that visual instructions reinforce and do not contradict audible instructions. • Add visible station staff to assist passengers • Ensure visual instructions to split passengers between pathways, portals, or stations • Locate signs and information to manage pedestrian dispersion	• Initiate dynamic messaging for scheduled train arrival time • Initiate dynamic messaging for other information • Redesign transit system maps to discourage use of crowded stations	• Initiate dynamic messaging based on real-time train locations
Design			
Portals and entrances	• Implement signage and messaging strategies	• Reduce visual clutter • Create clear lines of sight to mezzanine or fare collection area	• Build additional portals
Vertical circulation	• Consider one-way stairways to maximize bidirectional flow rates	• Adjust escalator speeds	• Use escalators that can vary in direction • Construct new vertical circulation elements
Platforms	• Add amenities to disperse passengers along the platform • Vary stopping locations of trains • Use platform markings to indicate locations of train doors	• Install platform screen doors • Remove columns, free-standing signs, or furniture	• Widen the platform

Table 26 summarizes the strategies described in this section. The strategies listed in the table should be thought of as a menu of potential options to be considered, in which the appropriate choice depends on the specific issues that exist at a station; the spatial, political, and budgetary constraints faced by an agency; and the predictability of future passenger flow conditions. The authors encourage transit station planners and designers to avoid universal rules-of-thumb and instead to make decisions based on the unique conditions within their own systems while also learning from the experiences of other transit operators.

APPENDIX A: LIST OF INTERVIEWEES

Please note that all quotations are based on the interviewees' own professional opinions and expertise and do not necessarily represent the interviewees' employers.

Greg Benz
Senior Vice President
Parsons Brinckerhoff

Robin Blair
Director of Planning, Operations, and Parking
Los Angeles County Metropolitan Transportation Authority

Vincent Chang
Partner
Grimshaw Architects

Robert Davidson
Senior Vice President
STV

Roderick Diaz
Director, Systemwide Planning/Transit Corridors
Los Angeles County Metropolitan Transportation Authority

Jenna Hornstock
Deputy Executive Officer, Countywide Planning and Development
Los Angeles County Metropolitan Transportation Authority

Mark Ingram
Director of Traffic Engineering
Cobb, Fendley, and Associates, Inc.

Michael Kennedy
Senior Transportation Planner
Fehr and Peers

Hanan Kivett
Senior Transit Architect/Manager
Parsons Transportation Group

Jeremy Klopp
Principal
Fehr and Peers

Judy Kunoff
Chief Architect
Metropolitan Transportation Authority, New York City Transit Authority
Kathryn Lim
Assistant Vice President
Parsons Brinckerhoff

James McConnell
Senior Vice President
HDR

Patrick O'Mara
Senior Transportation Engineer
STV

Ryan Park
Senior Transportation Engineer
AECOM

Stave Scalici
Senior Associate
STV

APPENDIX B: INTERVIEW INSTRUMENT

Please describe your background and experience with the design of public transit stops and stations generally, and specifically with analyzing passenger queuing and flows?

1. In your experience, is planning for passenger flows in transit stations typically handled in house by transit agency staff, or is such work mostly done by consultants?

2. Under what circumstances are (or should) forecasts, studies, or analysis of passenger flows conducted?

3. How have methods and assumptions used in planning for pedestrian flows to change over time? How should they change in the future?

4. In your experience, what are the principal challenges to planning for passenger movement (flows) in railway stations?

5. What are some of the specific characteristics of rail transit stations that affect or constrain the movement of passengers in underground railway stations? This would include both physical characteristics and station operations strategies.

6. In what ways do established evacuation procedures for emergency situations vary from station to station, or from agency to agency?

7. What innovations are you aware of that have been utilized to improve passenger flows in underground railway stations? New technologies? Signage and messaging? Station design and retrofit? Policy and operational?

8. What specific transit systems can you think of that have successfully implemented innovative strategies to improve passenger flow and train dwell time?

APPENDIX C: TRANSIT OPERATORS RESPONDING TO ONLINE SURVEY

Baltimore Mass Transit Administration

Bay Area Rapid Transit

BC Transit

Camden, New Jersey Port Authority Transit Corporation

Chicago Transit Authority

Greater Cleveland Regional Transit Authority

Los Angeles County Metropolitan Transportation Authority

Massachusetts Bay Transportation Authority

Metro Atlanta Rapid Transit Authority

Metropolitan Transportation Authority, New York City Transit Authority

Miami Metro-Dade Transit Agency

Newark Port Authority Trans-Hudson Corporation

Société de Transport de la Communauté Urbaine de Montréal

Southeastern Pennsylvania Transportation Authority

Toronto Transit Commission

Washington Metro Area Transit Authority

APPENDIX D: SURVEY INSTRUMENT

Welcome

How do transit agencies plan for passenger queuing and flows in rail stations?
We want your views and opinions

Overview

At the request of the Federal Transit Administration, the Mineta Transportation Institute is examining how transit agencies analyze, plan, and design for passenger queuing and flows in rail transit stations. We have carefully reviewed work written on the topic and have interviewed several consultants and station design experts about the tools and techniques they use. We now turn to you, the transit agency expert, to learn (1) whether and how such tools and techniques are used in the real world, and (2) what could and should be done to improve current practice.

This survey

This should only take 10 to 15 minutes to complete. We will not identify you, your title, or your organization in any of the work we publish or present on this survey – unless you give us explicit permission to do so. Your participation is completely voluntary; there are no negative consequences for you or your agency by not participating, and you are free to discontinue participation at any time. Answer as many questions as you can, and feel free to skip questions that may not apply to you or your agency. Comment boxes are provided in case you wish to clarify any of your responses.

If you would like to receive a copy of our final report, you can request one at the end of the survey. Should you have any questions about this survey, or our study, you should contact Carole Turley at (caroleturley@ucla.edu) or Anastasia Loukaitou-Sideris (sideris@ucla.edu).

Thanks in advance for your help in improving transit planning practice!

Background

Please provide your name and contact information

Name:_____
Title:_____
Email:_____
Telephone:_____

How knowledgeable are you about planning and designing for passenger queuing and flows at rail stations in your agency?

- Very knowledgeable
- Somewhat knowledgeable
- Not very knowledgeable
- Not knowledgeable at all

Who else in your organization would you recommend we contact on this topic?
Name:_____
Title:_____
Email:_____
Telephone:_____

*Comments:*_____

Agency Roles and Responsibilities

For each type of work described below, please indicate to what extent the work is done by in-house staff or by outside consultants.

	All work done in-house	Most work done in-house, some by consultants	Evenly split between in-house staff and consultants	Most work done by consultants, some in-house	All work done by consultants
Collecting data on existing passenger volumes and passenger crowding	o	o	o	o	o
Forecasting future passenger volumes	o	o	o	o	o
Analyzing existing or future passenger levels of service, queuing, or flows	o	o	o	o	o
Designing passenger-serving station areas	o	o	o	o	o

What is/are your role(s) in planning and designing for passengers at rail stations in your system (select all that apply)?

- ❑ Conducting analysis such as passenger volume forecasts and level-of-service analysis
- ❑ Managing analysis by others
- ❑ Interpreting analysis as a basis for capital investment and operations decisions
- ❑ Designing station areas to serve passengers
- ❑ Other (please specify)

Comments:_____

Design of New Stations

For how many new rail transit stops or stations has your agency completed detailed design work in the past decade?

- None
- One
- Two
- Three
- Four or more
- Don't know

For how many new rail transit stops or stations were you personally involved in planning, analysis, or design work in the past decade?

- None
- One
- Two
- Three
- Four or more

Comments:_____

Design of New Stations

For the following questions, please consider the most recent *new* rail transit station for which your agency completed detailed design work and for which you were personally involved in planning, analysis, or design.

How much of a challenge was the optimization of passenger queuing and flows?

Not a challenge				Very Challenging
(1)	(2)	(3)	(4)	(5)

Which tools or considerations applied to each of the following tasks (select all that apply)?

	Deterministic spreadsheet analysis	Microsimulation software	Consistency with other stations in system	Correction for problems at other stations in system	Best practices observed in other transit systems	Design based on published standards and codes	Don't know
Determining sizes for waiting and walking areas	☐	☐	☐	☐	☐	☐	☐
Selecting the type of fare collection machines and gates	☐	☐	☐	☐	☐	☐	☐
Determining the number of fare collection machines and gates	☐	☐	☐	☐	☐	☐	☐
Selecting locations of fare collection machines and gates	☐	☐	☐	☐	☐	☐	☐
Selecting the type of vertical circulation elements (e.g. stairs and escalators)	☐	☐	☐	☐	☐	☐	☐
Determining the number of vertical circulation elements	☐	☐	☐	☐	☐	☐	☐
Selecting locations for vertical circulation elements	☐	☐	☐	☐	☐	☐	☐

What design or operations issues at existing stations did you attempt to correct for in new station design?

- ❑ None; design is intended to be consistent with other stations
- ❑ Bottlenecks at fare collection gates
- ❑ Bottlenecks at vertical circulation elements
- ❑ Delays associated with boarding and alighting
- ❑ Overcrowding at station platform
- ❑ Passenger confusion due to inadequate wayfinding
- ❑ Other (please specify)

Comments:_____

Station Retrofits

What design or operations issues does your agency experience at existing stations?

- ❑ None that would justify corrective action
- ❑ Bottlenecks at fare collection gates
- ❑ Bottlenecks at vertical circulation elements
- ❑ Overcrowding at station platform
- ❑ Passenger confusion due to inadequate wayfinding
- ❑ Other (please specify)

In the past decade, for how many existing stations has your agency planned or implemented changes to improve passenger circulation?

- None
- One
- Two
- Three
- Four or more
- Don't know

What criteria do you use to determine whether a retrofit is needed at a particular station (select all that apply)?

- ❑ Passenger surveys
- ❑ Passenger complaints
- ❑ Passenger incident analysis
- ❑ Current or forecast passenger volumes
- ❑ Technical studies (including modeling or level-of-service analysis)
- ❑ Station centrality (e.g. key transfer stations)
- ❑ Other (please specify)

In the past decade, has your agency had to defer or cancel proposed retrofits?

- Yes
- No
- Don't know

Comments:_____

Why has your agency had to defer or cancel planned retrofits in the past decade (check all that apply)?

- ❑ We have not had to cancel or defer planned retrofits
- ❑ Budget constraints
- ❑ Lack of needed staff or other resources
- ❑ Lack of required approvals or permits
- ❑ Don't know
- ❑ Other (please specify)

For the following questions, consider the most recent station retrofit your agency undertook and in which you were personally involved.

Which station area(s) did the retrofit change?

- ❑ Mezzanine
- ❑ Platform
- ❑ Vertical Circulation
- ❑ Ticketing areas
- ❑ Entrances/exits
- ❑ Other (please specify)

Please provide a brief description of the retrofit

_____
_____
_____
_____

What motivated the retrofit?

	Primary motivation	Secondary motivation	Recognized benefit (not a motivation)	Not a motivation or benefit	Don't know
Funding availability	☐	☐	☐	☐	☐
Compliance with NFPA 130 or fire code requirements	☐	☐	☐	☐	☐
Compliance with ADA requirements	☐	☐	☐	☐	☐
Compliance with other state or local codes	☐	☐	☐	☐	☐
Passenger congestion	☐	☐	☐	☐	☐
Response to a particular incident	☐	☐	☐	☐	☐
Litigation	☐	☐	☐	☐	☐

To what extent do you believe the retrofit improved passenger flows?

No improvement				Major improvement
(1)	(2)	(3)	(4)	(5)

Comments:_____

Managing Passenger Flows

Over the past decade, has your agency improved signage, messaging, and/or wayfinding to improve passenger flows at any rail stations?

- Yes
- No
- Don't know

What is your agency's experience with each item below?

	Currently implemented at one or more stations	Planned or under discussion	Has been considered and rejected	Never considered	Don't know
Real-time displays about train arrivals	o	o	o	o	o
Dynamic signage for other passenger information	o	o	o	o	o
Platform markings to indicate train door entrances	o	o	o	o	o
Audible instructions during boarding and alighting	o	o	o	o	o
Visual instructions to improve boarding and alighting	o	o	o	o	o
Variable escalator flow rates	o	o	o	o	o
Variable escalator directions	o	o	o	o	o
Automatic train control	o	o	o	o	o
Platform screen doors	o	o	o	o	o

What is your own perception of the effectiveness of each item below in improving passenger flows and/or station operations?

	Is/would be effective	Is/would not be effective	Don't know
Real-time displays about train arrivals	o	o	o
Dynamic signage for other passenger information	o	o	o
Platform markings to indicate train door entrances	o	o	o
Audible instructions during boarding and alighting	o	o	o
Visual instructions to improve boarding and alighting	o	o	o
Variable escalator flow rates	o	o	o
Variable escalator directions	o	o	o
Automatic train control	o	o	o
Platform screen doors	o	o	o

*Comments:*_____

Experience with Passenger Crowding

Please indicate the degree of crowding your agency experiences at your busiest rail station in each of the following areas.

	Substantial crowding	Some crowding	Not much crowding	No crowding	Don't know
Ticketing areas	o	o	o	o	o
Entrances and exits to paid areas	o	o	o	o	o
Vertical circulation elements	o	o	o	o	o
Station platforms	o	o	o	o	o

What has your agency done, or what does your agency plan to do to address crowding in areas where it is a problem?

_____
_____
_____
_____

*Comments:*_____

Thank you very much for your time. Your participation in this survey is greatly appreciated.

Is there anything else you would like us to know about planning, analyzing, managing, and/or designing for passenger flows at rail transit stations?

_____
_____
_____
_____

APPENDIX E: ADDITIONAL RESOURCES

The following resources present specific methods for analyzing and designing for passenger flows. We have not attempted to repeat those methods here. Instead, we refer the reader to the following publications:

Fruin, John J. 1971. *Pedestrian Planning and Design*. Metropolitan Association of Urban Designers and Environmental Planners.

Kittleson & Associates, Inc., KFH Group, Inc., Parsons Brinckerhoff Quade & Douglass, Inc., and Katherine Hunter-Zaworski. 2003. *Transit Capacity and Quality of Service Manual*. 2nd ed. Washington DC: Transportation Research Board.

KONE Corporation. 2014. *Planning Guide of People Flow in Transit Stations*. Espoo, Finland: KONE Corporation. Accessed September 30. http://cdn.kone.com/www.kone.se/Images/hissar-rulltrappor-flygplatser-planering-kone.pdf.

NFPA. 2014. *NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems*. 2014th ed. National Fire Protection Association.

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2. Jia, H., L. Yang, & M. Tang. "Pedestrian Flow Characteristics Analysis and Model Parameter Calibration in Comprehensive Transport Terminal." *Journal of transportation systems engineering and information technology*, Vol. 9, No 5, 2009, pp. 117-123.

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4. Johansson, A., D. Helbing, D., and P.K. Shukla. "Specification of the Social Force Pedestrian Model by Evolutionary Adjustment to Video Tracking Data." *Advances in complex systems*, Vol. 10, No. supp02, 2007, pp. 271-288.

5. Peacock, Richard D., and Jason D. Averill. *Pedestrian and evacuation dynamics*. Springer, 2011.

6. Flyvbjerg, Bent, Mette K. Skamris Holm, and Søren L. Buhl. 2005. "How (In)accurate are Demand Forecasts in Public Works Projects?: The Case of Transportation." *Journal of the American Planning Association* 71 (2): 131–46. doi:10.1080/01944360508976688.

7. Wachs, Martin. 1990. "Ethics and Advocacy in Forecasting for Public Policy." Business & Professional Ethics Journal 9 (1/2): 141–57.

8. Pickrell, Don. "A Desire Named Streetcar Fantasy and Fact in Rail Transit Planning." Journal of the American Planning Association 58 (2): 158–76, 1992. doi:10.1080/01944369208975791.

9. Iseki, Hiroyuki, Allison Yoh, and Brian Taylor. 2007. "Are Smart Cards the Smart Way to Go?: Examining Their Adoption by U.S. Transit Agencies." Transportation Research Record: Journal of the Transportation Research Board 1992 (January): 45–53. doi:10.3141/1992-06.

10. Yoh, Allison C., Brian D. Taylor, and John Gahbauer. 2013. "Does Transit Mean Business? Reconciling Academic, Organizational, and Political Perspectives on Variable Transit Fares." In Transportation Research Board 92nd Annual Meeting. Washington DC.

11. Kittleson & Associates, Inc., KFH Group, Inc., Parsons Brinckerhoff Quade & Douglass, Inc., and Katherine Hunter-Zaworski. *Transit Capacity and Quality of Service Manual*. 2nd ed. (Washington DC: Transportation Research Board, 2003).

12. Interview 5.

13. Respondents could also select an “other” option and specify a role not included in the above list. Two respondents selected this other option, specifying their roles as “providing inputs to passenger modeling,” and “coordinating with operations.” These were counted as “Conducting analysis such as passenger volume forecasts and level-of-service analysis” and “Interpreting analysis as a basis for capital investment and operations decisions,” respectively.

14. The values below the diagonal are not shown because they would repeat the values above the diagonal. For example, the number of respondents who conduct analysis and also manage design is the same as the number who manage design and also conduct analysis.

15. Interview 4.

16. Interview 4.

17. Interview 3.

18. Interview 9.

19. Interview 3.

20. Interview 7.

21. Interview 11.

22. Interview 10.

23. Interview 7.

24. Interview 9.

25. Respondents could also select an “other” option and specify a criterion not listed above. Three survey responses chose the “other” option indicating age and state of good repair; accessibility for people with disabilities; and political considerations as additional criteria used by an agency to determine the need for station retrofit.

26. The values below the diagonal are not shown because they would repeat the values above the diagonal. For example, the number of agencies with both passenger surveys and station centrality as criteria is the same as the number of agencies using both station centrality and passenger surveys.

27. One respondent also used the “other” category to indicate the structural condition of the station as a primary motivation.

28. National Fire Protection Association.

29. Americans with Disabilities Act. Title II Public Services and Transportation. 1990.

30. Interview 9.

31. Interview 6.

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33. Li, H., Z. Maohua, S. Congling, S. Jiehong, C. Haicheng, and X. Qiaoxiang. “Experimental Research on Investigation of Metro Passenger Evacuation Behaviors in Case of Emergency.” In *Pedestrian and Evacuation Dynamics*, edited by Richard D. Peacock, Erica D. Kuligowski, and Jason D. Averill, 173–84. (Springer US. 2011). http://link.springer.com/chapter/10.1007/978-1-4419-9725-8_16.

34. Helbing, P., et al. “Simulation of Pedestrian Crowds in Normal and Evacuation Situations.”

35. Ibid.

36. Schachenmayr, Martin. *Application Guidelines for the Egress Element of the Fire Protection Standard for Fixed Guideway Transit Systems*. Monograph 13. William Barclay Parsons Fellowship. Parsons Brinckerhoff, 1997.

37. NFPA. 2014. *NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems*. 2014th ed. National Fire Protection Association.

38. Kittleson & Associates, Inc, KFH *Transit Capacity and Quality of Service Manual*.

39. Still, Keith. “Crowd Dynamics”. PhD, (University of Warwick, 2000) http://webcat.warwick.ac.uk/record=b1371042~S1.

40. Helbing, P., et al. “Simulation of Pedestrian Crowds in Normal and Evacuation Situations.”

41. Hiroyuki, Iseki, and Brian D. Taylor. “Not All Transfers Are Created Equal: Towards a Framework Relating Transfer Connectivity to Travel Behaviour.” *Transport Reviews* 29 (6): 777–800, 2009. doi:10.1080/01441640902811304.

42. Loukaitou-Sideris, Anastasia, and Camille Fink. “Addressing Women’s Fear of Victimization in Transportation Settings: A Survey of U.S. Transit Agencies.” *Urban Affairs Review*, August, 2009. doi:10.1177/1078087408322874.

43. Ibid.

44. Interview 12.

45. Interview 5.

46. Interview 5.

47. Interview 7.

48. Interview 7.

49. Interview 1.

50. Interview 10.

51. Interview 12.

52. Iseki, Hiroyuki, and Brian D. Taylor. 2009. “Not All Transfers Are Created Equal: Towards a Framework Relating Transfer Connectivity to Travel Behaviour.” Transport Reviews 29 (6): 777–800. doi:10.1080/01441640902811304.

53. Interview 9.

54. Interview 4.

55. Pickrell, Don. “A Desire Named Streetcar Fantasy and Fact in Rail Transit Planning.” *Journal of the American Planning Association* 58 (2): 158–76, 1992. doi:10.1080/01944369208975791.

56. Wachs, Martin. 1990. “Ethics and Advocacy in Forecasting for Public Policy.” Business & Professional Ethics Journal 9 (1/2): 141–57.

57. Flyvbjerg, Bent, et al. “How (In)accurate are Demand Forecasts in Public Works Projects?: The Case of Transportation.” *Journal of the American Planning Association* 71 (2): 131–46, 2005. doi:10.1080/01944360508976688.

58. Interview 4.

59. Flyvbjerg, Bent, et al. “How (In)accurate Are Demand Forecasts in Public Works Projects?: The Case of Transportation.”

60. Interview 7.

61. Interview 11.

62. Interview 6.

63. Interview 4.

64. Interview 9.

65. Interview 4.

66. Interview 7.

67. Tanaboriboon, Yordphol et al. “Pedestrian Characteristics Study in Singapore.” *Journal of Transportation Engineering* 112 (3): 229–35, 1986.

68. Tanaboriboon, Yordphol, and Jocelyn A. Guyano. “Analysis of Pedestrian Movements in Bangkok.”*Transportation Research Record*, 1991.

69. Lam, W., and C. Cheung. “Pedestrian Speed/Flow Relationships for Walking Facilities in Hong Kong.” *Journal of Transportation Engineering* 126 (4): 343–49, 2000.

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71. Yordphol Tanaboriboon et al. “Pedestrian Characteristics Study in Singapore.”

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73. In B.D. Hankin and R. A. Wright. “Passenger Flow in Subways.” *Journal of the Operational Research Society* 9 (2): 81–88, 1958, p. 81.

74. Ibid.

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77. Kittleson & Associates, Inc, KFH Transit Capacity and Quality of Service Manual.

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79. Ibid.

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82. Løvås, G. G. “Modeling and Simulation of Pedestrian Traffic Flow.” *Transportation Research Part B: Methodological*, Vol. 28. No. 6, 1994, pp. 429-443.

83. Fellendorf, M. and P. Vortisch. 2010. “Microscopic Traffic Flow Simulator VISSIM.” In *Fundamentals of Traffic Simulation*, 63-93. Springer, New York, 2010.

84. Castle, C. J. E., N. P. Waterson, E. Pellissier, and S. Le Bail. 2011. “A Comparison of Grid-Based and Continuous Space Pedestrian Modelling Software: Analysis of Two UK Train Stations.” In *Pedestrian and Evacuation Dynamics*, edited by Richard D. Peacock, Erica D. Kuligowski, and Jason D. Averill, 433–46. Springer US.

85. Kittleson & Associates, Inc, KFH Transit Capacity and Quality of Service Manual.

86. Americans with Disabilities Act (ADA) 1990.

87. *NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems*. (National Fire Protection Association, 2014).

88. Kittleson & Associates, Inc, KFH Transit Capacity and Quality of Service Manual.

89. Interview 1.

90. Interview 2.

91. Interview 2.

92. Interview 3.

93. Interview 2.

94. Interview 4.

95. Interview 2.

96. Interview 5.

97. Interview 5.

98. Interview 6.

99. Fruin, John. *Pedestrian Planning and Design*. 1971.

100. Interview 7.

101. Interview 8.

102. Interview 4.

103. Interview 7.

104. Interview 2.

105. Interview 9.

106. Interview 2.

107. Interview 5.

108. Interview 10.

109. Interview 4.

110. Interview 4.

111. Interview 9.

112. Still, Keith. “Crowd Dynamics.” 2000.

113. Helbing, P., et al. “Simulation of Pedestrian Crowds in Normal and Evacuation Situations.”

114. Interview 4.

115. Interview 6.

116. Interview 5.

117. Interview 2.

118. Interview 4.

119. Interview 10.

120. Interview 4.

121. Interview 5.

122. Interview 10.

123. Interview 3.

124. Interview 5.

125. Interview 12.

126. Interview 5.

127. Interview 3.

128. Interview 10.

129. Interview 12.

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132. Yoh, Allison et al. “Hate to Wait.” *Transportation Research Record: Journal of the Transportation Research Board.* 2011.

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134. Interview 4.

135. Interview 8.

136. Interview 2.

137. Interview 9.

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139. Interview 14.

140. Interview 9.

141. Interview 9.

142. Interview 7.

143. Interview 15.

144. Interview 9.

145. Interview 6.

146. Interview 6.

147. Loukaitou-Sideris, Anastasia, et al. “Rail Transit Security in an International Context Lessons from Four Cities.” *Urban Affairs Review*. 2006.

148. Interview 7.

149. Interview 9.

150. Interview 8.

151. Interview 8.

152. Iseki, Hiroyuki, et al. “Are Smart Cards the Smart Way to Go?: Examining Their Adoption by U.S. Transit Agencies.” *Transportation Research Record: Journal of the Transportation Research Board.* 2007.

153. Interview 4.

154. Interview 7.

155. Interview 2.

156. Interview 8.

157. Interview 13.

158. Interview 12.

159. KONE Corporation. *Planning Guide of People Flow in Transit Stations*. 2014.

160. Hankin B.D., and R. A. Wright. “Passenger Flow in Subways.” 1958.

161. John Fruin, *Pedestrian Planning and Design*.

162. Ibid.

163. Interview 11.

164. Interview 10.

165. At one agency from which two individuals responded to the survey, the two respondents disagreed as to whether the agency had implemented or even considered variable direction escalators. In that case, their responses were averaged.

166. Interview 8.

167. John Fruin, *Pedestrian Planning and Design*.

168. Hankin, B.D., and R. A. Wright. “Passenger Flow in Subways.” 1958.

169. John Fruin, *Pedestrian Planning and Design*.

170. Associated Press. “Man Caught between Subway Train and Safety Doors Dies in Shanghai.” *International Herald Tribune*, 2007.

171. Interview 8.

172. Interview 10.

173. Interview 13.

174. McConell, interview.

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ABOUT THE AUTHORS

ANASTASIA LOUKAITOU-SIDERIS

Anastasia Loukaitou-Sideris is a Professor of Urban Planning and Associate Dean of the UCLA Luskin School of Public Affairs. She holds degrees in architecture and urban planning. Her research focuses on the public environment of the city, its physical representation, aesthetics, social meaning and impact on the urban resident, and includes documentation and analysis of the social and physical changes that have occurred in the public realm; cultural determinants of design and planning and their implications for public policy; quality-of-life issues for inner city residents; and transit security, urban design, land use, and transportation issues. She has served as a consultant to the Transportation Research Board, Federal Transit Administration, Southern California Association of Governments, South Bay Cities Council of Government, Los Angeles Neighborhood Initiative, Project for Public Spaces, Greek Government, Portuguese Foundation for Science and Technology, and many municipal governments on issues of urban design, land use and transportation. Her projects have been supported by the US and California Departments of Transportation, Federal Transit Administration, Mellon Foundation, Haynes Foundation, Gilbert Foundation, Archstone Foundation, Sound Body Sound Mind Foundation, and the Mineta Transportation Institute. Her books include Urban Design Downtown: Poetics and Politics of Form (UC Press: 1998); Jobs and Economic Development in Minority Communities (Temple University Press: 2006); Sidewalks: Conflict and Negotiation over Public Space (MIT Press: 2009); Companion to Urban Design (Routledge: 2011); and The Informal American City: Beyond Taco Trucks and Day Labor (MIT Press: 2014).

BRIAN D. TAYLOR, FAICP

Brian D. Taylor, FAICP is Professor of Urban Planning, Director of the Institute of Transportation Studies, and Director of the Lewis Center for Regional Policy Studies at the UCLA Luskin School of Public Affairs. His research is examines travel behavior, transportation finance, public transit planning, planning history, and the politics of planning. His research on public transit has focused on cost-effective ways to increase transit use and how travelers perceive the burdens of waiting and transferring; his research on transit cost-allocation modelling received the Pyke Johnson Award from the Transportation Research Board (of the National Academies). He is Chair of a Transportation Research Board Special Report committee examining the public policy implications of new shared mobility systems in general and transportation network companies in particular. Professor Taylor holds a BA in Geography from UCLA, an MS in Civil and Environmental Engineering, and an MCP in City and Regional Planning from UC Berkeley, and a PhD in Urban Planning from UCLA. Prior to joining the UCLA faculty in 1994, he was on the planning faculty at the University of North Carolina at Chapel Hill, and before that he was a planner with Metropolitan Transportation Commission in the San Francisco Bay Area.

CAROLE TURLEY VOULGARIS

Carole Turley Voulgaris is a third-year doctoral student in Urban Planning at the UCLA Luskin School of Public Affairs. She holds bachelor's and master's degrees in Civil and Environmental Engineering from Brigham Young University and an MBA from the University of Notre Dame. She has four years of professional experience in transportation planning and engineering, including one year at a public transit agency and three years with a private transportation consulting firm.

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