The Journey to Work: 25 Years on the Jamaicaway

More than 600 observations were recorded for the author's home-to-work trip for the same route from Boston to Cambridge, Mass., over the period 1980 to 2004. With this data, it is possible to graph the pattern of travel times and travel time reliability as a function of departure times during the morning rush hour. The image of rush hour performance that emerges from this study is more complex than what is often used in network models or abstract economic analysis. For example, as rush hour progresses, variability increases even though expected travel times start to decline. There may also be lulls in rush hour, i.e. intervals of 10-15 minutes when expected trip times and reliability temporarily improve. This type of performance cannot realistically be modeled as a linear function of traffic volume, nor can it be approximated using a steady state queuing analysis. It will be far better to view rush hour performance as a steady state cyclical queuing phenomenon: every day may start afresh, but expected conditions on next Tuesday at 8:30 am are likely to be similar to conditions last Tuesday at that time.

Over the 25-year period, there was surprisingly little change in rush hour performance on this congested urban route. Average travel times were mostly in the range of 25-27 minutes with a standard deviation of three to four minutes. There was some spreading of the peak, especially during periods involving major construction, but performance in the most recent period was actually equivalent to performance in the 1980s despite an increase of about 10% in traffic volume. Variability in trip times is mostly related to variability in the delays associated with the most congested intersections.

by Carl D. Martland

INTRODUCTION

This paper documents the travel time distribution over a period of 25 years for a particular commute along one of the major arterial routes in the Boston metropolitan area. This route generally follows parkways with 40,000-45,000 vehicles per average weekday; it goes through three of the most congested, most complex or most dangerous intersections in the region. Traffic volumes have grown on the order of 10-20% on this route, and six new traffic signals were added during this period, while commuting time and reliability have been relatively stable. Average travel times and the standard deviation of travel times rose modestly if at all during this period, while the duration of the congested period increased by at most a half hour. Road and bridge construction projects along the route periodically hurt commuting times and traffic diversions during the Big Dig[1] were a burden for several years. However, commuting performance in 2003-2004 was actually equivalent to the best periods of the 1980s in terms of both travel time and travel time reliability. If improvements in quality of life within the automobile are considered – air conditioning, comfortable seats, better sound systems, cup holders for a wider variety of readily available beverages, and the ease of mind associated with more reliable cars – the commute is actually less onerous now than it was 25 years ago.

The morning rush hour is an example of what has been called a "steady state cyclical queue" (Martland and Jin 1997). Rush hour delays occur because the highway system lacks capacity to handle the peak traffic volumes: queues result because the arrival rate of cars into the system is greater than the service rate of the system. The queues are cyclical in nature, because the queue behavior varies from the beginning of the day through the end of rush hour, and the queues always dissipate overnight. The situation is in steady state in a cyclical sense, because expected traffic conditions at

8 a.m. on a Tuesday will be the same as they were on previous Tuesdays at 8 a m., with some predictable modifications for holidays, school vacations, and extreme weather conditions.

This paper uses trip time data for the author's commuting trip. More than 600 observations were recorded for the same route during the period 1980 to 2004. Each observation provides the departure time from home and the arrival time at the parking area, along with arrival and departure times from two of the most complex intersections. There are sufficient observations to understand how trip times vary with departure time and to see how the pattern of rush hour performance has varied over the decades.

It is naturally impossible to form any general conclusions regarding traffic congestion on a study of a single route. However, a single well-documented example can be sufficient to cast doubt upon the validity of commonly used assumptions concerning traffic congestion. The image of rush hour performance that emerges from this study is more complex than what is often used in network models or abstract economic analysis. In particular:

- Trip times cannot be estimated as a linear function of traffic volume because travel time depends on the length of the queues and the queues build up during rush hour (so that the end of rush hour is worse than the beginning, even though the traffic volumes are the same).
- Trip times cannot be estimated using a steady state queuing analysis because the queues are never close to steady state except in the cyclical sense described above.

It is better to view rush hour performance as a steady state cyclical queuing phenomenon. This methodology can accept arrival rates that are sometimes above service rates. It will predict increasing delays and decreasing reliability as rush hour progresses, and it will allow lingering delays even after arrival rates drop below service rates.

Understanding the options faced by one commuter may not seem like very much, but "one" is better than "none." The concepts displayed in this study are indeed general, and they should allow traffic engineers, modelers and highway officials to formulate better strategies for dealing with congestion.

LITERATURE REVIEW

There are various approaches to talking about and modeling highway congestion. To the public, traffic congestion is expressed in units of frustration rather than equations; studies periodically document the time spent commuting in various metropolitan areas and document the trends toward longer travel times. To emphasize the increasing magnitude of the congestion problem, these studies sometimes focus on particular aspects of the problem. For example, it is possible to estimate the increase in travel times for a metropolitan area or to estimate the increase in delays. Because delays are only a portion of the total trip time, the percentage increase in delays will always be greater – and therefore more alarming - than the percentage increase in travel times. Another factor is that people choose to live in more distant suburbs; as metropolitan areas have grown, more people have long commutes because of where they choose to live and work. Despite the headlines (e.g. Greenberger 2004), longer travel times often result from traveling longer distances, not just from longer times traveling on the same routes. Moreover, the commuters are presumably getting enough benefit from their trips to justify their time and expense. If not, they would move or change jobs.

Economists such as Boyer (1997), Button (1993), and Mohring (1999) emphasize that there is a tradeoff between the costs of delays and the costs of adding to highway capacity: even with the optimal level of capacity, there will usually be delay, as it is economically inefficient to size facilities for the peak load. Economists also note that delays would decline if people had to pay for the externalities related to congestion.

A different approach is used by traffic engineers, who address congestion in a very thorough and pragmatic manner. Using observations and theory, traffic engineers develop detailed equations to represent the capacity of roads and intersections, and they can estimate the performance of a road or an intersection as a function of the traffic mix and traffic volume. This approach is used to guide highway design, but it is far too detailed to be used in modeling a metropolitan network. Many textbooks provide a good introduction to traffic engineering, including Banks (1998), Garber and Hoel (1988), and Haefner (1986).

More aggregate approaches have been developed to study how networks respond to increasing traffic flows. The differences between the traffic engineering and the network modeling approaches are worth considering in more detail to understand how they view congestion. Text books on transportation systems analysis typically discuss congestion in terms of supply, demand, and equilibrium as applied to networks. At MIT, the first text used for the introductory transportation class was written by Manheim (1979). It examines system performance at increasing levels of detail, but always in the context of supply, demand and equilibrium. The performance of a transport system depends upon the demand and the operating strategy – but the demand also depends upon the performance of the system. The system is assumed to reach an equilibrium such that the performance and demand are consistent.

The simplest equilibrium analysis is introduced by defining three different volumes: equilibrium volume, capacity volume, and demand. The text notes that "the equilibrium volume cannot exceed capacity" (Manheim 1979, p. 177), so that the equilibrium volume cannot exceed the minimum of capacity or demand. This assumption makes it easier to solve the equilibrium equation, but the assumption is at odds with the reality of most transportation systems: transportation demand is cyclical and routinely exceeds capacity.

Manheim subsequently draws upon the concepts of steady-state queuing to develop equations that cause queues to build up as the arrival rate of the system approaches the service rate. His goal is to show that it is, in fact, possible to analyze the equilibrium conditions if you understand both the performance capabilities of the system and the responsiveness of demand to performance. He goes on to show the usual charts for highway level of service that show how operating speed deteriorates as volume approaches capacity.

Haefner (1986) takes a traffic engineer's approach to capacity analysis. In a chapter on highways, he devotes nearly 100 pages to a discussion of the capacity of a free-flowing road or highway and of a highway intersection. The ratio of traffic volume to capacity is a key factor for both roads and intersections, and numerous charts and equations are given to provide a means of determining the maximum volume that can be handled at a suitable level of service.

Haefner shows the level of service definitions for signalized intersections. Level of service A (LOS A) has less than an average of five seconds of stopped delay per vehicle; LOS F has average delays greater than 60 seconds per vehicle (Haefner 1986, p. 121). He notes that the lower bound of LOS E, with an average delay of 40 seconds, is often taken to be "the limit of acceptable delay" and an estimate of the capacity of the intersection. He also notes that site characteristics might be very important, with serious delays occurring at what the methodologies might compute to be a better level-of-service. As in the other texts cited above, there are no charts of actual highway performance nor any significant discussion of rush hour behavior.

There is no shortage of research in any of the three areas noted in this brief introduction to the literature. Many people have written about congestion from the perspective of an economist, a network modeler, or a highway planner. There are good studies of trends in average commuting time and congestion, most notably the Texas Transportation Institute's periodic studies of urban mobility (Schrank and Lomax 2004). What is not as common are good descriptions of what it is like for the commuter, which is the topic of the remaining sections of this paper.

THE COMMUTING OPTIONS

Anyone living and working in or near Boston has an option of driving to work or taking public transportation. There are always multiple routes for either option, and the relative advantages of driving and transit are quite site-specific, depending upon access to transit and the ability to use local streets to bypass major bottlenecks in the street and highway networks. The choice is not obvious, and spouses facing the exact same decision may select different routes. However, after some practice, perhaps a month of commuting and certainly within a year, an inquisitive individual will select one or two favorite routes. For me, the best highway option is clear: follow the parkways that pass by the Arnold Arboretum to the Charles River, cross the BU Bridge, and head for MIT. There are other routes, but the parkways are more scenic and, based upon personal experience, faster.

The basic route is depicted in Table 1. The door-to-door trip time includes the time to leave the house, get in the car, and back out of the driveway, as well as the time to walk from the parking lot or the parking garage to the office. In 1979, the approximate travel times for the 6.3 mile trip varied from 20 to 45 minutes, depending upon departure time:[2]

- Off-peak: 20 – 22 minutes (including five minutes walking)
- Near-peak: 24 - 30 minutes (including five minutes walking)
- Peak: 30 – 45 minutes (including five minutes walking)

Table 1: Initial Perceptions Concerning the Drive to Work

	Segment	Typical Elapsed Time	Distance
1	Walk to car	0.5 minutes	30 feet
2	Start car, leave driveway	0.5	
3	Drive to rotary, Center St. & Arborway	4.0 - 5	2 miles, 1 traffic signal in 1980 (now 3)
4	Queue at Rotary	0 - 5.0	
5	Drive to Intersection of Jamaicaway and Pond Street	2 - 2.5	1 mile, 1 signal (now 2)
6	Queue at light	0 - 3.0	
7	Drive to First Intersection of Jamaicaway and Brookline Avenue	2 - 3.0	1 mile, 1 signal
8	Queue at light	0 - 8.0	1 signal
9	Drive to Second Intersection of Jamaicaway and Brookline Avenue	1 - 2.0	0.3 miles, 1 signal (now 2)
10	Queue at light; go through jug handle; queue at next light	0 - 4.0	2 signals
11	Drive to Commonwealth Avenue	1.5 - 3.5	0.7 miles, 2 signals (now 3)
12	Queue at first light; cross Turnpike bridge; queue at Commonwealth avenue light; queue at BU Bridge light	0 - 10	3 signals
13	Drive to West Garage at MIT	2 - 2.5	1 mile, 1 signal (now 2)
14	Park in garage	1 - 3	
15	Walk to office	5	0.3 miles

Source: Personal Lecture Notes, November 28, 1979

Faced with these perceived travel times, it was necessary to allow 45 minutes for the peak period commute to make a 9:00 meeting, 30 minutes for the near-peak commute to make a meeting at 9:30, or 22 minutes for the off-peak commute for a later meeting.

Travel times and trip-time variability are related to the performance within each trip segment. The expected trip time can be calculated as the sum of the expected time for the various line haul and intersection segments. If necessary, the expected times can be estimated as finely as one likes, utilizing detailed calculations regarding cruise speed, acceleration and braking capabilities, the number of intermediate stops, and intersection times. Trip time variability can also be related to the variability associated with each trip segment. The variability in trip times would be expected to come predominantly from the difficult intersections, because delays at those locations often amount to several minutes or more, far outweighing variations in time related to traffic flow, the day-to-day variation in the number of red lights encountered in the other intersections, or nuances in flow characteristics along the roads. Thus, it was hypothesized that the variance of the trip time could be estimated as the variance of the times associated with troublesome intersections.

There are four key intersections along this route:

- Segment 4: the rotary (i.e. traffic circle) where Center Street meets the Arborway. During the morning peak, the heaviest flows are conflicting at this rotary.
- Segment 8: the intersection where the Jamaicaway crosses Brookline Avenue at the west end of the medical area. Traffic can back up more than a mile from this intersection, especially if traffic inbound to the medical area blocks Brookline Avenue.
- Segment 10: the so-called "Sears Rotary" or "jug handle" intersection where inbound traffic on the Jamaicaway is routed back-and-forth across Brookline Avenue before heading toward the Boston University (BU) Bridge. Two lanes of traffic from the northwest heading south and east merge with two lanes from the south heading northwest, north, and east at a five-point intersection. When traffic is heavy, capacity can decline as people maneuver more aggressively for position; anyone driving to Fenway Park from the south has gone through this intersection.
- Segment 12: the complex intersection at Commonwealth Avenue by the BU Bridge. This is where heavy north-south flows from the bridge intersect heavy east-west flows on Commonwealth Avenue. There is an entrance to Storrow Drive (an expressway along the Charles River), and there are many possible routes through this unusual intersection. For my route through this area, there are three traffic signals, and it is seldom possible to get through in less than a minute, even if there is no traffic.

Table 2 shows the route segments and typical travel times for the transit alternative, based upon personal experience from 1972 to 1979. The typical range of travel times was:

- Off-peak: 50-75 minutes (erratic headways)
- Near-peak: 53-63 minutes (frequent service, infrequent disruptions)
- Peak: 55-70 minutes (frequent service, but prone to delays at the bus stop and at subway stations because of bunching of buses and trains during the peak period).

The time advantage for driving was clear. To allow a reasonable probability of making a meeting, it was necessary to allow 75 minutes for an off-peak transit trip compared to only 22 minutes for the auto trip. During peak periods, it was necessary to allow 70 minutes compared to only 45 minutes for driving – closer, but still not close. If you had a car, and if your decision were based purely upon time, then you would surely drive.

Time was not the only consideration, however. The transit trip required 15-20 minutes of walking and climbing stairs, more than double of what was needed to walk to the office from the parking garage. The extra time spent walking could be viewed as a bonus. Indeed, another option was to walk the nearly two miles to Forest Hills through the Arnold Arboretum instead of taking the bus; this option added another 15 minutes to the commute – but resulted in a wonderful half-hour stroll through one of the finest parks in the region.

Table 2 - Perceptions Concerning the Transit Trip

	Segment	Typical Elapsed Time	Distance
1	Walk to bus stop in Roslindale Square	7 - 8 minutes	0.5 miles
2	Wait for bus	0 - 10	
3	Bus to Forest Hills	4 - 6	1.5 miles
4	Climb stairs, pay fare	1 - 1.5	
5	Wait for train	0 - 15	
6	Orange Line to Washington Street	15 - 18	
7	Transfer to Red Line Platform	1 - 2	
8	Wait for Red Line	0 - 10	
9	Red Line to Kendall Square Station	5 - 10	
10	Depart station and walk to office	8 - 10	

Source: Personal Lecture Notes, November 28, 1979

The 20-30 minutes on the train plus some of the waiting time could also be useful – especially good for reading novels, checking notes for a presentation, or contemplating a lecture. Thus at least 2/3 of the transit trip was actually useful or beneficial, particularly in near- and off-peak conditions when you were likely to get a seat. The time "lost" by taking transit was therefore on the order of 10-20 minutes, which was no worse and perhaps less than the time "lost" driving to work.

Cost is an interesting matter. The out-of-pocket cost for transit is a token for the subway (initially a quarter, now $1.25) and a bus fare (initially 20 cents and now 90 cents). The variable cost for driving includes gas and mileage-related maintenance and servicing, which was about 5 cents per mile initially and about 10 cents to 20 cents today (prices are up, but cars are more reliable). Because parking was an employee benefit in 1980 and more recently can be purchased in bulk for a year, the variable costs associated with parking were zero for the entire period. For this six-mile trip, the variable costs of driving were always less than the costs of transit.

Over the period of this study, I generally drove to work and always had a flexible work schedule. By habitually leaving after 9:30 a.m., it was possible to avoid the congestion associated with rush hour. Still, there were always some days when early arrivals were necessary, allowing for plentiful observations of rush hour conditions.

The study had the following objectives:

- Document actual travel times and reliability of travel times as functions of the time of departure.
- Test the hypothesis that the delays at the major intersections a) are independent and b) account for most of the variance in trip times.
- Document how long it takes for traffic flows to reach equilibrium.

The first objective was simply to obtain a picture of rush hour travel conditions that would be useful in an introductory class on transportation performance. The second objective was to test the hypothesis that the variance of the trip could be estimated as the sum of the variances at the major intersections. If so, then it would be straightforward to show how changes at a single difficult intersection would propagate into the network. The third question related to the time dimension of traffic equilibrium, a matter of interest because of the importance of equilibrium in transportation network analysis. The usual methodologies for estimating equilibrium flows use mathematical techniques to find the flows such that no traveler can save time by diverting to a different route. In fact, it takes time for travelers to test different routes, and it therefore takes time for travel conditions to reach an equilibrium. In metropolitan Boston, there is a dramatic change in traffic conditions before and after Labor Day, which marks the traditional start of the new school year for most universities and other schools. The sudden jump in traffic volume always causes unusually bad congestion, and it takes commuters weeks to figure out when they should leave for work and what route they should take. The problem is worse for those who are new to the region and those who moved or changed jobs during the summer. By monitoring travel times following Labor Day, it was possible to measure how many days or weeks it takes for traffic to reach equilibrium.

Data collection began in September 1980 and continued for 25 years. Trip time data were collected for essentially all trips beginning before 9:00 a m., most trips beginning between 9 a.m. and 9:30 a.m., and a few trips beginning after 9:30 a.m. In addition to the date, day-of-week, special characteristics of the day (e.g. school vacation or holiday), the data shown in Table 3 were collected for each trip. There is probably a minor variation of 15-30 seconds in the departure time introduced by the lack of an accurate recording of a specific starting event. The next event time is termed the "arrival at the 1st Brookline Avenue intersection," which is intended to represent the arrival time at the queue that is nearly always backed up from this intersection. This queue can extend a mile back along the parkway without fouling any other intersections. If the light at the intersection is working properly, then cars move through this stretch at about 5 mph (i.e. it takes 12-minutes to get through the intersection when the queue is a mile long). If the light is not working or if there is a tendency to gridlock, then the queue will be longer and move more slowly. At the start of the period, there was often a traffic officer at the intersection, which generally helped avoid grid-lock, but otherwise did not have much effect on capacity. The traffic signal at this intersection has operated on similar cycles (approximately two minutes) for the entire period.

Table 3: Data Recorded for the Journey to Work

Time	Description	Comments
Departure	Time of walking out of the house	Estimated to nearest minute or half-minute (does not include clearing snow off car or returning inside for forgotten cup of coffee or briefcase)
Arrive First Brookline Ave Intersection	Time that I stop in a queue of cars backed up from the 1st Brookline Ave intersection with the Jamaicaway	There is a half-mile without any intersections, so it is usually clear where the queue starts. In rare cases, the queue backs up even further, and the time of arriving at the queue is a judgment call.
Depart First Brookline Ave Intersection	Time that I cross Brookline Ave	Well-defined
Arrive Commonwealth	Time of arrival at the queue by the light at the bridge that crosses the Turnpike	Well-defined
Depart Commonwealth	Time of entry onto the BU Bridge	Well-defined
Arrive MIT	Arrival at MIT parking area	Actual parking in the lot or entry to the garage

MANAGING HIGHWAY PERFORMANCE IN BOSTON

The data collected in this paper provide exceptional detail for a single route. Public agencies in the region do not attempt to collect such detailed data, but they do monitor performance of the highway system. The City of Boston has a Transportation Department that recently produced its plan for improving mobility in the city (Boston Transportation Department 2003). The plan addresses major highways, local arterial corridors, transit, and neighborhood issues, and provides data concerning traffic volumes, congestion and safety.

The most heavily traveled arterial in the city, and the only arterial in Boston with heavier traffic than the route addressed in this paper, is Rutherford Avenue in Charlestown with average weekday daily traffic volume (AWDT) of 61,000 vehicles (Boston Transportation Department 2003, p. 82). The study route starts at the northern end of the VFW Parkway, the arterial with the second heaviest traffic volume (AWDT = 43,000), continues along the Jamaicaway (AWDT = 41,000), and crosses the traffic flows moving along Boyleston street (AWDT = 42,000). A traffic density map shows this route is clearly the most important approach from the southwestern neighborhoods and suburbs to the core of the city (Boston Transportation Department 2003, p. 92).

Traffic volumes have increased slowly on this route during the past 25 years, as shown in Table 4. The traffic counts of up to 45,000 AWDT along the Jamaicaway at Perkins Street are representative of the traffic volume approaching the heavily congested intersection with Brookline Avenue. At this intersection, much of the traffic diverts into the Longwood Medical area, and the traffic volume drops approximately in half, as measured along the Jamaicaway at Longwood. After going through the Sears Rotary, the traffic volume continues at about 20-24,000 AWDT along Park Drive, where the route crosses Commonwealth Avenue to reach the heavily traveled BU Bridge, which also handles nearly 40,000 AWDT.

In January 2002, the city began monitoring the average travel speed along each arterial in the six most heavily congested corridors. They established a baseline for travel times by driving each route during the morning peak period. The first part of the study route considered in this paper goes through Roslindale, one of the six routes that was monitored. The average speeds for the six routes ranged from 7.2 to 17.6 mph;

Table 4: Average Weekday Daily Traffic Volume Along the Study Route

Trip Segment	1980	1983	1986	1989-1990	1992	1995-1996	1998	1999	2001
Flows along route:									
Jamaicaway at Perkins St.		41,350	39,650	36,220	44,000	39,000	45,300		
Jamaicaway at Longwood Avenue	16,950	20,900	13,800	22,280	23,000	19,000	23,900	21,000	
Park Drive at Beacon St.	20,200	18,450	18,400		24,000	21,000	22,100		
BU Bridge						38,800			
Conflicting flows:									
Brookline Avenue	20,000	20,050		19,917				22,300	22,400

Source: Boston MPO website.

the route through Roslindale was the second slowest at 10.2 mph (Boston Transportation Department, p. 83).

The city conducted neighborhood studies to address specific needs for improving traffic flow. The most significant problems and the greatest need for improvement were related to the Sears Rotary, which is the complex intersection of five major routes that is approximately the mid-point along the route studied in this paper (Boston Transportation Department 2003, p. 88).

The Central Transportation Planning Staff (CTPS) is another group that monitors traffic conditions in Boston as part of its larger planning role for the Boston Region Metropolitan Planning Organization. CTPS collects travel time data on what they consider to be "regionally significant roadways," which include the major arterials with expressways. They compare the actual performance to speed limits to determine the threshold for congestion. For arterials, there are three thresholds for a road to be considered congested: average speed less than 15 mph; average speed less than 70% of the posted speed limits; or average delay (seconds when speed is less than 5 mph) of more than 54 seconds at an intersection (CTPS 2004, p. 3-8).

Performance was measured in two periods, in 1995-1999 and then again in 2001-2003, for both the morning and the afternoon rush hours (CTPS 2004, p. 3-2). For the morning peak period, probe vehicles made a dozen trips along the measured routes "primarily between 6:30 and 9:30 … which is equivalent to approximately one sample per 15-minute time period." In the reports on their congestion management system, they show the average travel speeds and average intersection delays for the dozen trips that were made (CTPS, p. 3-9). In the most recent period, for the 397 miles of arterial roads monitored in Boston and the inner suburbs, 9% had average travel speeds less than or equal to 14 mph, and 11% had travel speeds greater than 14 but less than 18 mph, while 31% had average speeds less than 70% of the speed limit, which was an increase from the 19% measured in the earlier period (CTPS 2004, pp. 3-13 and 3-19).

The Jamaicaway was monitored from Centre Street to Huntington Avenue, all of which is part of the route studied in this paper. Another 1.5-mile portion of the beginning of the route was monitored as part of the VFW Parkway/Providence Highway segment. These two segments were the fifth and seventh most congested arterials in the Boston region, with average delays of 76 and 70 seconds per mile (CTPS, Table 3-14). Huntington Avenue is approximately a half mile short of the congested intersection at Brookline Avenue, so this measurement avoids several minutes of delay from that traffic signal. There are 42 monitored intersections with approach delays of more than 80 seconds; none of these were along the route studied in this paper, but, as just noted, the worst intersections along the route studied in this paper were not on any of the routes monitored by CTPS.

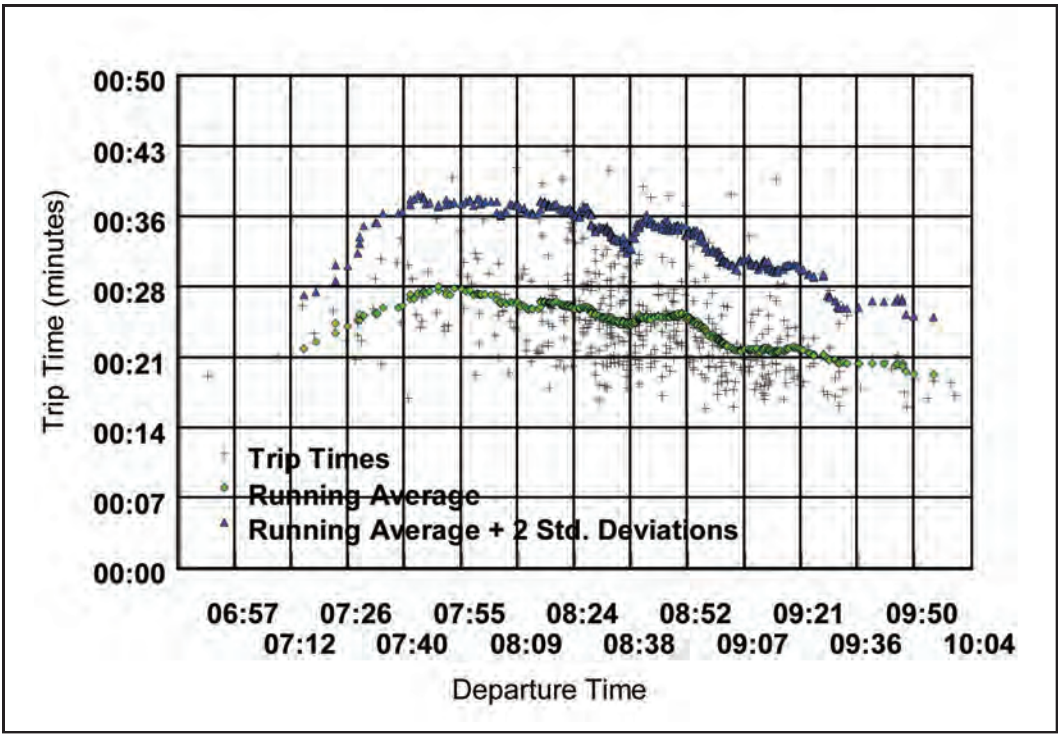
CTPS also monitors safety of the highway system. The intersection of the Jamaicaway and Brookline Avenue was the 16th worst in the region in terms of crashes, with 159 accidents reported between 1997 and 1999 (CTPS, Table 3.13).

In summary, the public agencies in the region have recently begun to monitor average travel speeds, delays, and intersection safety. Their goal is to provide a reasonably comprehensive data base for the performance of a major portion of the region's highway system. They make this information available to the public on various websites. They do not attempt to measure the variability of travel times or the variability of times associated with specific interchanges. Because their averages are based upon a dozen or so measurements per year, they do not have enough data to attempt to measure road system performance as a function of departure time.

RESULTS

Figure 1 shows the travel times for the entire 25-year period for the weekday commute. In addition to one point for each day, the figure shows the running average trip time and the running average trip time plus two standard deviations. The average trip time indicates the amount of time that is consumed in commuting; the trip time plus two standard deviations suggests the minimum amount of time to allow

Figure 1: Journey-to-Work Travel Times, 1980-2004



for the commute prior to a class or an important meeting.

Running averages are calculated for 30 to 70 observations centered on the departure time for each trip. More observations per time interval were used near the peak of rush hour where more data points were available. The running averages generally cover a period of about 20 minutes. It was necessary to vary the number of observations in the interval to keep the width of the interval close to 20 minutes.

The data does not include summer days (June – August), weekends, school vacations, holidays, days with bad weather, or days when there was an extremely unusual event that caused trip times in excess of 45 minutes. On days with bad weather, all commuters know to expect somewhat longer trip times; in snowstorms, commuters stay at home, prepare for the worst, or assume that snow delays will excuse a late arrival. It was necessary to exclude the very longest trip times to get reasonably smooth running averages for the standard deviation. The very worst day in 25 years was a 73-minute commute after torrential rains caused flooding of Boston streets and the Green Line. Three other commutes in excess of 45 minutes were associated with road work or other traffic restrictions on nearby streets. These four very bad days represented about 0.5% of the days in the sample; they were excluded to avoid strange breaks in the plot of the trip time plus two standard deviations.

The plot in Figure 1 covers the full 25 years, so there is somewhat more variation in the data than is observed in most of the shorter intervals. The advantage of using the entire interval is that it is possible to get many more data points and therefore get better estimates of the expected travel time, the standard deviation of travel time and of any other measures of performance for the journey-to-work. Figure 1 illustrates several key features of the journey-to-work:

- If you leave early enough, you can travel at off-peak speeds and reliability (before 7:15 a.m. in this case).
- However, congestion builds up rapidly, so if you are just a little late, you can suffer extensive delays (the longest and least

reliable performance is for departures between 7:45 a m. and 8:00 a.m.).

- There is a limit as to what people endure – performance is relatively constant over a fairly wide period at the peak. While trip times and reliability are worse for departures between 7:45 a.m. and 8:30 a.m. on this route, performance is pretty bad for the wider interval from 7:30 a.m. to 9:00 a m.
- Due to the vagaries of demand and geography, there may be minor lulls in congestion; commuters can learn about these and adjust their behavior accordingly. The dip in both the mean and the variability of trip times shown in the figure are real, not artifacts of the data. For this route, it was good to depart a little after 8:30 a.m. because businesses, hospitals and schools along the route have start times of 8:00, 8:30, or 9:00 a m., allowing some commuters to depart between two local peaks in demand.
- The standard deviation of travel time increases for quite a while after the expected travel time declines, (i.e. variability increases the further you go into rush hour between 7:45 a m. and 8:30 a.m.).
- The end of rush hour is not as sharply defined as the beginning; expected travel times and variability declined more slowly than they rose.

These observations will not provide much of a surprise to commuters, who know the vagaries of their own routes and who usually figure out when to leave if they really need to get to work on time. However, it may be useful for planners and traffic engineers to see some actual statistics from the perspective of a commuter. It is certainly useful for researchers, especially those who may never have owned a car or driven during rush hour on a regular basis.

It is interesting to compare what is shown in Figure 1 with the initial estimates of performance from 1979, which were given above. Eliminating the walking time, those estimates could be restated as:

- Off-peak: 15-17 minutes (plus five minutes walking)
- Near-peak: 19-25 minutes (plus five minutes walking)
- Peak: 25-40 minutes (plus five minutes walking)

The actual performance shown in Figure 1 is not far from this, especially for the expected time. Departing at 10 a.m. has an expected travel time of 20 minutes with a standard deviation of three minutes. The best travel times on commuting days were about 17 minutes; 15 minutes is possible late at night or on Sunday mornings when there is little or no traffic. Departing at 9:10 a.m., the expected travel time is 22.5 minutes with a standard deviation of 4.5 minutes; the mean is about what was estimated in 1979, but the variability is higher. Departing during the peak, the mean reaches 29 minutes with a standard deviation of five minutes.

Is Congestion Increasing?

The number of observations per year was too sparse to support more figures with the detail shown in Figure 1 for the entire period. Figures 2-7 simply show the distribution of travel times for each of six periods. The travel time and departure time scales are the same in each chart, so it is possible to see at a glance some interesting differences that have occurred over the years. The first chart (Figure 2) covers two years from 1980 to 1982. During this time, departures are tightly clustered around an 8:30 a.m. departure. Note that the trip time is almost always less than 21 minutes if the departure is after 9:05 a.m. The longest trip times are close to 40 minutes. Figure 2 is not unexpectedly closer than Figure 1 to the performance that was estimated in 1979, prior to the start of data collection. Figure 3 shows similar performance for the longer period from 1988 to 1994; this figure includes data for just a few departures after 9 a.m., because this was clearly after the end of rush hour.

Between 1995 and 1999, the rush hour spread (Figure 4). Performance deteriorated both early and late, although the peak does not appear worse than in the earlier years. The flattening of the peak continued between 1999 and 2001 – some trip times were close to 30 minutes even with a 9:30 a.m. departure (Figure 5). Still, the very worst times remained less than 40 minutes.

Figure 2: Trip Time, by Time of Day
November 1980 - November 1982

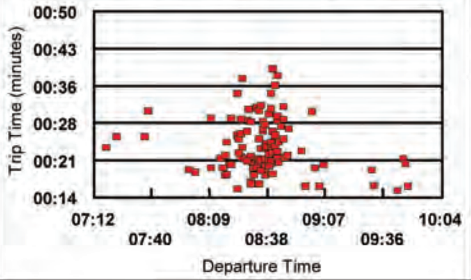


Figure 3: Trip Time, by Time of Day
January 1988 to December 1994

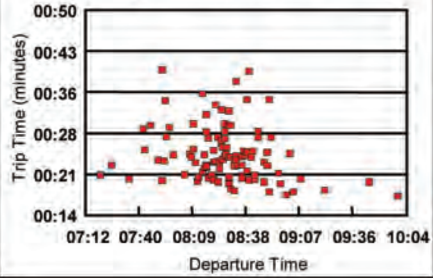


Figure 4: Trip Time, by Time of Day
January 1995 to May 1999

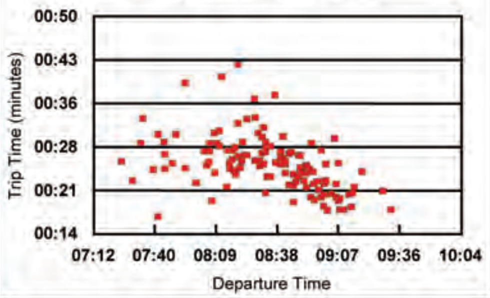


Figure 5: Trip Time, by Time of Day
September 1999 to May 2001

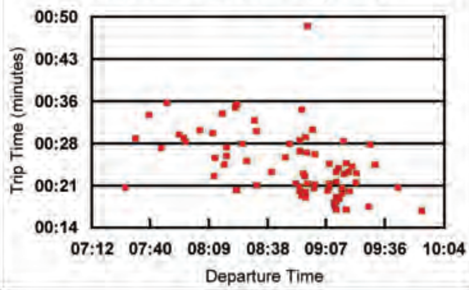


Figure 6: Trip Time, by Time of Day
September 2001 to May 2003

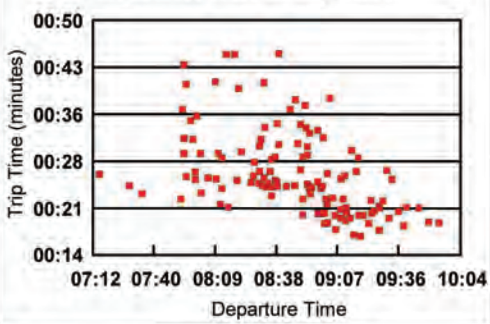
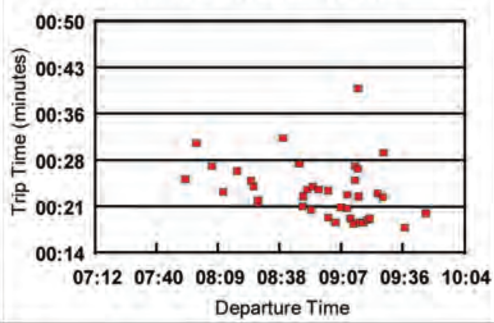


Figure 7: Trip Time, by Time of Day
September 2003 to May 2004



After 2001, performance was seriously affected by the "Big Dig." As construction caused delays in the Interstate 93 corridor, commuters shifted to new routes throughout the rest of the city. Hence, traffic volumes seemed higher, and performance clearly deteriorated. Between September 2001 and May 2003, there were many days with 40-minute commutes, and there continued to be problems for departures between 9 a m. and 9:30 a m. (Figure 6).

In 2003-2004, significant portions of the new routes were opened, and the "Big Dig" seemed to become a positive factor. Travel times dropped, especially before 9 a m., as shown in Figure 7. Travel after 9 a.m. was still hampered by congested conditions within the medical area.

Trip Times for Major Trip Components

Tables 5 and 6 show the mean and standard deviation for the total trip time and for the major components of the trip. These charts are based upon the performance summarized for the eight 15-minute intervals between 7:30 a m. and 9:30 a.m. Where data were insufficient to compute an average or a standard deviation, estimates were made based upon the data that were available or upon patterns that were observed over the entire period. If data were unavailable for one 15-minute period, the first option would be to use the average of the prior and succeeding periods. If data were unavailable for the first or second period, then the missing value was estimated as a percentage of the 8:00-8:15 a.m. interval (80% of the peak for the 7:30-7:45 a.m. interval and 90% of the peak for the 7:45-8:00 a.m. interval). The averages shown in Tables 5 and 6 are not weighted by the number of actual observations that were available. Instead, they reflect the expected performance over this two-hour period. It might be argued that the averages should be weighted by the number of travelers during each period, but that data is not available – and it is not clear that the weights would be the same for each trip component. The statistics shown here have the merit of being readily computed and easily compared. Most importantly, they provide an excellent insight into trends in performance on this route over the past 25 years.

One fact is striking. For most of this 25-year period, the overall mean trip time was 25-27 minutes with a standard deviation of three to four minutes. If the poor performance for the 2001-03 period is disregarded as being unduly affected by the Big Dig, then there hasn't been much change over the entire period. In fact, if we consider the mean plus two standard deviations, the best performance was in the most recent period.

The Time Required to Reach Equilibrium

In September and October 1980, data were collected on almost a daily basis to determine the time that would be required for the system to reach equilibrium after the increase in demand related to the beginning of the school year and the end of summer vacations. The first two rows of Table 5 compare performance for September and October in 1980 to performance for the

Table 5: Average Times for the Total Trip and for Major Trip Components

	Total Trip	1st Leg	1st Brookline	2nd Leg	BU Bridge	3rd Leg	N
1980 Sep-Oct	25:57	08:46	4:12	6:02	2:48	3:56	23
1980-82	25:43	09:22	3:21	6:01	2:45	4:14	102
1984-86	26:42	11:13	3:56	6:23	1:41	3:28	28
1988-94	24:11	09:55	2:49	6:34	1:53	3:00	103
1995-99	25:57	10:23	4:12	6:25	1:43	3:22	123
1999-2001	26:55	11:06	4:23	6:19	1:43	3:17	77
2001-03	28:16	11:42	4:02	6:40	2:33	3:17	124
2003-04	26:06	11:04	2:58	7:23	1:40	3:00	40

Note: Times are shown as minutes:seconds

Table 6: Standard Deviations for the Total Trip and for Major Trip Components

	Total Trip	1st Leg	1st Brookline	2nd Leg	BU Bridge	3rd Leg	N
1980 Sep-Oct	3:58	1:02	4:05	1:48	0:33	0:47	23
1980-82	4:38	1:08	1:54	1:56	1:44	1:18	102
1984-86	3:20	3:25	3:00	1:42	0:24	0:29	28
1988-94	3:55	1:19	3:01	2:19	1:06	0:40	103
1995-99	3:48	1:49	2:49	1:17	0:33	0:41	123
1999-2001	3:55	2:10	2:57	1:24	0:41	0:37	77
2001-03	5:27	2:25	3:39	1:17	2:11	0:52	124
2003-04	2:49	1:08	1:24	1:27	0:24	0:16	40

Note: Times are shown as minutes:seconds

three-year period 1980-1982. The total trip time and the variability of trip time were similar for both periods. However, performance during this period was severely impacted by extensive work on the roads and an overpass at the northern end of the BU Bridge, which disrupted flows both through the complex intersection at the bridge (shown here as “BU Bridge”) and across the bridge into Cambridge (Leg 3). Consequently the average times and variability for these two segments were much higher than in subsequent years. The performance of the 1st Brookline intersection provides a better indication of the time required for the equilibration process. In September and October 1980, the average time and the standard deviation of the time at this intersection were both over four minutes. For the entire 1980-1982 period, the average time was less than 3.5 minutes and the standard deviation was under two minutes. This data supports the perception that it takes several weeks or more for traffic to settle down into a reliable pattern.

Average Speeds

The results in Tables 5 and 6 can also be used to compute measures such as those used by the public agencies in Boston. Typical rush hour travel speeds for this six-mile commute are on the order of 12-15 mph, which is much slower than the congestion-free speeds achieved in off-peak hours. The congestion-free speed cannot simply be calculated using speed limits, as the route includes four complex intersections where delays in excess of one minute are common plus another 15 traffic signals where some red lights will cause delays on every trip. Someone traveling the entire route at the speed limit (which ranges from 25 to 35 mph), encountering mostly favorable signals, will complete the trip in about 18 minutes, which is in fact the approximate minimum observed time seen above in Figure 1. Taking 18 minutes as the congestion-free travel time, the congestion-free average speed would be 20 mph. The public agencies in Boston use various thresholds to identify congested routes. One threshold is that travel times are less than 70% of the congestion-free speed and another is that average speeds on an arterial drop below 15 mph. Using either of these criteria, this route would qualify as a congested route, as the typical rush hour speeds of 12-15 mph are 60-75% of the congestion-free travel speed.

Delays at Intersections

The four complex intersections on the study route would all qualify as LOS F (i.e. delays greater than 60 seconds). Table 5 shows that the delays at 1st Brookline approached three minutes during the best years; more often delays were on the order of four minutes, which is equivalent to the delays at the worst intersection in the region. CTPS (2004, Table 3.11) monitored 42 intersections with approach delays greater than 1.33 minutes; only two had delays greater than three minutes, and none had delays averaging more than four minutes. The Sears Rotary, which is included as part of the second leg of the study route, was identified by the Boston Transportation Department (2003) as the intersection most in need of improvement within the Boston area.[3]

Finally, the information in Tables 5 and 6 can be used to test the hypothesis that trip time variability is dominated by the variability in the time spent at the major intersections. This hypothesis can be tested by comparing the variances associated with each segment. Table 7 shows that the standard deviation of trip time was greatest for 1st Brookline in all but one of the time periods. The typical standard deviation for this intersection was three minutes, so the typical variance was nine minutes.[2] Taking the variance of the typical trip time as 16 minutes,[2] this one intersection accounted for more than half the variability for the entire trip. The next most variable segment was usually the second leg of the trip, which includes the highly variable Sears Rotary plus several other intersections that very seldom are backed up. The standard deviation in the second leg is typically 1.5 minutes, so the variance for this segment would be 2.25 minutes.[2] The variance for the BU Bridge is about one minute,[2] so that the total variance associated with these three complex intersections is on the order of 12 minutes.[2] Assuming independence, these three intersections (in the space of one mile in the middle of the route) account for 75% of the total variability in the trip time. The first and third legs of the trip, although they amount to five miles or 85% of the total commuting distance, contribute very little to the reliability of the trip.

The importance of the complex intersections can also be seen by looking at the coefficient of variation, i.e. the ratio of the standard deviation to the mean travel time, again using typical values from Tables 5 and 6. The more complex and congested the intersections, the higher the coefficient of variation:

- Intersection at 1st Brookline: 0.75
- Intersection at BU Bridge: 0.5
- Second leg, including Sears Rotary: 0.25
- First leg, including Center Street Rotary: 0.15
- Third leg, with no complex intersections: 0.15

The sum of the variances of the five segments is generally close to the variance for the entire trip, suggesting that the performance at the major intersections can be considered reasonably independent. Table 7 compares the standard deviation of the trip time (from Table 6) to the square root of the sum of the variances of the individual segments. If the times spent in the five segments were independent and normally distributed, then the two measures would be identical. In fact, the two measures are very close (within 10%) for four of the periods and reasonably close (15-25%) for three more. The only major discrepancy is for the 1984-86 period, where the estimated measure is nearly 50% higher than the actual measure.

Table 7: Using the Variances of the Individual Segments to Estimate the Standard Deviation of the Trip Time

	Std. Deviation of Total Trip Time	Estimated Std. Deviation	Ratio of Estimated to Actual Std. Deviation
1980 Sep-Oct	3:58	4:41	118%
1980-82	4:38	3:35	79%
1984-86	3:20	4:54	147%
1988-94	3:55	4:13	108%
1995-99	3:48	3:42	97%
1999-2001	3:55	4:01	103%
2001-03	5:27	5:08	94%
2003-04	2:49	2:21	84%

Note: Times are shown as minutes:seconds

CONCLUSIONS

To summarize, there are various approaches to studying congestion. Highly publicized studies of commuting times tend to emphasize the increasing delays in commuting and the alarming trends if nothing is done to overcome the problem. Economists respond to calls for more highways with their own calls for tolls, and they note that there can be substantial congestion even in an optimal system. Highway engineers delve into the minutiae of delays, while network modelers devise elegant frameworks for predicting equilibrium traffic flows. While each perspective undoubtedly has its strengths for some purposes, it is striking that none of them (i.e. none of the dozens of exhibits in the works cited) shows any data about how service actually varies during rush hour for any specific commute. It apparently is not necessary to observe the phenomena of congestion to write about how bad it is or how to deal with it.

The purpose of this paper is to provide some insight into congestion by documenting one commuter's long-time experience in driving to work. While this is merely one commute out of many millions in the United States, it is at least an in-depth analysis of the actual performance of that route as perceived by a real commuter. The nature of this commute is believed to be representative of the nature of millions of commutes, so that some of the insights gained by looking at this one commute may be broadly applicable. At the least, understanding one real commute will prevent researchers from grievous errors in trying to model rush hour performance.

The key insights can be summarized as follows:

- For any particular route, travel times and travel time variability vary predictably during the rush-hour period. Rush performance can be viewed as a steady-state cyclical-queuing phenomena: every day may start afresh, but conditions on next Tuesday are likely to be similar to conditions last Tuesday.
- We can expect commuters to understand their options regarding both routes and departure times. They know that travel times and the reliability of travel times are not constant during rush hour, and they can choose their departure times based upon this knowledge. Modeling or imagining the peak as having a single level of performance (as is commonly done in network models or in traffic capacity analysis) will not give correct results.
- Traffic engineering models may not deal well with the length of delays that actually may occur at key intersections – delays that average two to five minutes are dramatically different from delays of 40 to 60 seconds that may be termed to be "unacceptable" by traffic engineers. The commuter doesn't mind the two to five minutes, but is really upset on the days when delays are 10 minutes or more because of a signal malfunction or the lack of a police officer to prevent gridlock.
- As more people use a route, the peak travel conditions may not be appreciably worse, as the congested conditions can be spread over a wider peak.
- There may be lulls at predicable times within the rush hour, reflecting highly localized commuting habits and routes.
- The trip time and variability for a route may depend upon just a few key intersections. Monitoring and modeling a relatively small number of key intersections may therefore provide an efficient way to model performance for a metropolitan area.
- It takes about a month after Labor Day for commuting times to settle down into what will become "normal" performance for the rest of the fall.

Endnotes

1. The "Big Dig" is the name commonly used for the major reconstruction of the expressways through Boston, including the depression and enlargement of Route 93 and the construction of a new tunnel linking South Boston to Logan Airport.

2. In 1979, I used my commute as an example of the journey to work and included these estimates in class notes for the introductory transportation class at MIT. That lecture motivated the collection of the data that, 25 years later, formed the basis for this paper.

3. The Sears Rotary is too complex and too dangerous for a driver to attempt to document specific entry/exit times, as there is a major merge with considerable cross-over traffic and a second, simpler merge, in addition to two traffic signals. This intersection accounts for most of the variability and all but about two minutes of the average time for Leg 2 of the trip. Leg 1 of the trip includes a congested rotary, which sometimes will back up a half mile or more along the approach used in the study route.

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