Evaluating Capacity of the Zion – Mt. Carmel Tunnel in Zion National Park

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Constructed in 1930 and recently designated as a National Historic Civil Engineering Landmark, the 1.1 mile long Zion – Mt. Carmel Tunnel served Zion National Park well for several decades. With the passage of time, however, vehicles became larger and this necessitated the use of one-way operation to allow large vehicles to pass through the narrow tunnel.

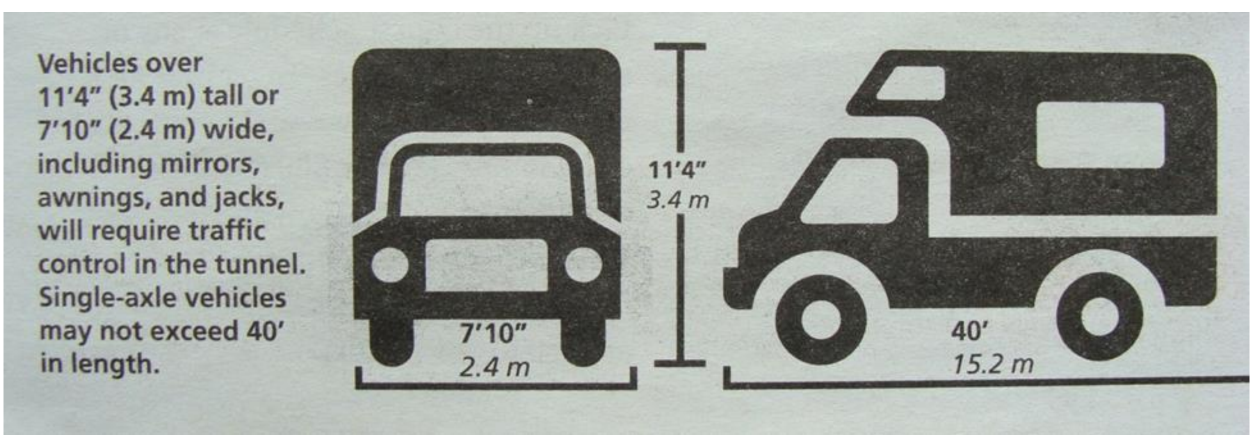
In recent years visitation to National Parks in the Colorado Plateau region has skyrocketed. For example, Zion National Park's visitation increased 61 percent from 2.7 million in 2010 to 4.3 million in 2016. The recent increases in visitation have created traffic congestion at the Park's South Entrance Station, parking and traffic congestion within Zion Canyon and the gateway community of Springdale, crowding on shuttlebuses, long waiting times to board shuttle buses, and crowding on recreational trails.

While not yet a severe problem, it was recognized that tunnel traffic congestion was a potential future problem. The objectives of this study were to determine: 1) the tunnel's capacity; 2) how soon traffic volumes would grow to the tunnel's capacity; and 3) waiting times associated with a range in service volumes.

Current Tunnel Operation

In 1989 a study by the Federal Highway Administration determined that vehicles greater than a certain size could not negotiate the curves in the tunnel without crossing the centerline. As a result, the National Park Service began a one-way traffic control service in the spring of 1989 for certain oversize vehicles. In addition, some classes of vehicles or users are prohibited from using the tunnel:

- Vehicles over 13 feet 1 inch tall
- Semi-trucks and commercial vehicles
- Vehicles carrying hazardous materials
- Vehicles weighing more than 50,000 pounds
- Single-unit vehicles over 40 feet in length
- Combination vehicles (a powered unit towing a trailer) over 50 feet in length
- Bicycles and pedestrians.



Vehicles otherwise permitted to use the tunnel that are over 11 feet 4 inches tall or 7 feet 10 inches wide may use the tunnel only under one-way traffic control. Vehicles exceeding these dimensions are referred to in the remainder of this paper as "large vehicles". "Small vehicles" refers to all other vehicles.

A tunnel traffic control operation, handled by Park staff, runs 365 days a year. Hours of operation are from 8:00 a.m. to 8:00 p.m. during most of Daylight Savings Time and earlier ending times during the remainder of the year. The tunnel operates as two-way operation during the hours of the day when the traffic control operation is not in effect. Large vehicles may not pass through the tunnel when the traffic control operation is not operating.

During the hours of tunnel traffic control the tunnel operates as a two-way operation if there are no large vehicles in the traffic stream. When a large vehicle arrives at either the east or west portal of the tunnel, the large vehicle is stopped until a one-way operation can be initiated. The large vehicle is then allowed to pass through the tunnel in a stream of one-way traffic. Large vehicles are directed to travel down the center of the tunnel, with lights on, at a speed of 25 mph, and to not stop while in the tunnel. When the tunnel is cleared of a large vehicle (or vehicles), two-way operation is resumed until another large vehicle arrives.

Concept of Roadway Capacity

Every roadway has a "capacity", which is the maximum number of vehicles that can pass a given point in a given period of time under prevailing traffic, roadway, and control conditions. Different types of roadways have different capacities. As examples: a freeway lane is different from an arterial street with periodic traffic signals; a two-lane rural highway is different from either a freeway lane or an arterial street. The traffic, roadway, and control conditions also affect capacity. The percentage of trucks in the traffic stream, the grade (steepness) of the roadway, and type of traffic control (traffic signals, stop signs) are examples of these conditions.

Most types of roadways have been well studied and there are tools in the Highway Capacity Manual that can be used to determine the capacity of a specific roadway. A facility like the Zion – Mt. Carmel Tunnel – especially when it is operating under a tunnel traffic control operation – is a special case that cannot be evaluated using Highway Capacity Manual techniques.

Why is the Tunnel's Capacity of Interest?

The capacity of the Zion – Mt. Carmel Tunnel is unknown. If Zion National Park visitation continues to grow, and if traffic volume on the Zion – Mt. Carmel Highway route continues to grow, there will be a point in time that traffic volume reaches the capacity of the tunnel. Beyond that point, as traffic volume then continues to grow, traffic demand will exceed the capacity of the tunnel. Simply put, more traffic will arrive at the tunnel than can pass through the tunnel, causing congestion and long waiting times.

Additional Background – a Capacity Problem will be Temporal

Zion National Park visitation varies day-by-day throughout the year. Traffic volume on the Zion – Mt. Carmel Highway displays a similar distribution, with a few extremely high days.

In addition, traffic volume varies by time of day, with a "peak hour" that has the highest traffic volume during the day.

As the Zion – Mt. Carmel Tunnel approaches capacity, there will first be a congestion problem during the peak hour on the day of the year with the "highest" traffic volume (a worst case combination of number of large vehicles plus other traffic). As traffic volumes and Park visitation then continue to grow, there will be more and more days of the year, and more hours on many of those days, when traffic demand exceeds capacity. In these ways, a capacity problem at the tunnel is a temporal problem.

Additional Background – the effect of different control conditions

As noted earlier, capacity depends upon traffic, roadway, and control conditions. Control conditions frequently change at the Zion – Mt. Carmel Tunnel. Two-way operation is a different control condition than one-way operation. Under one-way operation, releasing vehicles every five minutes is a different control condition than releasing vehicles every ten minutes. Thus, there is not just one capacity for the Zion – Mt. Carmel Tunnel; there are many different capacities (or service volumes). Each different capacity has a different level of delay associated with it.

Data Collection

One individual was located at the traffic control point at the east end of the tunnel (commonly referred to as "Tunnel East") and a second individual was located at the traffic control point at the west end of the tunnel (commonly referred to as "Tunnel West"). Each of the data collectors used a laptop computer. The internal clocks in the two laptops were synchronized. Between 10:50 a.m. and 3:10 p.m. the following data was collected.

- Departure Time (clock time in hours:minutes:seconds) of each vehicle from traffic control point at entering end of tunnel.
- Arrival Time (clock time in hours:minutes:seconds) of each vehicle at traffic control point at exiting end of tunnel.
- Whether each vehicle was a large vehicle
- A brief vehicle description to assist in matching vehicles

Subsequent processing and evaluation of the raw data allowed the following information to be created.

- Travel time (minutes and seconds) through the tunnel for each vehicle
  - Average travel time for large vehicles was 3 minutes 45 seconds [Note: some large vehicles were "free-flow" and some were impeded by the preceding vehicle]
  - Average travel time for free-flowing small vehicles was 2 minutes 57 seconds
- Average travel speed (mph) through the tunnel for each vehicle
  - Average travel speed for large vehicles was 19 mph
  - Average travel speed for free-flowing small vehicles was 24 mph
- Headway (the time between vehicles) in a platoon [Note: "platoon" refers to a group of vehicles passing through the tunnel. If a queue of vehicles has been waiting to enter the tunnel and are then released to pass through the tunnel, the vehicles will travel in a platoon.]
  - Average headway was 5 seconds

- Headway for large vehicles that were not the first vehicle in a platoon (this reflects the time required for staff to process a large vehicle)
  - Average headway was 27 seconds
- Turnaround Time (the time required to reverse the direction of traffic flow)
  - Turnaround Time was 34 seconds

Further processing and analysis provided the findings in the following sections of this paper.

Comparison of Tunnel to a Two-Lane Two-Way Rural Highway

Of the several types of roadway facilities covered by the Highway Capacity Manual, the tunnel most closely resembles a Two-Lane Two-Way Rural Highway. Under "ideal conditions" a Two-Lane Two-Way Rural Highway has a capacity of about 2,800 passenger cars per hour (both directions combined).

Obviously, none of the conditions in the tunnel are ideal and most conditions are far from ideal. With the sharp curves in the tunnel, the design speed is likely about 25 to 30 mph. Lane width is less than 12 feet. There are no shoulders. Passing is not allowed. There are buses and recreational vehicles in the traffic stream. Some of the time the tunnel is operating as one-way operation. The grade is 4.5 percent.

From the field data that was collected, it is possible to determine a tunnel capacity if two simplifying assumptions are made: 1) There are no large vehicles in the traffic stream: and 2) The tunnel always operates as two-way operation

The empirical (field collected) data show that vehicle headways for vehicles (that are not large vehicles) is five seconds when there is a continuous platoon of vehicles. If there are 3600 seconds in an hour and one vehicle passes by every 5 seconds, then 3600 / 5 vehicles can pass by in one direction per hour. That's equal to 720 vehicles per hour in one direction or 1440 vehicles per hour in two directions. 1440 vehicles per hour is a lot less than 2800 passenger cars per hour; the difference is the result of low design speed, narrow lanes, no shoulders, no passing allowed, and the 4.5 percent grade.

The number of 1,440 is theoretical, but it does help to provide some context, and helps to understand in subsequent discussion why the actual capacity of the tunnel is much lower.

How One-Way Operation Degrades Capacity

To further explore the tunnel capacity, it is useful to compare the potential flow of vehicles through the tunnel (when all vehicles are small) in two-way operation with the disruption to the flow of vehicles that occurs when one-way operation is initiated. Paragraphs below are numbered for convenience.

1. When the tunnel is operating under two-way operation, vehicles can enter the tunnel at 5 second intervals (every 5 seconds eastbound and every 5 seconds westbound).

What now happens when a large vehicle arrives at the east end of the tunnel?

2. Westbound traffic is stopped at the east end of the tunnel because a large vehicle is the first in line.

3. Eastbound traffic is stopped at the west end of the tunnel. A "stick" is given to the last eastbound vehicle to enter the tunnel. For purposes of this example, it is assumed that the request from the east end of the tunnel to stop traffic plus the time to hand out the "stick" is at least 9 seconds.

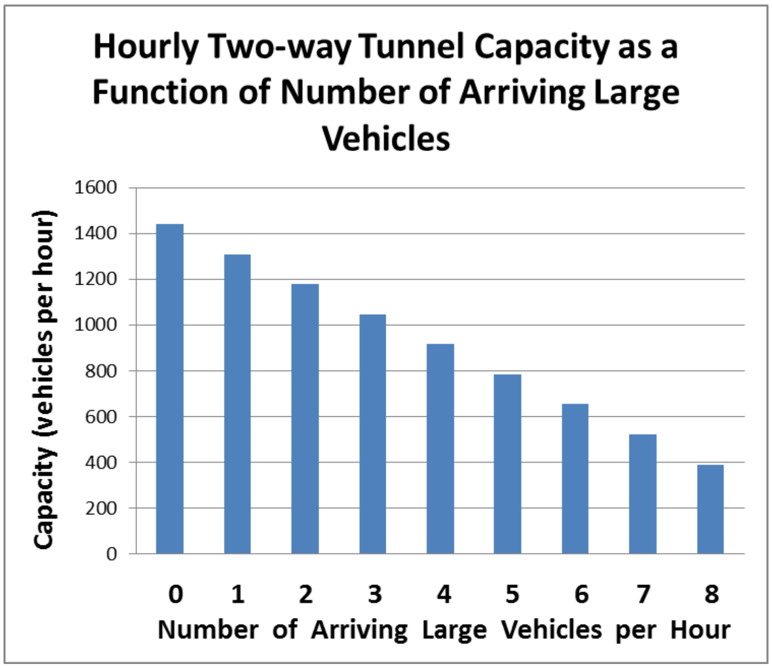
4. The travel time for that last eastbound small vehicle to pass through the tunnel is 2 minutes 57 secs.

5. Upon arriving at the east end of the tunnel, that last eastbound vehicle hands the "stick" to the Visitor Use Assistant. The Visitor Use Assistant then releases the westbound large vehicle. The elapsed time between the last eastbound vehicle arriving and the westbound large vehicle being released is 34 seconds. Any westbound small vehicles that are in queue behind the large vehicle follow along.

6. The large westbound vehicle takes 3 minutes 45 seconds to pass through the tunnel. If no other large westbound vehicles have been released at the east end of the tunnel, then eastbound small vehicles can proceed into the tunnel after the large westbound vehicle has exited the tunnel.

Adding up the times in paragraphs 4, 5 and 6, eastbound traffic was stopped for a total of over 7 minutes to allow one westbound large vehicle through the tunnel. If not for the large westbound vehicle, 87 small eastbound vehicles could otherwise have entered the tunnel. In addition, westbound vehicles were stopped for at least the amount of time in paragraphs 3, 4 and 5 (3 minutes 40 seconds). Westbound, 44 small vehicles could otherwise have entered the tunnel. In other words, one large vehicle reduced the tunnel capacity by 131 vehicles.

The above step-by-step example shows how large vehicles have a very degrading effect on tunnel capacity. It begins to become obvious that tunnel capacity will be much less than 1,440 vehicles per hour and only a few large vehicles will create a large reduction in capacity.



This figure emphasizes how small numbers of large vehicles can quickly reduce capacity. The chart presumes that arrivals of large vehicles are uniformly distributed in time. In other words, if 6 vehicles arrive during the hour, the vehicles arrive at intervals of 10 minutes. While arrival of large vehicles in the real world will be random rather than uniform, the figure does provide the sense that large vehicles have a huge impact on capacity. The figure shows an hourly capacity of 392 vehicles per hour when 8 large vehicles arrive during the hour. In comparison, from August 6 to September 22, an average of 12 large vehicles per hour arrived at the tunnel. As a further comparison, the 2016 record for the number of large vehicles passing through in one day was 289.

Calculation of Tunnel Capacity and Waiting Times

Information derived from field data collection permits the creation of scenarios that illustrate tunnel capacity and the associated waiting times under a range of different control conditions.

Tunnel capacity and waiting times were calculated based upon assumptions listed below. The scenarios included releases of vehicles from opposite ends of the tunnel every 5, 6, 7 ½, 10, 12, 15, 20, and 30 minutes.

Assumptions

- There is a continuous demand of vehicles at both ends of the tunnel
- One out of every 20 vehicles is a large vehicle (this reflects current conditions)
- Large vehicle arrivals are frequent and therefore one-way operation is required continuously
- Large vehicle arrivals are frequent and therefore (except for the 5 minute release interval) there is at least one large vehicle in every platoon

- There is a large vehicle at the beginning of each platoon (except for the 5 minute release interval)
- When there is more than one large vehicle in a platoon, the large vehicles are spread out through the platoon (large vehicles are not grouped together)
- The travel time for large vehicles is 3 minutes 45 seconds
- The travel time for the last vehicle in the platoon is 3 minutes 45 seconds
- The turnaround time is 34 seconds
- Headway between vehicles is 5 seconds
- The processing time for large vehicles is 27 seconds

The following table presents the results of these calculations and serves three purposes.

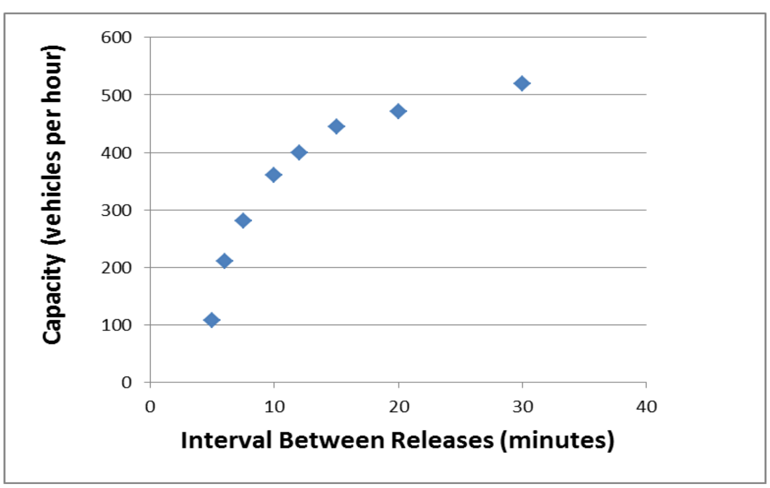
HOURLY CAPACITY AND WAITING TIME AS A FUNCTION OF INTERVAL BETWEEN RELEASES

Interval between releases at opposite ends of tunnel (minutes) Example: Tunnel East begins to release a platoon of westbound traffic. 5 minutes later, after westbound traffic clears, Tunnel West releases a platoon of eastbound traffic	Interval between releases at one end of tunnel (minutes) Example: Tunnel East begins to release traffic. The next release at Tunnel East begins 10 minutes later	Total number of vehicles in platoon	Number of large vehicles in platoon	Hourly Capacity (vehicles per hour)	Waiting time for first vehicle in platoon (minutes:seconds)	Average waiting time - all vehicles in platoon (minutes:seconds)
5	10	9	0-1	108 *	9:20	4:35
6	12	21	1	252 *	10:20	5:10
7 1/2	15	35	2	280 *	13:35	6:50
10	20	60	3	360	18:20	9:10
12	24	80	4	400	22:40	11:20
15	30	111	5	444	28:10	14:05
20	40	157	8	471	38:20	19:10
30	60	260	12	520	58:10	29:05

* Hourly capacities for 5, 6, and 7 1/2 minute intervals are slightly understated because there would be opportunities to "send small" (release small vehicles in the opposing direction) once a large vehicle has cleared the tunnel. The probability for opportunities to "send small" is very low for intervals of 10 minutes or more. Thus, the hourly capacity for intervals of 10 minutes or more is more precise.

Currently, the Park tunnel staff do not release traffic from opposite ends of the tunnel at set time intervals. Thus, the table does not reflect current tunnel operation. However, the above table is useful to show that increasing the interval between releases will increase the tunnel's hourly capacity – the table's first purpose. This effect is also shown in the following illustration.

CAPACITY AS A FUNCTION OF INTERVAL BETWEEN RELEASES

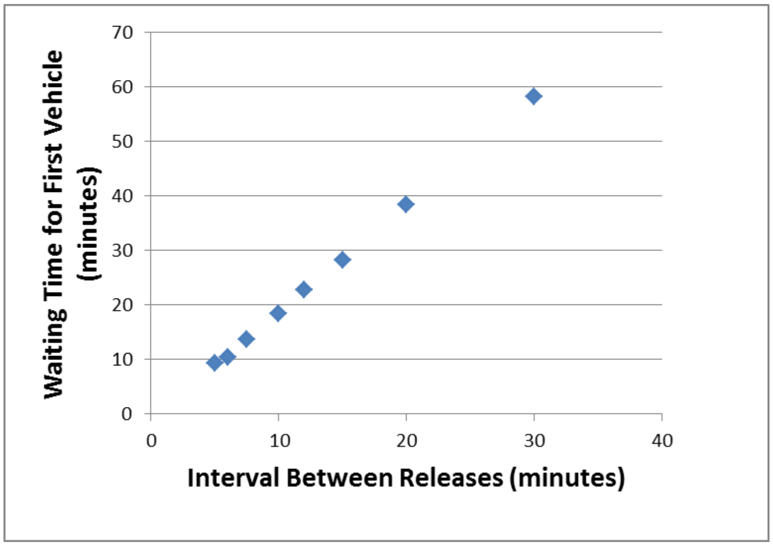


Why does tunnel capacity become larger when the interval increases? When the interval continues to grow, there is less and less "lost time" due to clearing the tunnel. In the extreme case of the 30 minute interval, the tunnel is cleared only once in each direction each hour.

However, as the interval becomes longer and longer, there are diminishing returns of increased capacity.

Although Park staff do not release vehicles at set time intervals, current operation does, in a sense, respond to increasing demand by lengthening the time between releases of vehicles at each end of the tunnel. Generally, when one-way traffic is released at one end of the tunnel the entire waiting queue is allowed to proceed. When traffic volumes are lower, the lengths of the queues are shorter and the time between alternating releases is shorter. When traffic volumes become higher, the lengths of the queues are longer and the time between alternating releases is longer. In effect, as traffic volume grows, the operation climbs up the capacity curve. But, in so doing, waiting times increase (see next paragraph). This self-correcting effect helps to get more traffic through the tunnel but visitors endure longer and longer waiting times.

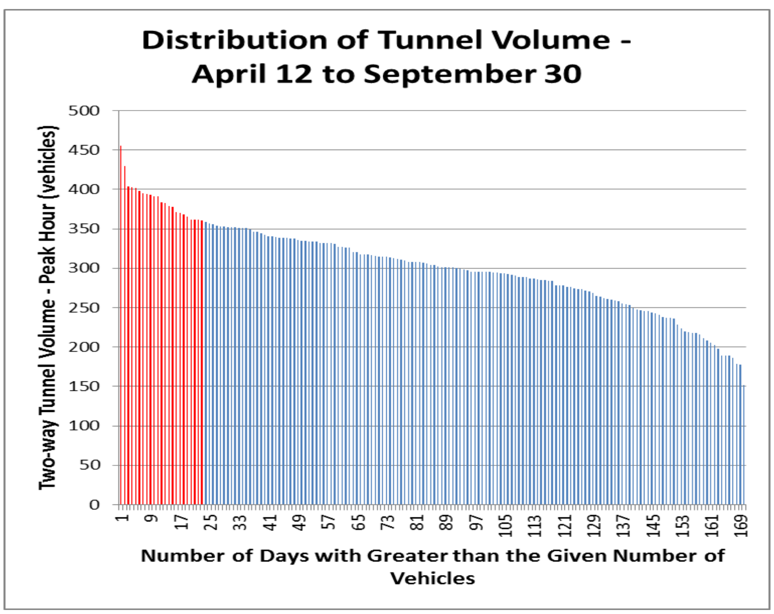
WAITING TIME AS A FUNCTION OF INTERVAL BETWEEN RELEASES



The data in the Hourly Capacity table is also useful in showing that increasing the interval between releases will increase waiting time – the table's second purpose. Waiting time is presented for both the first vehicle waiting in line (the vehicle that "just missed" an opportunity to catch the end of the preceding platoon) and the average waiting time for all vehicles in the platoon. As the interval becomes longer, the waiting time increases. This illustration shows waiting time for the first vehicle in the platoon.

How close is the tunnel to capacity?

Finally, as a third purpose, the Hourly Capacity table is useful to relate the various hourly capacities to current traffic demand. A permanent traffic counting station that continuously counts hourly volumes by direction is located west of the tunnel at Canyon Junction.



As noted earlier, traffic volume varies by hour of the day and from day to day during the year. The peak hour of the day is the most critical time for tunnel operation. At Canyon Junction the peak hour of the day is most commonly the hour from 11:00 a.m. to noon. Traffic counts for 11:00 a.m. to noon (both eastbound and westbound) were obtained for each day from April 12 to September 30. When those counts are ordered from highest day to lowest day, in the form of a histogram, the above figure is produced.

From April 12 to September 30 there were 23 days on which the peak hour tunnel volume was greater than 360 vehicles per hour (shown in red). The highest day was 455 vehicles per hour. The Hourly Capacity table presented earlier shows that release intervals of 10 to 15 minutes are needed to handle volumes ranging from 360 to 444 vehicles per hour.

What are current waiting times?

The release intervals of 10 to 15 minutes that are needed to handle current peak hour volumes have waiting times ranging from 18 minutes 20 secs to 28 minutes 10 secs for the first vehicle in line, and from 9 minutes 10 secs to 14 minutes 5 secs for the average waiting time (see Hourly Capacity table).

Conclusion

During many days of the year, and during most hours of those many days, the Zion – Mt. Carmel Tunnel operates at a satisfactory level, accommodating traffic demand and having tolerable waiting times. When there are no large vehicles and two-way operation is possible, traffic flows well through the tunnel. But as more and more one-way operation is required to accommodate large vehicles, the operation becomes more strained and waiting times grow to levels that may be undesirable.

There are currently about two dozen days a year when waiting times during the peak hour range from about 18 to 28 minutes for the first vehicle waiting in line to pass through the tunnel.

Alternatives for Addressing the Capacity-related Issues

This study revealed that at selected times during the year the Zion – Mt. Carmel Tunnel has long waiting times. Several alternatives were identified that could solve this "capacity" issue. The alternatives are simply listed below for the reader's information. It will be a decision of Park managers to determine which alternatives are most practical and feasible, and the advantages and disadvantages of each.

- Enlarge the existing tunnel
- Construct a second, parallel tunnel
- Ban large vehicles 24/7/365
- Ban large vehicles on a temporal basis
- Restrict large vehicles to smaller time periods during the day
- Restrict large vehicles to only certain portions of each hour
- Construct pulloffs to serve as large vehicle holding areas
- Automate tunnel operation

The findings and opinions presented in this paper are those of the author. They do not necessarily represent the views of Zion National Park or the National Park Service.