**Final Research Report**
Agreement T4118, Task 67
SR 167 HOT Lanes

# Examination of SR 167 HOT Lane Violation Patterns

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16. ABSTRACT

The HOT lanes on SR 167 south of Seattle, Washington, are separated from their respective general purpose lanes by a double white lane line. Legal access to the HOT lanes is limited to four locations southbound and six locations northbound. This study examined the frequency with which motorists illegally cross the double white lane line, rather than waiting for one of the legal access points. The study determined the locations and operating conditions under which violations most commonly occur.

The study showed that during most times of the day and along most portions of the corridor, the number of illegal entry and exit movements is negligible. However, at a small number of locations and under specific congestion conditions, violation rates can exceed 1 per minute. The worst violation location is northbound, north of the S. 180th St on-ramp, just before the end of the northbound HOT lane and after the last toll collection gantry. Violations at this location appear to be caused by the three main factors: 1) In anticipation of the lane becoming a general purpose lane in less than another 500 feet, some motorists “jump in early.” 2) This location is often the point to which the queue from the I-405 interchange ramp backs up. Violation rates increase significantly near the upstream end of any queue. 3) Many vehicles entering the freeway at the S. 180th St ramp move as directly as possible to the left lane of the freeway and then merge into the HOT lane. In congested conditions, these movements result in lane-line violations because the slow, heavy traffic allows the weave process to occur in a short distance. Under faster free flow conditions, this weave movement requires a much longer distance, resulting in vehicle merges at the intended legal locations.

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# Introduction

In May 2008 the Washington State Department of Transportation (WSDOT) opened high occupancy toll (HOT) lanes on State Route (SR) 167. The HOT lanes were converted from preexisting high occupancy vehicle (HOV) lanes on SR 167. The HOT lanes stretch approximately 10 miles north to south, with six access points northbound and four access points southbound (WSDOT). The HOT lanes are demarcated by double solid white lines, which are not legal to cross. Legal access points are indicated by toll signs and single skip striping.

WSDOT commissioned this study to determine the rate and locations at which drivers are violating the double white lines and either entering or exiting the HOT lanes illegally. WSDOT asked that, where possible, factors that increase HOT lane violation rates be identified. The resulting information about general violation rates and any exacerbating factors will inform future HOT lane design decisions.

This research took advantage of existing WSDOT surveillance cameras along SR 167. WSDOT and the University of Washington Smart Transportation Applications and Research Laboratory (STAR Lab) have a fiber optic connection that allows users at the STAR Lab to select two video channels from WSDOT's available cameras. This connection allowed the research team to collect research video from SR 167.

# Methodology

## Camera Evaluation

Understanding the cameras' limitations was important in designing an effective data collection plan. Accounting for camera limitations was also important to interpreting results. Research video needed to be collected so that enough of SR 167 could be analyzed to be representative. Specific locations of interest could then be identified for more in-depth analysis.

Using the STAR Lab video connection, the research team was able to access any WSDOT surveillance camera on SR 167. Fourteen cameras on SR 167 are located between the northern and southern ends of the HOT lanes. These cameras are shown in

Figure 1.[1] Unfortunately, many of these cameras were problematic in terms of the researchers' ability to view HOT/GP lane changing behavior.

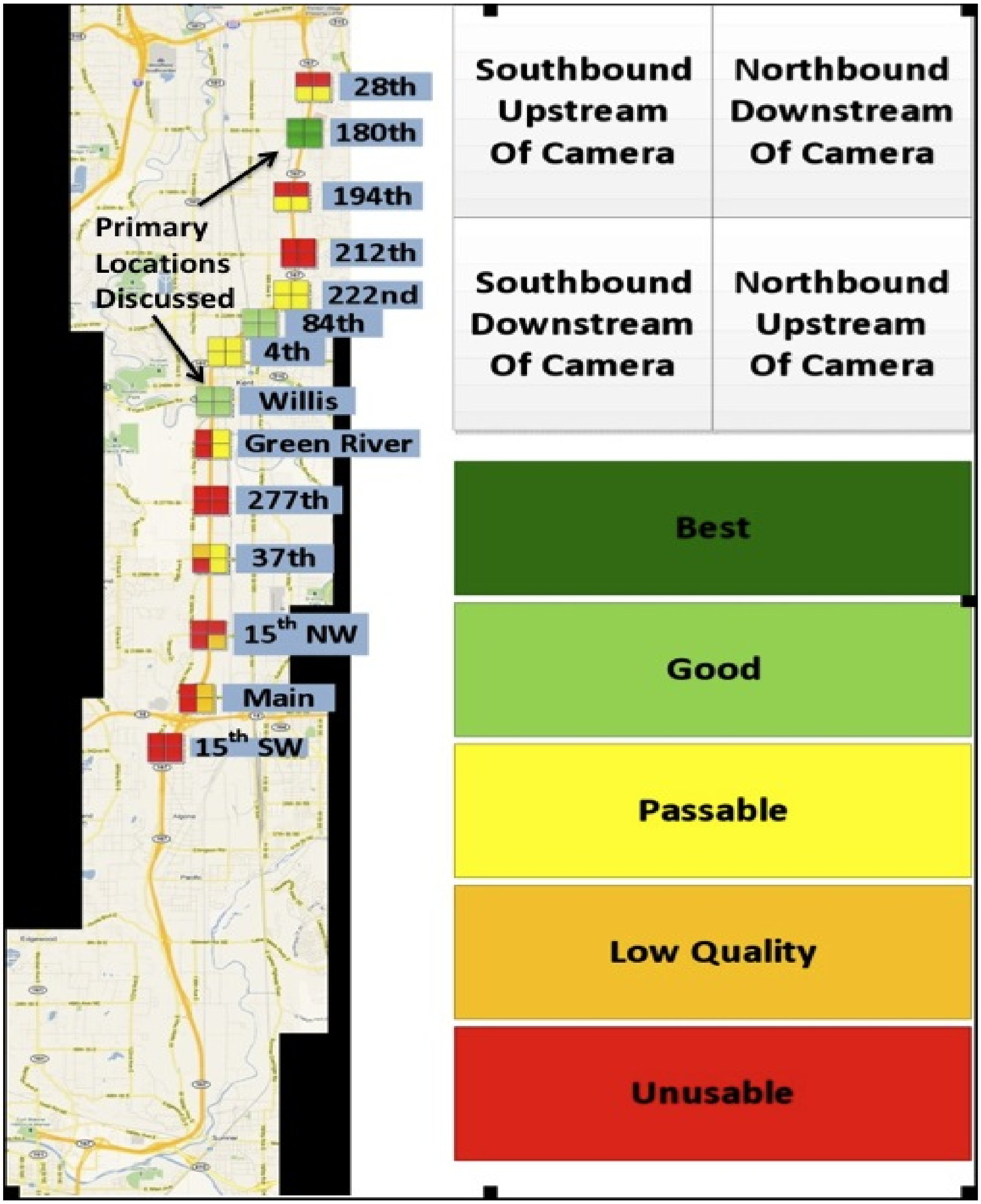


**Figure 1: SR 167 HOT Lane Camera Locations and Quality**

[1] Note: The WSDOT naming convention is to name the camera after the closest cross-street. This can lead to cases in which the name of the camera location does not make sense to casual users of the data. An example is the Willis Street camera, which is located at the SR 516 (S Kent-Des Moines Road) interchange.

Many of the cameras on SR 167 presented challenges because they are limited by view obstructions and roadway curvature. Two examples are 212$^{th}$ and 194$^{th}$, seen in Figure 2. Another example is the 15$^{th}$ Street SW camera, located on the 15$^{th}$ St. SW overpass at the southern end of the northbound HOT lanes. Its northbound view is limited to approximately 1,000 feet by intervening trees. Unfortunately, because of the angles necessary to see between trees, those 1,000 feet could not all be viewed at the same time.

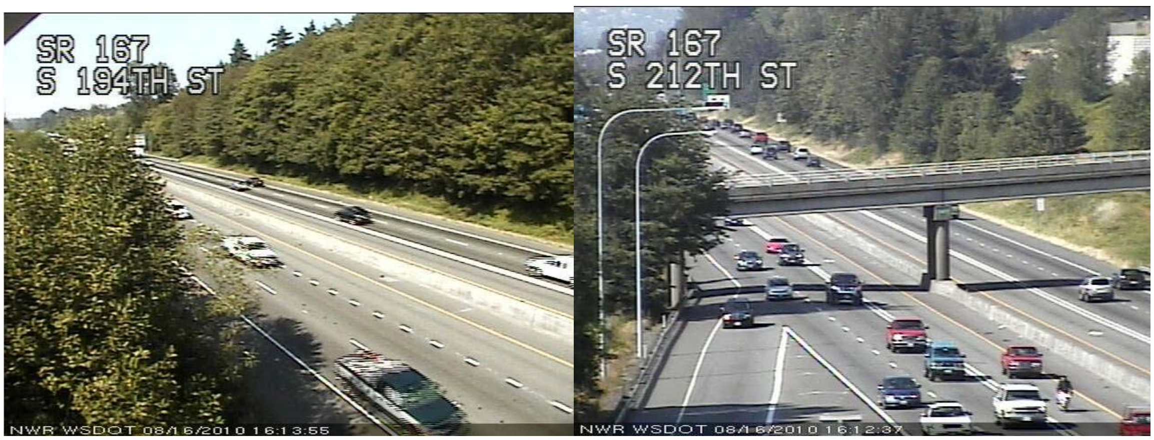


**Figure 2: Examples of Camera View Limitations for the 194$^{th}$ St. and 212$^{th}$ St. Cameras**

Another problem was that the cameras are generally placed at interchanges, whereas the merging behavior that is a likely factor in vehicles violating the double white lines frequently happens upstream of the off-ramps and downstream of the on-ramps. (For example, in Figure 2, lane changing to reach the off-ramp observed on the left side of the S. 212$^{th}$ St picture will mostly occur on the roadway obscured by the tree on the left side of the image.) It is not uncommon for cameras at interchanges to be nearly a half mile from a merge zone. Generally, the next camera is located at the merge zone; however, at many merge zones with cameras, some of the most relevant locations were not easily seen.

The final set of challenges to using the existing cameras included resolution and angle of incidence to the road. Because of the age of the cameras on SR 167, the video formats and pixel density were somewhat limited. Consequently, there was a practical limit to the segment length that could be reasonably viewed at one time before pixel size limited visibility.  At longer distances, the visible size of the vehicles became close to the pixel sizes.  The picture in Figure 3, taken from the South 180th Street camera, serves as an example.  The circled vehicle is approximately even with the northbound off-ramp, which is approximately 1,800 feet from the camera.  The circled vehicle consists of ten pixels.  The cameras could be zoomed in and out, somewhat mitigating the problem.  However, at longer distances the downward angle of view became flatter, so that vehicles occluded other vehicles beyond them.  In addition, camera instability increased with zoom level, so the farther away the camera viewed, the more it was affected by shaking from wind and traffic.  The more unstable cameras sway in even the lightest winds.


**Figure 3: Viewing Length Limitation**

## Data Collection

The data collection methodology had to take the limitations of camera view and stability into consideration.  Since each camera could view only a limited area at one time, the first step was for the research team to visit WSDOT's Northwest Region Traffic Systems Management Center (TSMC) in Shoreline.   With the cooperation of the TSMC staff, the research team was able to gather information about camera views. This information included a number of screen shots, such as those seen in figures 2 and 3.

The research team then gathered video from each camera for analysis. Video was recorded for approximately a week at each location. After video had been collected for a location, the research team determined how well traffic could be seen at each location under various traffic conditions. A camera view over a long, unobstructed distance that included relevant points such as ramps was more important than a camera with a limited view or a view of most of a an access point but not all of the merge/diverge areas associated with that ramp. Traffic patterns were also noted at this time.

The camera image analysis showed that the camera at S 180$^{th}$ St. had the best view of any camera along the corridor. The camera is located at the center of a more than one-mile-long straight section and has additional height because of its installation on an overpass. The straight road and additional height allow the camera to zoom in and maintain good vertical viewing angles for anywhere it can see. The location on the overpass does have one drawback: traffic on the overpass can vibrate the camera. The Willis St. and 84$^{th}$ St. cameras also had higher quality views.

## Results

In analyzing the results, it is important to acknowledge the narrow scope available from any given video camera. Most videos offered a view of approximately 1,200 feet of SR 167 at one time. Given that the HOT lane corridor is 11 miles long northbound and 9 miles long southbound, 1,200 feet represents a little over 2 percent. Although the research team made every effort to gather representative video, because only a small percentage of the corridor could be observed at one time, there was a limit to how much variability could be controlled. Given that limitation, the research team spoke with the TSMC staff who monitor the cameras on SR 167 daily to get their impressions of traffic patterns and behavior on SR 167.

The typical general purpose lane traffic pattern is that in the morning, the northbound SR 167 section congests modestly approaching Kent (WSDOT Traffic Map Archive). After the SR 516 ramps, it then generally operates in free flow conditions until it congests again at the northern end of the roadway as it approaches I-405. On high congestion days, traffic queues at the northern end can extend far enough south that the queue affects the performance of the northern end of the HOT lane. Except for this periodic AM peak period congestion, the HOT lane operates in a free flow condition throughout the corridor. During the evening commute period, the northbound general purpose lanes on SR 167 congest only at the northern end. As in the morning peak period, that congestion is highly variable, with the queue extending back to the HOT lane only periodically.

Southbound, in the morning peak, SR 167 has minimal congestion. The evening peak is an entirely different story. Congestion commonly backs up from the SR 18 interchange. However, the extent of this back up varies dramatically from day to day, ranging from very little congestion to extensive congestion throughout the corridor. In addition, even as congestion spreads northward, sections of the freeway within the "congested" portion of the corridor can become free flowing as shock waves travel up and down the corridor. A common location where congestion forms is around the SR 516 interchange near the Willis St. camera. When congestion reaches this far north, the over-all back-up is approximately 5 miles and can last for several hours.

In looking at the entire length of the corridor and all parts of the day, the study found that violation rates are generally low. For most of the day in most locations, very few violations occur. However, under specific congestion conditions that occur during some peak periods, violations rates can become substantial. These study findings are discussed below.

### Off-Peak Analysis (Uncongested General Purpose Lanes)

During non-peak traffic hours, the maximum violation rate observed was less than one per four hours per camera observation zone (~1,000 feet) measured in the peak traffic direction. Violations occur as vehicles both enter and exit the HOT lane.[2] Generalized to the entire corridor, this translates to a worst-case violation rate of 26 violations per hour for the entire corridor if both directions are assumed to violate at the same rate as the

[2] The short segment length observable within any given camera view prohibited the determination of whether specific vehicles jumped into and then back out of the HOT lane to pass slower vehicles in the general purpose lanes, but our observations suggest that most of these movements are "moves of convenience" rather than toll avoidance efforts. (That is, the drivers want to enter/exit at that location and no legal entrance/exit is present, so they simply change lanes across the double white line.)

peak direction. However, the limited data we saw indicated that violation rates in uncongested sections of the corridor are considerably lower than this worst-case scenario.

### Peak Period Analysis (Congested General Purpose Lanes)

Peak hour analyses showed that the violation rate is closely tied to traffic conditions. Under low congestion conditions, there are very few HOT lane violations, similar to the results of the off-peak analysis. However, when the general purpose (GP) lanes are congested and the HOT lanes are free flowing, the violation rate increases dramatically. Three different types of frequent violations are then observed, most involving movements *into* the HOT lane. These violations are most frequently associated with

- the end of the queue where congestion forms in the general purpose lanes
- where on-ramps bring large traffic volumes into a congested traffic stream upstream of an access point
- the terminus of the HOT lane.

The increase in violations associated with the point where the general purpose lane congestion queue begins is very geographically localized, as the highest violation rate is within the last 300 to 500 feet of the beginning (upstream end) of the congestion queue. It appears that drivers are content to drive in the GP lanes until they encounter stop-and-go traffic, at which point some drivers choose to move to the HOT lane, even if there is no legal access point at that location, and even if there are toll points downstream of that location. This result can be interpreted to indicate that drivers do not choose to pay the toll to enter the HOT lane until they see a clear benefit. Once they become convinced that a benefit will be gained (by physically observing the end of the queue), they become willing to pay the toll; but wishing to gain that advantage, they jump immediately into the HOT lane, rather than waiting until the next legal access point.

Once congestion forms in the general purpose lanes, the violation rate that occurs approaching the point where the congestion queue forms then increases from less than 0.25 violations per hour to roughly eight violations per hour for a 1,000-foot-long segment. All of these violations are vehicles moving *into* the HOT lane. Unfortunately, this result is not easily generalized along the entire corridor because of the violation rate's dependence on congestion. If there were only one predictable congestion spot, there would be one high violation location. However, when multiple congestion spots exist on the corridor, it is not clear how that changes total violation rates. The total corridor violation rate could increase at rates noted above with each new queuing location. However, the presence of an upstream congestion location may also lower the downstream violation rate by convincing some motorists to shift to the HOT lane early in the corridor, thus decreasing the number of potential users later in the corridor. For example, when queues are forming at more than one location at the same time, say near Central Ave. northbound and also at 180$^{th}$ St, high violations may occur at both locations, thus potentially doubling the level of violations occurring during the period that both queues are present. However, it is possible that the queues at Central Ave may encourage travelers coming from Sumner to move into the HOT lane at that point, thus reducing the number of individuals willing to violate the HOT lane lines to only those individuals entering the corridor north of Central Avenue.

This study was not able to determine whether the presence of an upstream congestion location caused a decrease in violation rates at a downstream congestion location. This was in part due to our inability to see much of the southern section of the HOT lane corridor effectively from the existing cameras, and in part due to the limited number of cameras we could record at any one time. (This, combined with the fact that the end of the queue moves up and down the freeway, limited our ability to observe multiple congestion queue locations on the same day.)

Another factor associated with an increase in HOT lane violations is the presence of an on-ramp. On-ramps can contribute to violations in two ways. First, the merge zone where on-ramp traffic enters the highway can become congested, and in response, some vehicles already on the mainline choose to jump into the HOT lane in the behavior noted above. Second, when the GP lanes are congested, any traffic from the on-ramp that wishes to enter the HOT lane may violate the double white lines rather than wait in stop-and-go traffic to reach a legal access point. This occurs because the legal HOT lane merge areas have been placed at a distance downstream from the ramp that allows safe weaving movements from the ramp to the HOT lane under near free flow conditions. However, under heavily congested conditions, this same weaving movement requires much less physical distance. Once weaving vehicles reach the left hand GP lane, they frequently take the first acceptable gap into the HOT lane, rather than sitting in the slow moving GP lane until they reach the legal HOT lane merge area.

The GP lanes must be heavily congested for this on-ramp weaving movement to create a significant violation rate. This research found two cameras that had views of on-ramps with significant violations, the Willis St. and S 180th St. cameras. At Willis Street, the SR 516 (Kent-Des Moines Road) on-ramp is associated with an increase in violation rate whenever the congestion front has passed the end of the on-ramp. The ramp's contribution to the total SR 167 HOT lane violation rate is highly variable because the location of the end of the congestion queue varies over the course of the peak period. The varying levels of congestion sometimes create a weave condition for vehicles entering from SR 516 that causes high violation rates, while at other times free flowing GP traffic extends the on-ramp weave location to the legal HOT lane entrance. When the GP lanes are congested at the ramp terminal, the SR 516 on-ramp location may experience ten violations per hour. A similar but smaller violation rate was also observed for vehicles exiting the HOT lane south of the SR 516 interchange. It was not possible to determine whether this was caused by drivers attempting to avoid the toll gantry or by drivers simply choosing to exit the HOT lane in that vicinity because they found a gap in the slow moving GP lanes.

The entrance from S 180th St. to northbound SR 167 is a somewhat special case. Not only is this an on-ramp that feeds into a frequently congested GP lane, but the on-ramp merge zone is very close to the end of the HOT lane. Therefore, this location also demonstrates the third major cause of HOT lane violations: the end of the HOT lane.

Congestion often backs up from the I-405 interchange in both the AM and PM peak periods. When the GP lanes are congested, there is a significant increase in violations, with many, but not all, of those violations occurring after weaving movements from the S. 180th St. on-ramp. The violation rate at this location can easily exceed 100 vehicles per hour in an approximately 500-foot-long section. Figure 4 shows a screen capture from the S 180th St. camera looking north toward the merge zone from the S 180th St. on-ramp. The HOT lane ends just out of view of the camera (around the corner to the left of the image).


**Figure 4: HOT Lane Violations at S 180$^{th}$ St.**

The high violation rate here appears to result from a combination of several factors. The first factor is the on-ramp, which contributes to violations in a fashion similar to the on-ramp at SR 516. The second reason is that northern SR 167 has little room for the Washington State Patrol to pull vehicles over, which can limit enforcement (WSDOT). The third reason is that drivers enter the HOT lane before the end of the HOT double white line lane marking, treating it as the GP lane it will become. This behavior is very similar to violations in traditional HOV lanes. For HOV lanes, violation rates can be quite low until just before the end of the HOV lane or before the temporary removal of the HOV lane restriction leading to an off-ramp (e.g., the eastbound SR 520 approach to 92$^{nd}$ Ave NE). In these cases, violations spike as vehicles planning to exit or to use the GP lane that begins in less than ½ mile "jump in early."

The research team also made several other observations. First, a very high proportion of HOT lane violators used their turn signals to indicate their intent to change lanes. This indicates that the violators are more concerned about the safety of their movement into the HOT lane than about being observed as violators of the double white line. Second, violators typically wait for suitable gaps to make their lane change maneuver. Third, when the GP lanes are congested, the violation rate is highest when the HOT lane is emptiest, then decreases as the HOT lane becomes more heavily utilized. This pattern holds until the speed differential between the HOT and GP lanes decreases, i.e., the HOT lane starts to congest. Then the violation rate increases again as long as the HOT lane is moving faster than the GP lane. If both the HOT and GP lanes are congested, there are effectively no violations.

## Conclusions

This study was undertaken to determine the rate at which drivers violate the double white line lane marking used to separate the SR 167 HOT and GP lanes. The findings indicated that drivers generally obey the lane markings when traffic is moderate to light. The background violation rate appears to be negligible. However, as traffic congestion increases, the violation rate increases. The locations of general purpose lane congestion and on-ramp traffic were found to be associated with violation locations and higher violation rates.

Once congestion forms, the violation rate appears to be approximately 8 violations per hour, with those violations generally occurring at any location where free flowing general purpose traffic approaches the beginning of a congestion queue. This indicates that 16 of these types of violations occur during the common 2-hour peak period on SR 167. When general purpose lane congestion is heavier than usual, the number of violations is expected to increase both with the number of distinct congestion queues and with the longer duration of the period when general purpose lane congestion is present.

Traffic from on-ramps also increases the violation rate. It appears that traffic from the on-ramps frequently appears unwilling to wait in GP lane congestion to reach a legal access point. Therefore, when an on-ramp feeds traffic into a congested GP lane, violation rates will increase. The size of this increase changes from location to location, with the most common rate being about 8 violations per hour, but with violations reaching as high as 1 per minute northbound at S. 180$^{th}$ St. Ramp traffic can also contribute to the formation of congestion in the GP lanes, exacerbating the problem by helping create the congested mainline conditions that lead to violations at the end of on-ramp weaving movements.

The situation at S 180$^{th}$ St, where the northbound violation rate is unusually high, seems to be caused by the confluence of multiple factors and is not solely a function of the on-ramp weave occurring through congested general purpose lanes. A major contributing factor is that the HOT lane ends a short distance after the on-ramp merge zone, encouraging "end-of restriction" queue jump behavior, as many vehicles make an early move into the last several hundred feet of HOT lane to avoid the congestion that regularly backs up from the I-405 interchange to the S 180$^{th}$ St. on-ramps. Finally, because the end of the congestion queue is often located near the S. 180$^{th}$ St ramp terminal, this is also the location where many "end of queue" violations occur. All of these factors result in a violation rate that can exceed 100 vehicles per hour.

Ultimately, this is a driver behavior problem. Understanding drivers' reasoning will be required to solve this problem. While this topic deserves further research, some initial insights can be gleaned from this study. Drivers are nearly unanimous in using their signals when changing lanes into the HOT lane. Drivers are also looking for appropriate gaps when they wish to enter the HOT lane. This indicates that drivers are either not really considering the legality of the movement or are at least downplaying the significance of the movement's illegality in favor of increasing the safety of the maneuver. They consequently treat the movement like a normal lane change, requiring only an acceptable gap in oncoming traffic. This suggests that these drivers need additional information to understand that these movements are illegal.

## Recommendations

The research team would like to make some recommendations for future consideration with regard to SR 167. First, improved cameras and camera locations would greatly increase the ease with which future studies could be accomplished. Even trimming selected trees in key locations could have significant benefits. Second, driver behavior in congestion suggests that some fraction of the drivers currently making illegal lane changes might be willing to pay the toll—and would be willing to enter the HOT lane in a legal manner upstream of congestion—if they knew when approaching the legal

HOT lane entrance that they would save travel time by entering the HOT lane at that point. WSDOT may be able to entice these drivers to enter the HOT lanes legally by providing additional information on current roadway conditions to drivers. One possible way of doing this may be to post HOT vs. GP lane travel times or “Congestion Ahead” messages on variable message signs before those legal entry points. Various other communication mechanisms may also meet this driver information need at lower cost than new variable message signs. The project team has not looked extensively at options for improving motorist awareness of actual travel benefits.

Finally, the placement and length of legal entrance zones in ramp areas may benefit from review. The current placement of HOT lane entrance areas is significantly downstream of the on-ramp so that vehicles traveling at 60 mph can safely change lanes from the ramp to the access point. This study indicated that the entrance points should perhaps start closer to the on-ramp, allowing congestion-period merges to be less problematic.

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