

Work-zone traffic operation and capacity

Goran Nikolic P.Eng., Head of Traffic Planning, Ministry of Transportation of Ontario

Rob Pringle P.Eng., Senior Project Manager, MMM Group

Kevin Bragg, Senior Analyst, INRO

Diego Mendoza, Consultant, Demasimulations

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Abstract: *In assessments of the impact of expressway lane closures on traffic flow, current practice generally involves an assumption of the nominal capacity per lane which varies, in some cases significantly, by jurisdiction. Situations have been observed by the Ministry of Transportation of Ontario (MTO) where application of such a simplistic guideline, particularly in the absence of specific consideration of the effects of heavy vehicles in the traffic stream, has led to significant congestion issues and negative public reaction. Preliminary research, conducted on behalf of MTO with respect to overnight lane closures on MTO's 400-series expressways in the GTA, suggests the existence of two operational regimes. The first regime, found where the demand is insufficient to result in queue formation at the lane closure and merging from the closed lanes is orderly, suggests a capacity in the order of 1,750 veh/h/lane, towards the higher end of the range of currently assumed values. The second regime, found where demand is such that a queue has formed, suggests a much lower capacity in the order of 1,100 to 1,300 veh/h/lane, towards the lower end of the range of currently assumed values. This research also looked at the equivalency of heavy vehicles in a work-zone, lane closure context. These results were based on relatively limited data and further data collection and analysis is recommended to verify these preliminary findings.*

1. Introduction

The Ontario Ministry of Transportation operates and maintains an extensive system of freeways and lesser highways across the province. Due to climatic considerations, rehabilitation and improvement activities are concentrated during the non-winter months, meaning that at any given time there may be a number of work zones active on the freeway system in the Greater Toronto Area. Typical construction staging may call for one of several possible work zone schedules, including 24-hour lane reductions, more extensive overnight lane reductions, and complete closures of either the express or collector lanes over a weekend. In many cases, timing restrictions on lane closures are based on a relatively rudimentary evaluation of hour-by-hour traffic volumes and the impact of heavy commercial vehicles, which often travel in the evening or overnight to avoid congestion during commuting peak periods, is not taken into account. In part, this is due to a lack of concrete data and a suitable methodology.

The objectives of this study were to:

1. Evaluate the capacity of single-lane work zones on GTA highways; and,
2. Evaluate the impact of heavy commercial vehicles on work zone capacity.

Operations were observed at overnight work zones on Highway 401 and the Queen Elizabeth Way during the fall of 2008. Data was collected during those periods where two of the three available lanes were closed and queuing was present during at least part of the observation period (typically between 11 pm. and 1 am.).

2. Background

2.1. Previous research

The Highway Capacity Manual 2000 (1) provides a manual method for estimating work zone capacity, reducing the capacity of a work-zone lane in comparison to a normal freeway lane but assuming that the passenger car equivalent (PCE) of heavy vehicles is the same as for unencumbered freeway lanes. The methodology is based primarily on a study by Krammes and Lopez (2) of 33 work zones in Texas prior to 1991.

Other models have accounted for the presence of heavy vehicles in work zones, such as that by Sun, Lv and Paul (3), based on observations in Illinois, or by Sarasua et. al. (4), based on lane closures in South Carolina. Sun, Lv and Paul developed PCE values based on work-zone speed and heavy vehicle percentage, using a multiple-regression method and closed-loop calibration. Sarasua, et. al. developed a model based on speed-flow relationships observed at lane closures in South Carolina. The model accounted for the “intensity” of work zone operations, lane and closure configuration, and heavy vehicle proportion using a PCE value varying with work zone speed. Al-Kaisy and Hall (5) observed a series of long-term lane closures in Ontario. They proposed a model using multiplicative capacity reduction factors, as opposed to additive, to better account for their interactive nature. Edara and Cottrell (6), and the extensive literature review undertaken by the Transportation Research Centre at the University of Florida (7) survey other similar studies.

Of particular relevance to the current work is a binomial model developed by Enberg and Mannan (8) to estimate the capacity of a freeway work zone in Finland. The model uses headways, differentiated by vehicle following combinations, and an estimate of the occurrence probability of each headway type based on the proportion of heavy vehicles. This model was of particular interest as it coincided with the authors’ belief work zone capacity might be estimated from the average headways and proportions of different headway types. Enberg and Mannan found that this method tended to overestimate capacity by 1-3 per cent relative to observed values. However, since daily traffic can vary by 5 to 10 per cent or more and variations during overnight construction periods can be even greater, this overestimate is of little practical significance.

2.2. Ontario practice with respect to work zone configuration

To provide context and facilitate comparisons with other sources, it is necessary to describe the prescribed layout for the work zones addressed in this study. The Ontario Traffic Manual defines typical work zone configurations for use on Ontario highways. The layout for the situation being studied here, that of a freeway being reduced from three lanes to a single lane, is shown in Figure 1 for a typical posted speed limit of 100 km/h. Normally, buffer vehicles, in conjunction with flexible drums or construction markers, would be used to delineate short-term work zones unless moveable concrete barriers could be used effectively. Often, these work zones are signed for a reduced speed of 80 km/h., with drivers being advised that fines are doubled when workers are present. Overnight lane closures may be introduced in a staged fashion, closing a single lane first and a second later as dictated by the pattern of volume reductions during the evening.

3. Collection of work zone data

The expressway locations where data was collected and the characteristics of the sample in each case are summarized in Table 1. The work zone configurations at the data collection sites were all generally in accordance with the configuration guidelines described in the previous section. Construction activity at each site was of a similar nature, involving one or more of the following activities: - asphalt grinding, resurfacing, median barrier replacement, or striping. The work zones were on straight and level sections of highway, were illuminated and no adverse weather conditions were encountered. It is possible that the driver population might vary from location to location at that time of night but it is noted that all survey locations were on inter-regional freeways with connections to the United States border and in a generally semi-rural to suburban environment. It was believed that variations in capacity at the sites observed would primarily derive from operational differences or the effect of commercial vehicles.

Data collection involved the recording of the times at which vehicles entered and left the single-lane portion of the work zone, along with the type of vehicle and whether or not a queue was present at that time.

4. Evaluation of work zone capacity and the impact of heavy vehicles

Several different approaches were taken towards the estimation of work zone capacity and the effects of differing proportions of heavy vehicles on capacity. These are discussed below.

4.1. Direct estimate of capacity

To obtain a direct estimate of capacity, the observations made while queuing was present were divided into 5-minute time-slices. The throughput for each slice was then plotted against the heavy vehicle proportions as seen in Figure 2. This graph shows a relatively wide range in terms of observed capacity, even among points where the heavy vehicle proportions were similar and, to a certain extent, among points at the same site and time period. In fact, there appears to be two primary clusters among the points with less than ten per cent of heavy vehicles, one located between 900 and 1,150 veh/h and another between 1,300 and 1,500 veh/h.

The variations in capacity evident in Figure 2 among the various work zone sites and among data points at the same site, given that the sites themselves were quite similar and the conditions under which data was collected were similar, suggests that there is another significant factor influencing work zone capacity. It is hypothesized, based on anecdotal evidence and personal observation, that the capacity of a given work zone might vary depending on the nature of the merging process upstream of the lane drops. If vehicles are able to merge smoothly ahead of the lane drops without causing traffic in the open lane(s) to come to a complete or virtual stop, one would expect to achieve a higher capacity than if vehicles in the open lane(s) came to a complete or virtual stop, either voluntarily or by necessity, to accommodate merging of vehicles from the dropped lane. There could be a number of factors involved in determining which “regime” a given work zone would operate under. Traffic demand and the level of cooperation (or aggression/impatience) among the drivers are likely factors. Queue length and duration may affect the level of driver impatience. The presence and effectiveness of advance warning information may also play a role. The proportion of heavy vehicles could also influence this behaviour since auto drivers may attempt to get past as many heavy vehicles as possible before being funneled into the work zone. This hypothesis is revisited in later sections.

We note that the collection of data was undertaken without a specific definition of queuing, relying on visual observation and the judgement of the surveyor. In retrospect, and as a guide for future data collection, it would be useful to differentiate between situations where vehicles typically had to stop or drastically slow upstream of the lane drop(s) and situations where this did not occur. Specific criteria could be developed in this regard.

4.2. Estimate of capacity based on headway types and proportions

It was hypothesized, as in the analysis of Enberg and Mannan, that headways vary with the “type” of headway, the four types or “following combinations” being:

1. car followed by another car (car-car);
2. truck followed by a car (truck-car);
3. car followed by a truck (car-truck); and
4. truck followed another truck (truck-truck).

Table 2 summarizes the mean headways for each headway type based on the combined set of observations. As might be expected from the differences in vehicle acceleration performance, the combinations with a following truck exhibited larger headways. Analysis confirmed that the means for the various combinations were statistically different at the 95% confidence level. Note that Table 2 includes only headway observations during periods identified with a queue present.

The analysis reported by Enberg and Mannan assumed that the proportion of different headway types in the traffic stream was based on a binomial distribution for the given heavy vehicle percentage. In the current study, it was hypothesized that the proportion of truck-truck headways may be higher than would be found with random arrivals, based on the proportion of heavy vehicles, due to a tendency for truck-drivers to travel in platoons. The observed frequencies of the various headway types, during periods of continuous queuing, were compared with the probabilistic frequencies from the binomial distribution, as shown in Table 3, and the Chi-square test applied. It was found that the proportions for all headways types, except for the truck-truck headways, were statistically no different from that predicted based on the binomial distribution at the 95 per cent confidence level. The proportion of truck-truck headways was statistically different; however, the net impact of this difference on the calculated capacity, as shown in Table 3, is insignificant and binomially-distributed headways can be substituted with minimal loss of accuracy.

When the mean headways summarized in Table 2 are combined with the probabilities of occurrence of the different following combinations in the traffic stream, a relationship can be derived between the work zone capacity and the proportion of heavy vehicles. Binomially-distributed headways have been assumed as per the previous discussion. The following equation defines this relationship:

$$Q = \frac{3600}{(1 - P_t)^2 t_{cc} + (1 - P_t)(P_t)t_{ct} + (P_t)(1 - P_t)t_{tc} + (P_t)^2 t_{tt}}$$

Substituting the values for the mean headways, the average capacity estimate is:

$$Q_{avg} = \frac{3600}{0.4P_t^2 + 2.1P_t + 3.0}$$

where: Q = capacity in veh/h

P_t = proportion of heavy vehicles

t_{xx} = time-mean headway for following combination x-x

c = car, t = truck or heavy vehicle

This relationship is also shown in Figure 3 and reasonable error bounds have also been shown based on the 15th and 85th percentiles for each headway type. However, considering this estimate of capacity based on mean headways in the context of the wide variation in the direct capacity observations discussed previously, it is obvious that a simple mean does not adequately cover all possible traffic situations and the associated variation in capacity. Obviously, a single mean value does not contribute to the evaluation of the hypothesis suggested in the previous section. It is also noted that the estimated maximum capacity based on “mean” headways and no heavy vehicles, approximately 1,200 veh/h, is much less than the commonly used value of approximately 1,750 veh/h.

It is possible to derive PCE (Passenger Car Equivalent) values for heavy vehicles based on these headway and capacity estimates. It was found that the PCE for heavy vehicles ranged between 1.7 and 1.8, depending upon the proportion of heavy vehicles and therefore the relative proportions of different headway types (following combinations).

4.3. Estimate of capacity based on micro-simulation

To further understand the factors affecting capacity, it was decided to use micro-simulation (VISSIM) to assess the impacts of different merging protocols and possible operating “regimes” as discussed previously. A VISSIM model was constructed of a generic work zone with a lane reduction from three lanes to a single lane using the standard physical configuration from Figure 1. This model was calibrated to match the observed mean headways through relatively minor adjustments to the various acceleration and headway parameters available in VISSIM. A nominal proportion of 7 per cent heavy vehicles was used for most of the scenarios tested although several scenarios were assigned higher proportions. The demand was varied dynamically, beginning at 1,200 veh/h and increasing in increments of 25 veh/h every five minutes.

To examine the impact of different merging protocols, different combinations of routing decisions and associated lane-changing distances were evaluated. Lane-changing distance is the distance upstream of a required lane change that drivers will begin to attempt to change lanes. When higher percentages of the traffic stream are assigned an increased lane-changing distance (700 meters), this has the effect of promoting early lane changes and smoother flow through the work zone. When more of the traffic is assigned a reduced lane-changing distance (150 or 75 meters, there is a reduced probability that vehicles will be able to merge smoothly before the lane drop, potentially resulting in the formation of a queue in the dropped lane. When this situation is prevalent, vehicles tend to alternate from the open and dropped lanes when entering the work-zone and vehicles in the open lane may either stop or slow down to allow a vehicle from the dropped lane to proceed in accordance with this informal but often-observed protocol. Table 4 summarizes the various combinations of parameters tested.

Figure 4 summarizes the results of the simulation analysis, depicting the variation in work zone throughput for the different scenarios reflecting a variety of merging protocols.

For scenarios 1, 3, and 4, where the proportion of traffic assigned to change lanes early was at least 90 per cent, throughput increased with demand up to a maximum throughput in the range of 1,700 to 1,850 veh/h, before further increases in demand resulted in a reduction in throughput to approximately 1,200 to 1,300 veh/h. Prior to the drop in throughput, vehicles tended to merge relatively smoothly without requiring vehicles in the open lane to stop or slow drastically. Scenario 1, with 100 per cent of vehicles assigned to change lanes early, achieved a throughput at the top end of this range.

When the merging protocol involves late merging of vehicles with the open lane and requires vehicles already in that lane to stop or slow dramatically, the throughputs drop significantly. Scenarios 2,5,6, and 9, with anywhere from 20 to 80 per cent of vehicles assigned to a lane-changing distance of 75 or 150 meters, exhibit a relatively consistent throughput of approximately 1,200 to 1,300 veh/h. Scenario 8, with a higher percentage of heavy vehicles, operated at an even lower throughput of 1,000 to 1,100 veh/h. Scenario 7 represents perhaps an approximate threshold between the “high throughput” and “low throughput” regimes, with approximately 12 per cent of vehicles assigned to the shorter lane-changing distances.

Although the throughputs achieved in simulation were generally higher than those observed, the two regimes observed in the simulated results appear to correspond to the two clusters evident in the observed data of Figure 2. Differences probably result from factors not considered or from behavioral aspects not included in the simulation model. In addition, the data points shown on Figure 2 are themselves averages which may include stretches of time in both regimes. However, we believe it is reasonable to conclude that the variation in throughput achieved during the site surveys is likely due to the variation in merging protocol at the entrance to the work zone, possibly confirming our earlier hypothesis. More definitive confirmation would require more refined data: the site observations did not include information on merging behaviour and was general with respect to the definition of queuing. Further surveys, possibly including video-recording, would be beneficial in this regard.

5. Conclusions

Observed throughput at overnight, single-lane work zones on Toronto-area expressways were not consistent with commonly assumed work zone capacities and varied substantially between sites and between observations at the same site. It was hypothesized that variations in the quality of the merging process upstream of the work zone may explain the observed variation. An analysis of headways for different following combinations and capacities derived from these headways found that headway varies with following combination but the mean headways thus derived do not contribute to an explanation of the variation observed. A micro-simulation model was used to analyze the impact of varying merging behaviour on throughput. The simulation results provided preliminary evidence of two operating regimes. The first, with throughputs in the range of 1,750 to 1,850 vehicles per hour, corresponded to early lane changing, smooth merging, and more-or-less continuous flow in the open lane. The second, with throughputs in the range of 1,000 to 1,300 vehicles per hour, corresponded to late lane changing, slowing or stopping of vehicles in the open lane, and alternating vehicle departures into the work zone from the open and dropped lanes.

This study suggests that currently-used assumptions concerning the capacity of work zones do not adequately reflect the possible range in quality of operation and resulting throughput. There is therefore a risk associated with operational planning on the basis of a single value of work zone capacity. However, it is noted that the data collection and analysis reported here covers only one work zone configuration (two lanes closed out of three), does not include data on merging behaviour or quality, and reflects only a general definition of queuing. Additional data collection and analysis are required to confirm the preliminary findings reported here and to extend the methodology for more general application.

References

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Tables

Table 1: Data collection sites and samples

Site	Date	Study period		Percent of study period with queue present	Total number of vehicles observed	Percentage of heavy vehicles
		Start time	End time			
Queen Elizabeth Way near Dorval Drive Oakville, Ontario	Sept. 12	23:15	01:15	85%	2,646	4.4%
	Sept. 17	23:42	12:11	79%	1,459	10.4%
	Sept. 18	23:20	01:23	77%	2,018	7.9%
	Sept. 19	23:40	01:20	50%	2,565	3.7%
Highway 401 near Trafalgar Road Milton, Ontario	Sept. 24	23:21	01:36	32%	1,983	23.0%
	Sept. 25	23:46	01:38	73%	1,700	18.7%
Highway 401 near Bennett Road Clarington, Ontario	Nov. 27	22:08	23:10	63%	1,030	25.6%

Table 2: Headways for different headway types/following combinations

Headways (seconds)	Car-Car	Car-Truck	Truck-Car	Truck-Truck
Mean	3.0	4.5	3.5	5.4
Standard deviation	1.7	2.5	2.0	2.7
15 th percentile	2.5	3.1	2.9	3.3
85 th percentile	3.4	6.4	4.6	8.0
Number of observations	5,347	498	492	147
<i>Note: All headways observed during periods of continuous queuing</i>				

Table 3: Statistical evaluation of frequencies associated with different headway types/following combinations

Date	Location	Heavy Vehicle Percentage	Relative Frequency								Capacity calculated from headways	
			Car-Car		Car-Truck		Truck-Car		Truck-Truck		Observed Headways	Binomial Headways
			Observed	Binomial	Observed	Binomial	Observed	Binomial	Observed	Binomial		
12-Sep	QEW	4.4%	92%	91%	4%	4%	4%	4%	0.5%	0.2%	1,133	1,134
17-Sep	QEW	9.5%	82%	82%	8%	9%	8%	9%	1.4%	0.9%	1,091	1,093
18-Sep	QEW	7.9%	85%	85%	7%	7%	7%	7%	0.9%	0.6%	1,105	1,106
19-Sep	QEW	3.8%	93%	92%	4%	4%	4%	4%	0.2%	0.1%	1,138	1,139
24-Sep	Hwy 401	23.1%	61%	59%	16%	18%	16%	18%	7.2%	5.3%	1,144	1,144
25-Sep	Hwy 401	18.7%	68%	66%	13%	15%	13%	15%	5.7%	3.5%	1,186	1,187
27-Nov	Hwy 401	25.8%	57%	55%	17%	19%	17%	19%	8.3%	6.6%	1,119	1,119
Chi-Square Test	Chi-Square statistic (reject hypothesis if > 14.1)		3.1		11.7		12.5		62.4			
	Reject binomial process?		No.		No.		No.		Yes.			
<i>Note: All headways observed during periods of continuous queuing</i>												

Table 4: Variation in merging protocols and associated lane-changing assumptions across scenarios evaluated

Scenario	Percentage of traffic assigned given lane-changing distance			Heavy vehicle percentage
	700 metres	150 metres	75 metres	
1	100	0	0	7
2	0	100	0	7
3	95	5	0	7
4	90	10	0	7
5	80	20	0	7
6	0	0	100	7
7	88	12	0	7
8	0	0	100	20
9	0	0	100	10

Figures

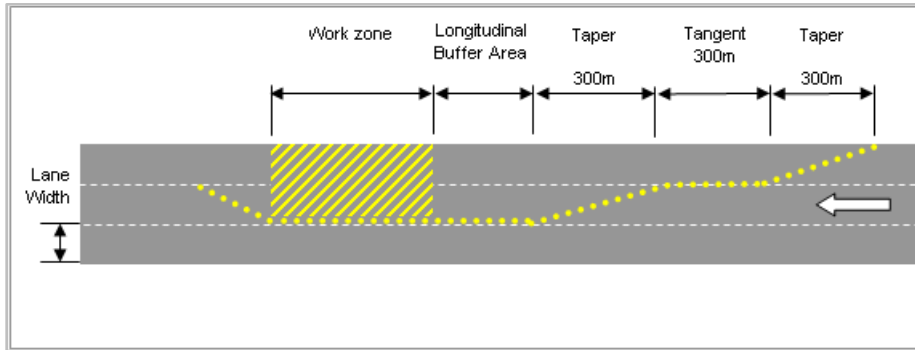


Figure 1: Freeway work zone configuration for reduction to a single lane

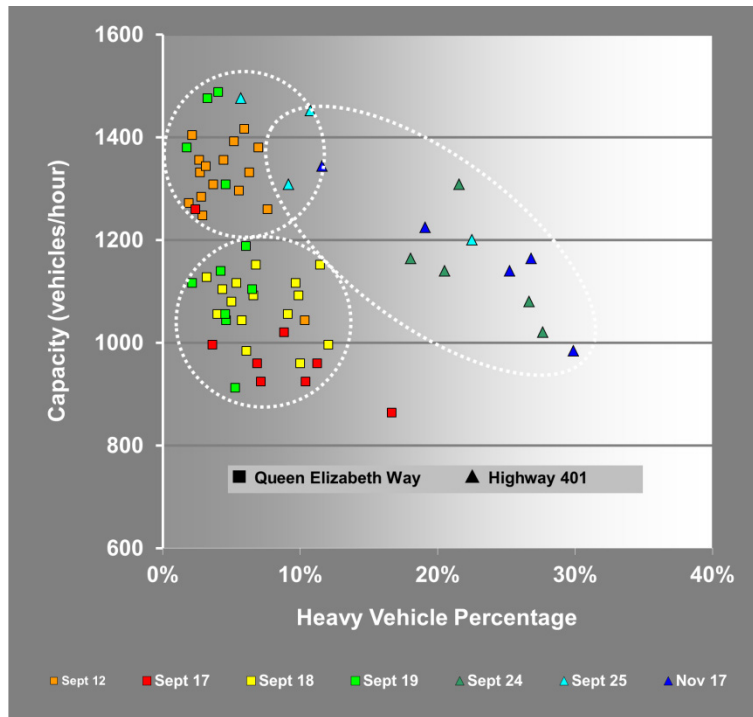


Figure 2: Capacity (throughput) vs. heavy vehicle proportion from direct observation

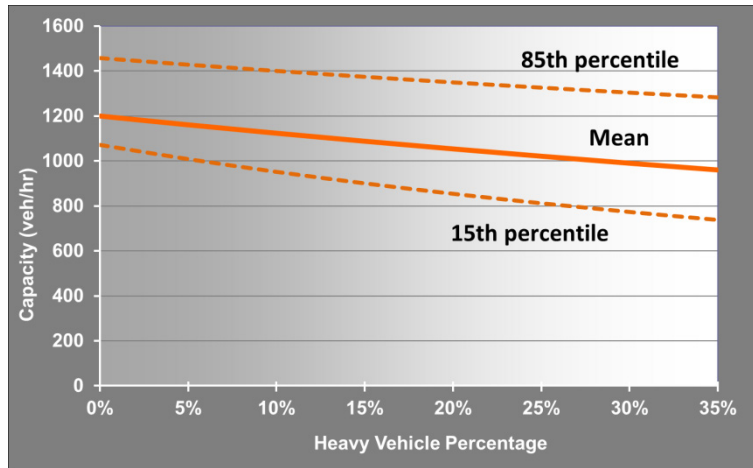


Figure 3: Capacity (throughput) vs. heavy vehicle proportion from headway analysis

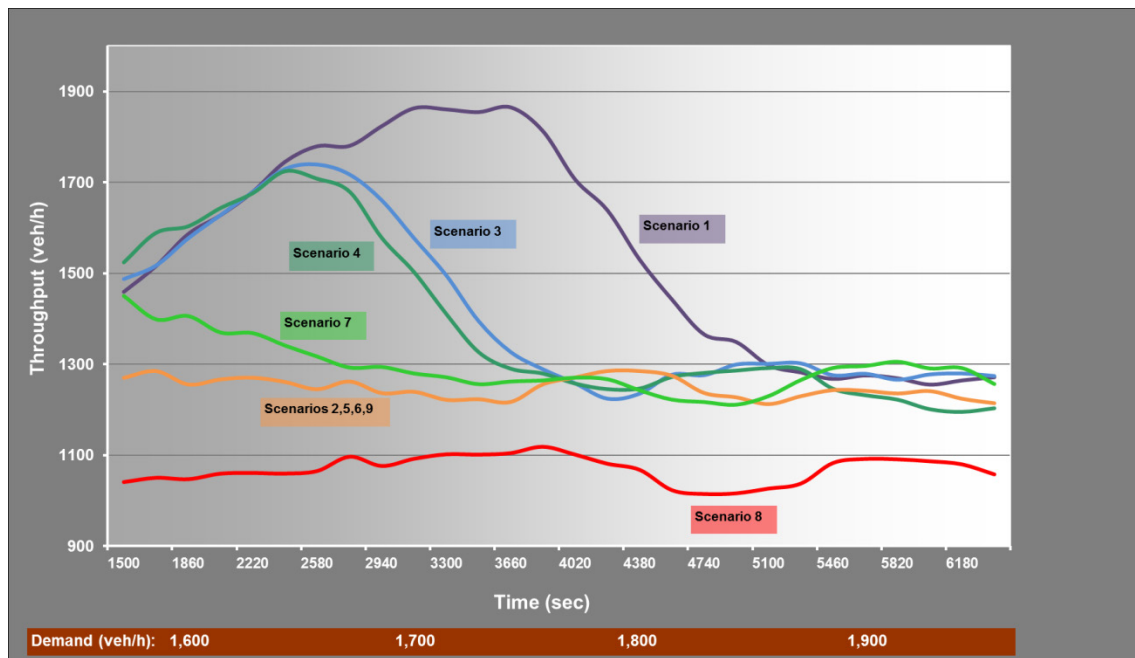


Figure 4: Simulated work zone throughput under different merging protocols