Smart 25 Managed Motorways Pilot Demonstration

Performance Evaluation Report

Revision 2, 26 October 2022 - DRAFT

VICTORIA State Government | Department of Transport

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Executive Summary

The SMART 25 project deployed a pilot demonstration of the Australian Managed Motorways concept on the Interstate Highway 25 (I-25) northbound, a concept that was pioneered on the M1 Freeway in Melbourne by VicRoads (now part of the Victorian Department of Transport). The temporary Managed Motorways pilot project was deployed in Denver, Colorado, along I-25 northbound between Ridgegate Parkway in the south and University Boulevard in the north. During the operational stages of the pilot demonstration, the coordinated ramp metering system operated a total of 18 entry ramps at 14 interchanges. The ramp metering system employed the ALIENA-HERO (AHS or HERO-LIVE) suite of real-time, feedback control algorithms, and the Transmax STREAMS freeway management system to manage mainline traffic flows and entry ramp queues and delays.

The figure below shows the extents of the pilot project operational area and the 18 ramps managed as part of the project.

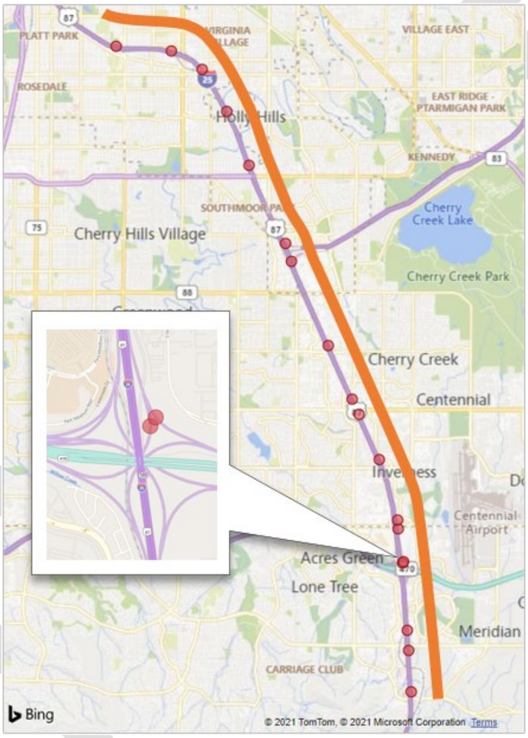


Figure A: SMART 25 Project Extents along the I-25 Northbound and Controlled Ramps

Three main stages of the pilot project took place between July 2021 and July 2022. The stages, their descriptions and respective dates are summarised in the table below.

Table A: Summary of Project Stages

Stage	Description	Start Date	End Date	No. of Weeks
Baseline	Data Collection Period (Legacy CDOT Algorithm)	Mon, 12 July 2021	Sun, 31 Oct 2021	16
Arterial Ramps Only (Soft Launch)	Arterial Ramps Only, No Systems Ramps	Mon, 1 Nov 2021	Sun, 6 Mar 2022	18
Full Operations	All Ramps, Including System Ramps	Mon, 7 Mar 2022	Fri, 29 July 2022	21

Throughout the data collection and operational stages of the project, data was collected and processed from a number of sources, including in-field detection devices along the corridor mainline and on entry ramps (TIRTL side fire detectors and Wireless Sensys Pucks respectively) and third-party travel time probe data (from INRIX).

To assist with the project evaluation, the corridor was split into three sections for more detailed evaluation, being the southern, central and northern section. A range of different measures and metrics were derived for each section and the full pilot project corridor from the collected traffic data. Details around the sections and measures are described in more detail within this evaluation report. Key measures summarising the improvements in operating conditions and traffic performance are provided in the sections below.

Travel Time Improvements

Reductions in travel times through the pilot corridor and the sub-sections was a key goal of the project due to the high travel times and variability of travel times experienced prior to the project. The table and figures below show the summary of the measured travel times and changes from the base line conditions. Further detail and breakdown by sections is provided in the corresponding main body of this report.

The whole peak period averages show a small reduction in travel times during the AM peak and it is also evident in the daily profile plots that some improvement occurred in the AM peak. A minor shortening of the AM peak is also evident compared with the baseline average staying up for a bit longer at the end of the peak period than during the operational stages.

It can be seen that there have been significant improvements (reductions) in travel times, particularly during the PM Peak after application of the AHS ramp metering operations. The 14.3% improvement in the PM peak-period average represents a 2.5 minute reduction in travel time for vehicles driving the full length of the pilot corridor. The travel time profiles indicate a reduction of up to 4.1 minutes (or 19%) at the height of the PM peak.

Figure C below also includes results for the changes in planning time, which is an indicator of travel time variability. Planning time (95th percentile travel time representing the higher travel times experienced) was reduced across all periods although the PM peak saw the biggest average reduction of 5.4 minutes (20%) and up to 7.3 minutes (24%) at the height of the PM peak.

Table B: Percentage Change in Travel Times through the Pilot Section by Period

Peak Period	*Arterial Ramps Only (vs Baseline)*	*Full Operations (vs Baseline)*
AM Peak	-0.9%	-2.0%
High Off-Peak	-5.0%	-0.7%
PM Peak	-6.0%	-14.3%

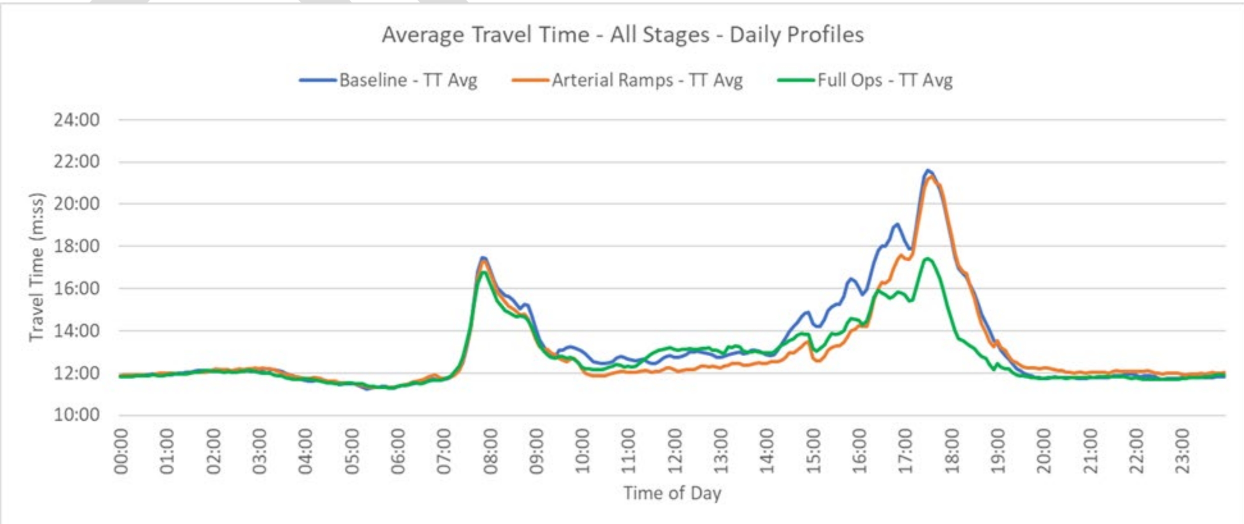


Figure B: Average Travel Time Daily Profiles by Project Stage

Figure C: Average Travel Time and Planning Times – AM and PM Peaks

Changes in average travel times are useful for understanding the change in the user experience although by themselves they do not capture the combined benefit to all road users utilizing the pilot sections. Further measures below demonstrate these broader benefits.

Accumulated Delay Reductions

Delays are calculated as the difference between the resulting travel time and the travel time at nominal speed along the corridor (adopted as travel at 60mph). Total or accumulated delays incorporate the volume of traffic passing through each section providing a better overall measure of overall corridor benefits.

The table below summarises the changes in daily average total delays and demonstrates significant reductions in average total delays across the whole day and also across the main daily peak periods. The peak period results are shown as the times when the coordinated ramp metering is in operation.

Table C: Percentage Change in Daily Average Total Delays (Hours) through the Pilot Section by Period

Time Period	Baseline Daily Total Delays (Hours)	Arterial Ramps Only Change from Baseline		Full Operations Change from Baseline	
All Day	*1,958*	*-495*	***-25.3%***	*-827*	***-42.2%***
AM Peak	*424*	-119	**-28.1%**	-23	**-5.3%**
PM Peak	*1,374*	-262	**-19.1%**	-661	**-48.1%**

Throughput and Productivity

In order to effectively increase throughput of a motorway corridor, sustained operational capacity increases need to be applied for an extended time period to enable traffic demand and pattern changes to occur from corridor capacity change. Also, to some degree amenable conditions need to exist upstream and downstream that allow additional demands and patterns to adjust. As the length of the pilot project was time limited, there is insufficient time for land-use and other transport utilization changes to occur to affect a significant uplift in throughput that can be attributed to the pilot project.

In order to appreciate the potential for throughput to increase over time, it is useful to assess the change in operational capacity at key bottleneck locations in the pilot corridor section.

Analysis of the Speed, Flow and Productivity at key bottleneck locations showed an extended shift towards better conditions, with lifts in the average flows and speeds during peak periods. Similar to the travel time and delay measures, improvements in the PM peak period were dominant with small improvements during the AM peak period. The changes in speed were more significant that the flow changes, although this is expected – reduced occurrence and severity of flow breakdown conditions will mainly impact speed and improve flow where a significant flow loss (capacity drop) was previously experienced. Further increases in flow may be achieved over time and can be dependent on demand changes and the performance of other bottlenecks and conditions on adjacent sections.

Derivation of maximum sustainable flow rates (MSFR) at bottleneck locations also support the improvements and indicate that improved conditions can be maintained, allowing additional operational capacity to be achieved within the same physical capacity available. Figure D shows a general trend of increasing MSFR at key bottleneck locations with gains more evident in the south and central sections. Figure E shows probability of flow breakdown curves, derived from the available data in the baseline and operational period – MSFR is calculated as the flow corresponding to 1% (0.01) probability of flow breakdown. In addition to the MSFR increasing, the curves form the Full Operational period shift to the right indicating higher flows were generally achieved before flow breakdown occurred.

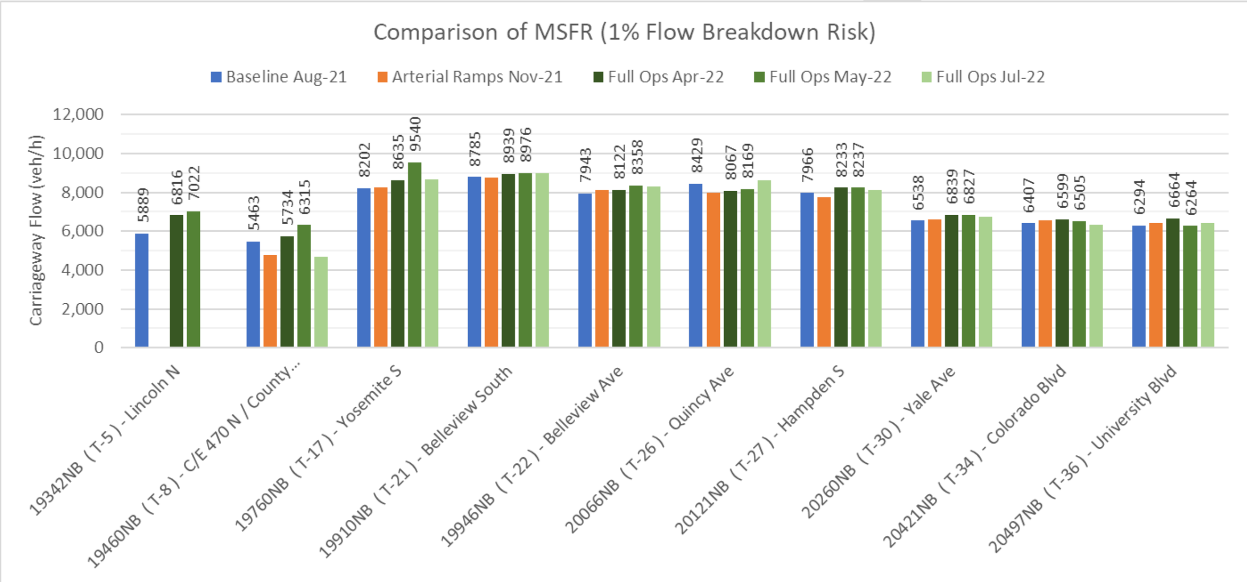


Figure D: Comparison of MSFR at recurrent bottleneck sites across project stages

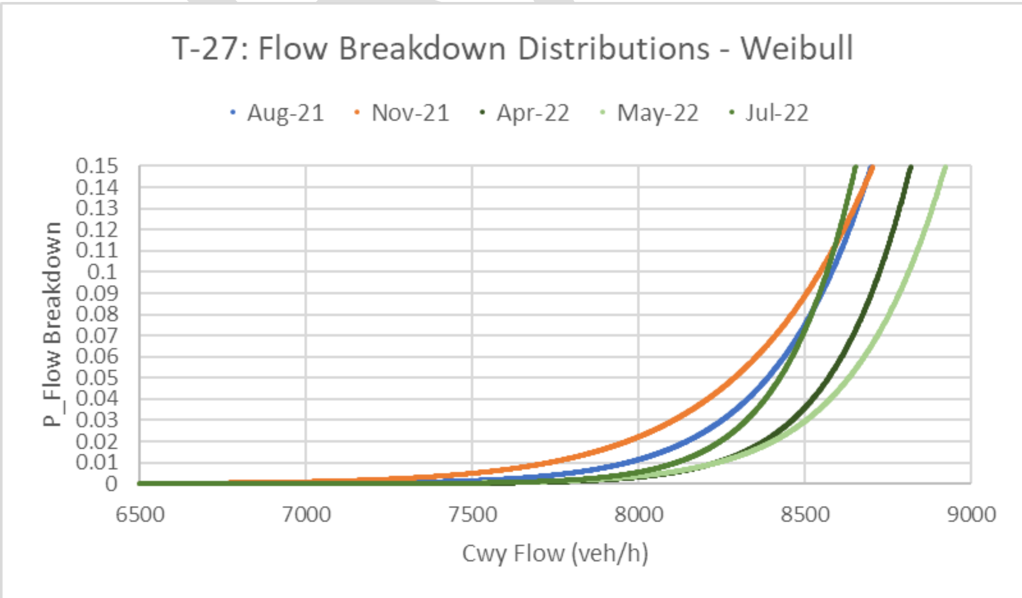


Figure E: Comparison of Flow Breakdown Distributions for Site T-27 (I-225 to Hampden)

Context of Improved Conditions

Excess traffic demand on urban motorways is typically a significant contributing factor to flow breakdown and congestion. When assessing travel times, delays, and overall productivity of corridor operations, it is also important to ensure measured improvements are not just the result of reduced demand (below levels that contribute to flow breakdown). The following points summarise the assessment of various indicators measured along the pilot section of the corridor undertaken to ensure that any benefits measured can be associated with the changed operations applied through AHS/STREAMS pilot project operations. In general, the assessment of traffic flows and entering demands do not indicate that there has been a significant change in the volumes using the pilot section (noting a 2-4% Baseline to Full Operations increase during peak periods entering from the south and then varies along the corridor). It is reasonable to conclude that operational improvements, especially during the peak periods, are strongly influenced by the improved ramp metering operations in the corridor and not due to a reduction in demand.

Vehicles Mile Travelled

The table below shows the changes in Vehicle Miles Travelled (VMT). During the Arterial Ramps Only stage (which covered winter and the holiday / new year periods of late 2021 and early 2022) there was a reduction in VMT. During the full operations period, which is the better indicator stage for system benefits, VMT was almost the same across the whole corridor although some minor increases and decreases are evident by section.

Table D: Percentage Change in Daily Average Total Delays (Hours) through the Pilot Section by Period

Section	Baseline	Arterial Ramps Only			Full Operations		
	Daily VMT	Daily VMT	Change from Baseline		Daily VMT	Change from Baseline	
All Sections	1,419,739	1,315,741	-103,998	-7.3%	1,424,389	4,650	0.3%
Section 1	203,277	200,118	-3,158	-1.6%	214,728	11,451	5.6%
Section 2	648,897	603,306	-45,590	-7.0%	653,525	4,629	0.7%
Section 3	567,566	512,317	-55,249	-9.7%	556,136	-11,430	-2.0%

Segment Flows

The figure below shows the percentage changes in the 95th percentile measured 15minute flows across AM, High Off-Peak and PM periods. The changes compare the full operations stage with the baseline stage. It can be seen that the variations are generally all less than 5% across most of the sites (mostly with a range of 1-3%). There is a general minor increase in the southern half of the pilot section and a small decrease in the northern half. (A known error in detector counts at T-4/5 is identified and should be disregarded.)

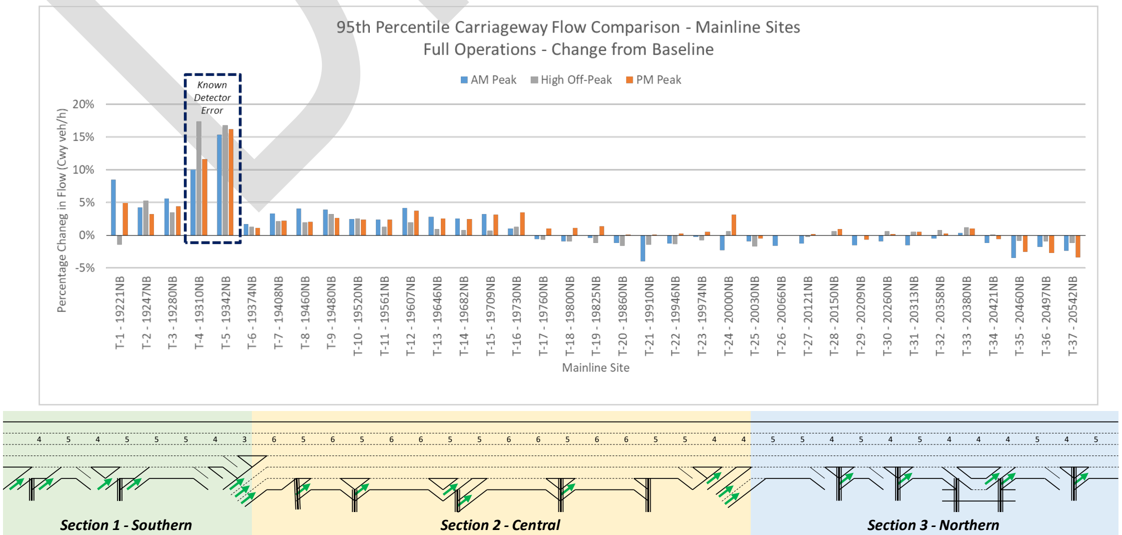


Figure F: Change in Peak Period Flows – Full Operations vs Baseline

Challenges for Operations

Throughout the baseline data collection stage and the operational stages of the pilot project, pre-existing and new challenges were encountered along the corridor.

Downstream and Off-Corridor Queue Back

One of these challenges was the impact of congestion occurring on motorway sections either downstream or off the main corridor causing queuing and congestion back into the pilot section. The main two locations where this was encountered was:

- Queuing from the I-225 northbound connector ramps – flow breakdown occurs on the I-225 northeast of the I-25 and causes queues and congestion to extend back onto northbound I-25.
- Queuing on the I-25, north of University Boulevard – flow breakdown or incidents causing queueing back into the pilot section

Neither of these challenges and their causes were able to be directly addressed by the pilot operations on the I-25. While there is the potential that a very limited amount of traffic can be held back on ramps to delay them arriving at these congested locations, the ramp metering is unable to resolve the queue back conditions. There is the potential that ramp metering operations could assist or even increase the arrival high volumes approaching the problem locations downstream although based on the data available, the extent to which this might have occurred is not able to be determined.

Limited Ramp Storage on Metered Ramps

Part of the SMART 25 project involved minor civil work and pavement repurposing to increase the available queue storage on entry ramps within the pilot section. Despite these works, a small number of key locations were unable to be suitably upgraded to cater for the high traffic demands that were expected and/or experienced during operations. This can be a real-world challenge when provisioning of additional storage can potentially impact high costs assets, such as the widening of bridge structures or ramps with little physical space for expansion.

Ramp designs were initially based on traffic data from 2016/17. Significant changes occurred between the design and the operations phase of the project resulting in much higher flows on some ramps than anticipated.

Examples of such locations were:

- **Ridgegate Parkway Entry Ramp:** No modifications were undertaken at this ramp and pilot period traffic demands greatly exceeded the stopline discharge and storage provisions.
  - Queues extended onto the adjacent arterial for significant distances during the early stages of operations.
  - An additional detector was also added during pilot operations to detect some vehicles drifting into the wide shoulder – this enabled more responsive queue management.
- **C-470 to I-25 System Entry Ramp:** Widening of the ramp at the stopline enabled very high discharge flows, however the length of the overall storage was significantly below design requirements for the expected design flows and the flows eventually experienced during operations. Long queues were able to quickly develop when metering was too restrictive, and drivers did not use the additional lanes at the stopline.
  - Following activation, the ramp was initially inhibited during the heaviest part of the AM peak but gradually switched on for longer periods during the busy period while being closely monitored whenever it was operating and manually overridden is queues did reach agreed threshold lengths.
  - To limit the impact of queues extending to the upstream facility, the ramp metering was not able to run with full flexibility during the full operations stage, thereby allowing too much traffic to enter the corridor at critical times.
- **Evans Road Entry Ramp:** No modifications were undertaken on this ramp. In addition to having only half the desired design storage, two additional aspects limited the effectiveness of this ramp to manage the nearest downstream bottleneck.

  - The ramp feeds into a short collector-distributor arrangement and also provides a non-conventional access to a local road exit ramp.
  - Traffic can “re-bunch” before reaching the mainline merge leading to some platoons at the mainline merge location.
  - Metering of traffic not bound for the mainline has the effect of using queue storage for non-freeway traffic. Due to the unknown balance of traffic accessing the mainline, the metering algorithms cannot appropriately gauge the amount of traffic to resolve instability at the merge bottleneck.

The resulting inability to run fully flexible operations resulted in excess or platooned flows from these ramps, particularly during the height of the peak periods, that contributed to the occurrence of flow breakdown at downstream bottlenecks.

Driver Familiarity with Changed Conditions

New conditions were presented to Denver drivers that they had not previously experienced locally. While these conditions presented some initial challenges that impacted early periods of the operational stages, drivers were observed to adjust to the conditions over time, which assisted in increasing the effectiveness of the ramp provisions and dynamic operations. These new conditions included:

- Provision of 3 or more lanes at ramp metering locations – generally only two metered lanes had been used in Colorado prior to the pilot project.
  - In the initial period of the Arterial Ramps Only stage, drivers did not immediately start using the additional right side shoulder conversions for queueing on approach to the metering stopline, despite the provision of signs permitting them to do so. Additional and dynamic message signs provided by CDOT were provided which influenced greater use of the additional queue storage over a relatively short period. Lead vehicle “pilot runs” were also taken by project team members to visually demonstrate the use of the shoulder lane during peak-periods.
- Implementation of ramp metering on system ramps (freeway-to-freeway connections) – the pilot project was the first implementation of this type of system ramp meter in Colorado. It is noted that a limited media campaign, and variable message signage, were used to assist with driver awareness of the coming changes.
  - While this metering approach was new, it was observed that drivers adapted to the need to slow and be metered on these connections – once a queue forms, compliance was generally seen to be quite good. As some of these ramps also had additional queue storage lanes provided, a similar transition period to using these lanes (as noted above) was also observed.

The impact of underutilisation of queue storage results in longer queues in the lanes that are used. In the early periods of operations, this resulted in queue management algorithms engaging more frequently and allowing more traffic onto the mainline (impacting mainline conditions), which limited the ability to go to fully responsive and flexible operations until lane utilization improved.

Device Faults, Incidents and Conditions Limiting Dynamic Operations

Faults and incidents that impact operations and device and system availability are part of operating real-world systems. Throughout the pilot project stages, there were some significant events and faults that reduced the ability of the coordinated ramp metering system from operating at full capacity. A short summary of some of the more significant events are listed below and discussed in more detail in this report.

- Intermittent communication or power faults with detection, limited available data for operations and data collection.
- Prolonged ramp detector faults (on a small number of ramps) limited ramp operations to either fixed time operations or switched off – operations is not effective for mainline control. E.g. the Belleview entry ramp did not have effective queue management throughout the entire project, although queue impacts could be mitigated due to the excess available storage at this site.

- Delayed availability of flashing warning beacons on system ramps – initially delayed transition to full operations and resulted in the C-470 ramp meter being deactivated (and therefore ineffective) for 2+ months during the full operations
- Failed flashing warning beacons on the C-470 Ramp resulted in metering operations being suspended for safety reasons. The beacons remained in a failed state from 9 May 2022 until the end of the full operations stage, resulting in uncontrolled high flows especially during the AM peak for the last 12 weeks of the pilot operations.
- Lantern pedestals being struck by vehicles, removing the ability to meter at some sites for varying periods. This situation also caused a delay in the transition to full operations.
- Roadside detector installations being struck by vehicles and remining inactive for a time.
- General debris blocking TIRTL detector beams, although this was generally remedied promptly onsite.
- Significant and regular (above average) snowfalls throughout the December to February period resulted in blocked TIRTL detector beams often for days until melted. This often resulted in ramp operations being disabled or reverted to fixed-time operations based on agreements with CDOT project managers.

COVID-19 Impacts

At the time of the commencement of the Smart 25 pilot project in July 2021, a significant number of workers in the greater Denver area were still working from home due to stay-at-home orders associated with the COVID-19 Pandemic response, although with the easing of some restrictions. Some activities involving on-road travel was returning to the road network, impacting different parts of the network at different times of the day. It is also understood that the utilization of public transit services (such as the light rail services in the I-25 corridor) was lower than prior to the pandemic.

Throughout the operational stages of the pilot project, there were continued changes to traffic patterns as travel and economic activity returned to the transport network after periods of stay at home orders and other restrictions. Historic traffic volume and travel time data was sourced from available CDOT sources to understand the conditions leading up to and during the pilot project and the various phases.

The two figures below are provided to assist in understanding the context of traffic demand entering the southern end of the pilot corridor section using data available from one of CDOT's permanent traffic count stations.

Figure G compares the daily average hourly traffic profiles for years 2019-2022 and shows both a change in demand patterns across the day as well as the reduction and return of traffic demand. The 2020 reduction due to the pandemic restrictions is observed. It is notable that there is a shift in demand from the AM to the PM peak and that northbound demand in 2022 is higher across the board than 2021. A review of average total daily flows also indicated that 2022 flows are higher than 2019.

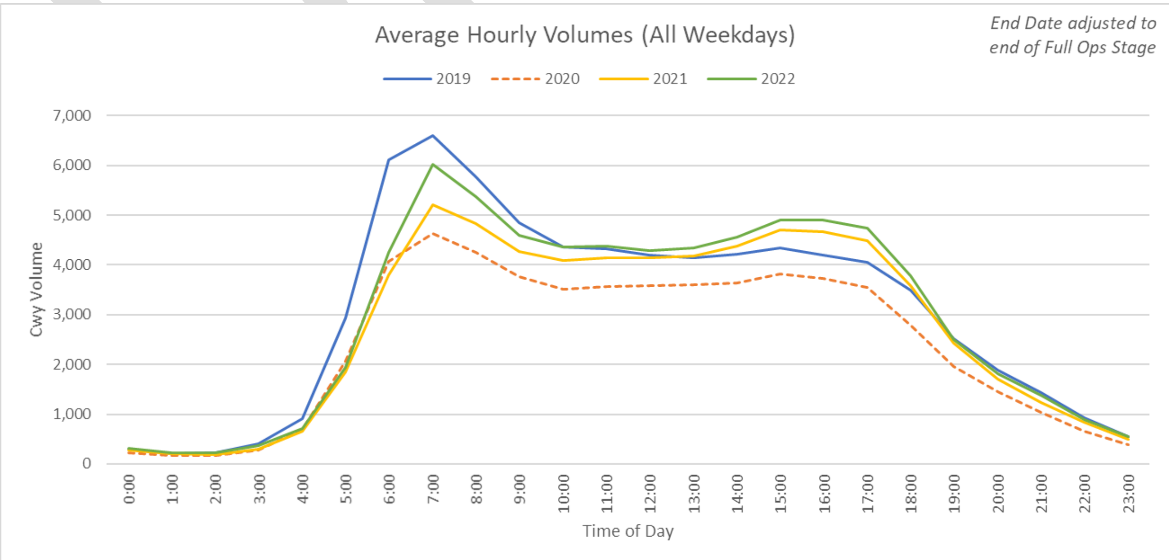


Figure G: Daily Average Weekday Volume Profile from 2019 to 2022

Figure H uses data from the same count location to assess the traffic demand and hourly profiles for the three project stages. It is evident that the northbound entering demand in 2022 is holding the same patterns and marginally higher (2-4% during peak periods) than during the baseline data collection stage.

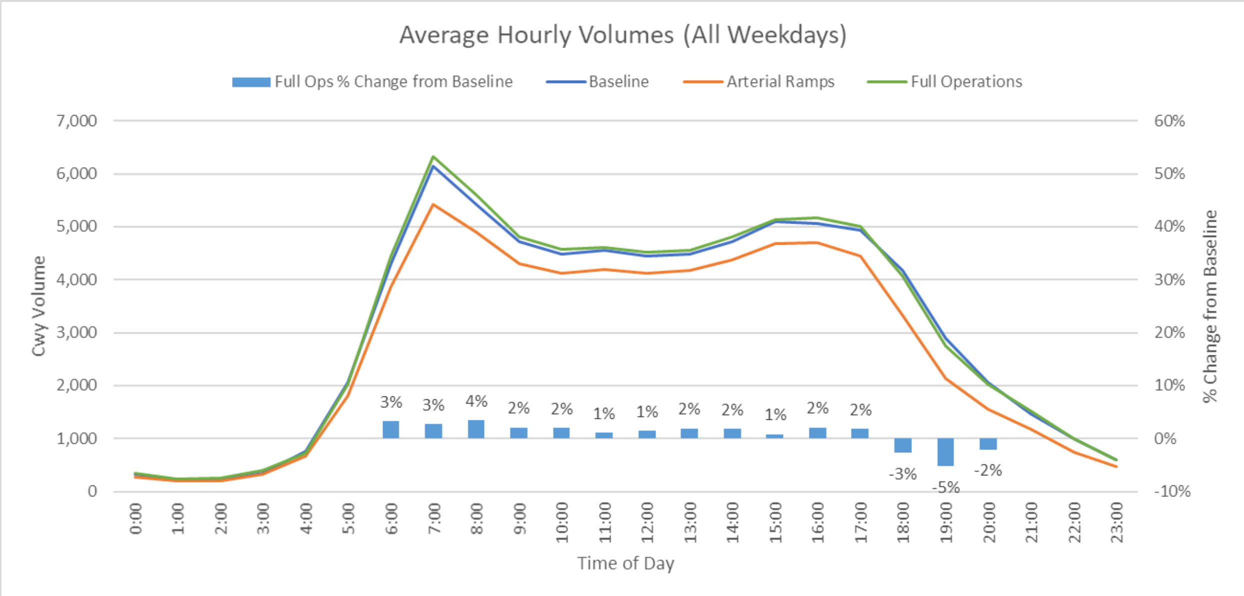


Figure H: Peak Period Average Volumes – Pilot Project Stages

Figure I compares average weekday daily volumes across the years 2019-2022 by month, in part to understand the potential seasonality patterns as well as the impacts of the COVID-19 pandemic.

It can be seen that the Arterial Ramps Only stage (yellow highlight) is below the levels of the Baseline (blue highlight) and Full Operations (green highlight) stages. The Full Operations and Baseline stages are fairly similar although the Full Operations starts a bit lower and ends a bit higher.

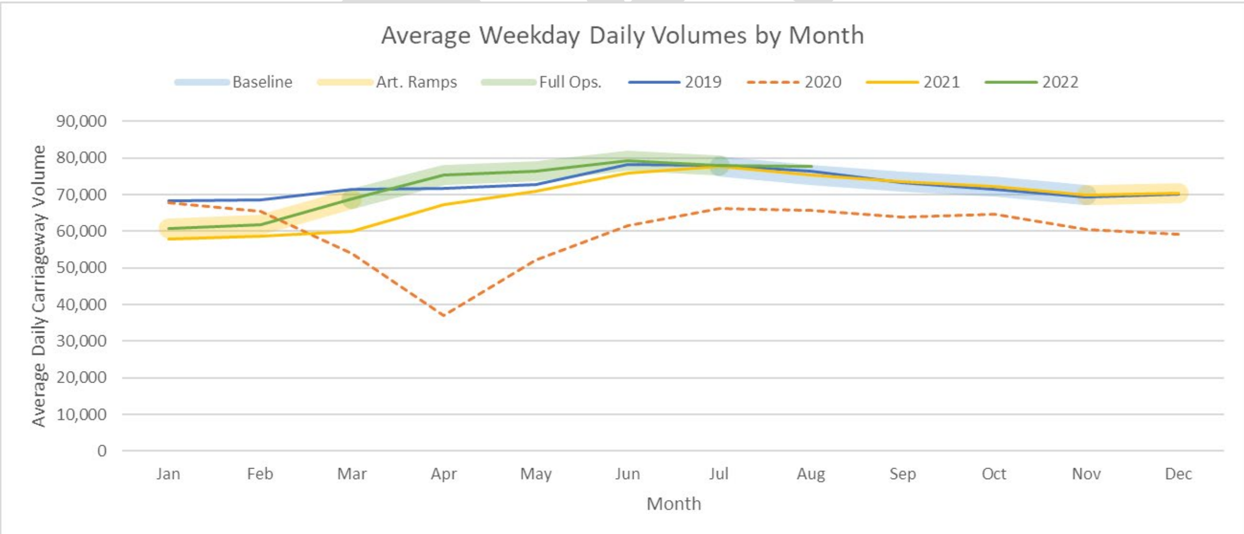


Figure I: Peak Period Average Volumes – Pilot Project Stages

Beneficial Outcomes Achieved

The main performance indicators that have been used to assess the full operation stage of the SMART 25 pilot project shows that significant travel time and delay reductions have been achieved. Greater improvements were experienced during the PM peak. Although significant reduction in delays were still measured during the AM peak, the changes in travel times were small.

Challenges in managing the AM peak period demands are likely due to the very short but very high traffic demand peak the generally occurs in the corridor between 7:30 and 8:00AM. This was particularly evident on the C-470 system ramp. While challenges at this ramp are not the only contributor, the lack of physical queue storage to enable effective restrictive control when needed, and the device faults inhibiting operations during the project, limited the system's ability to prevent more flow-breakdown than occurred.

While areas of flow breakdown still occurred during the PM peak period, the reductions in travel time and delay as a result of the pilot ramp metering operations, in spite of the rise in demand in the PM peak (compared with prior periods – baseline and pre-pandemic).

1 Introduction

This report is the full evaluation report for the Smart 25 Managed Motorways Pilot Demonstration project. The outcomes presented within this report are based on comparisons of performance two pilot operational stages with the baseline operating conditions and demonstrate the impact of the coordinated ramp metering operations on the pilot section of the I-25 northbound.

The two operational stages were:

- Arterial Ramp Only Operations only (also referred to as the soft launch period) as the name implies deployed coordinated ramp metering control on the entry ramp from arterial road only. 15 out of the 18 ramps were controlled during this stage of the project.
- Full Operations included metering operations on the three northbound system to system (freeway to freeway) connector ramps in addition to the arterial ramp operations.

The report describes and compares key metrics from before and after the application of coordinated ramp metering operations to understand the changes to operating conditions. Various conditions and changes of utilization are also reported to support the validity of the measured outcomes and impact of the changed operations. Challenges encountered during the pilot operations that impacted traffic conditions and the effectiveness of the operational approach are discussed. The impact of the COVID-19 Pandemic on the operation of the corridor is also included to provide context for the timing and assist interpretation of the applied changes in the corridor.

2 Background

The SMART 25 project deployed a pilot demonstration of the Australian Managed Motorways concept on the I-25 northbound, a concept that was pioneered on the M1 Freeway in Melbourne by VicRoads (now part of the Victorian Department of Transport). The I-25 corridor has historically suffered from severe unreliability during peak periods: motorists have needed to allocate up to three times the free-flow travel time in peak periods to ensure on-time arrival, despite an average travel speed of approximately 40 mph during the same peak periods.

The I-25 corridor has previously had ramp metering in place although the ramp metering system controlling ramp operations used an older plan-based approach to applying metering rates. The older system was adaptive to a degree, in that pre-defined metering rates could be selected based on detected traffic conditions and a simple form of upstream assistance from an adjacent ramp could be enacted. However, operations under the older system were limited, lacking true closed feedback based control and little ability to effectively manage ramp queues or delays.

The pilot deployment included implementation of a contemporary coordinated and dynamic ramp metering system across 14 interchanges (with 18 entry ramps) and real-time mainline flow management. The STREAMS system deployed along the pilot corridor to operate the ramp metering strategy runs a highly customised version of the ALINEA-HERO algorithm suite (also referred to as the ALINEA-HERO System (AHS) or HERO-LIVE). The I-25 pilot traffic management system was tuned to optimize the performance of the system in real-time to achieve travel time savings and reliability benefits throughout the pilot section of the corridor.

To support the dynamic operations along the corridor, a significant investment in reconfiguration and increased ramp storage capacity was included as part of the project to better manage ramp demands to improve mainline performance and reduce delays across the whole system.

2.1.1 ALINEA-HERO System

The ALINEA-HERO System (AHS or HERO-LIVE) suite of algorithms is a comprehensive and complete concept (and corresponding implementation software) that applies coordinated ramp metering to motorway networks of arbitrary size, topology and characteristics. HERO-LIVE is fully traffic-responsive (with configurable update period that may be selected as short as 20 seconds) and adapts automatically to the prevailing traffic conditions aiming at maximising stable motorway throughput; while, at the same time, monitoring the current situation at the on-ramps and limiting any incurred vehicle queues or waiting times. HERO-LIVE uses real-time measurements from multiple locations on the motorway network and from the on-ramps and dynamically adjusts the ramp meter cycle times.

The HERO-LIVE algorithms have been conceived based on the latest insights of contemporary traffic flow theory for optimising motorway flow; moreover, they apply a variety of powerful and proven automatic control methods that guarantee stable, robust and efficient operation on the basis of feedback principles. This distinguishes HERO-LIVE from any approaches based on heuristic constructions or lack the fundamental feedback control principles. In addition to the theoretically sound background, HERO-LIVE decisions are transparent in operation, which enables operators to be fully aware at any time about the reasons behind the employed control actions. Further information about HERO-LIVE and its associated modules is available in the Managed Motorway Design Guide, Volume 2, Part 2, Managed Motorway – Network Optimisation Tools (VicRoads, 2019).

3 I-25 Northbound Ramp Metering and Monitoring Components

The Managed Motorways pilot project was deployed along Interstate Highway 25 (I-25) northbound between Ridgegate Parkway in the south and University Boulevard in the north. The coordinated ramp metering system operated a total of 18 entry ramps at 14 interchanges as outlined in the Table 1 below and shown in Figure 1 (Left). The mainline detector locations are shown in Figure 1 (right). Figure 2 shows a lane schematic of the pilot section of the I-25 northbound including the number of mainline lanes, the metered ramps, mainline detectors, and ramp lanes.

Details around the ramp metering system and the broader supporting ITS systems are covered in other project documentation and not discussed in detail in this report.

Table 1: List of I-25 metered ramps controlled as part of the Managed Motorway pilot

Name	Description	Number of Lanes @ Stopline	Ramp Type
RS-1	Ridgegate Parkway Direct (NE)	2	Arterial
RS-2	Lincoln Avenue Loop (SE)	2	Arterial
RS-3	Lincoln Avenue Direct (NE)	3	Arterial
RS-4	C-470 EB	4	System (F2F*)
RS-5	E-470 WB	2	System (F2F*)
RS-6	County Line Road Loop (SE)	2	Arterial
RS-7	County Line Road Direct (NE)	2	Arterial
RS-8	Dry Creek Road	3	Arterial
RS-9	Arapahoe Road Loop (SE)	2	Arterial
RS-10	Arapahoe Road Direct (NE)	3	Arterial
RS-11	Orchard Road	3	Arterial
RS-12	Belleview Avenue	2	Arterial
RS-13	I-225 NB	4	System (F2F*)
RS-14	Hampden Road	2	Arterial
RS-15	Yale Avenue	2	Arterial
RS-16	Evans Avenue	2	Arterial
RS-17	Colorado Boulevard	2	Arterial
RS-18	University Boulevard	2	Arterial

* F2F: *Freeway* to Freeway

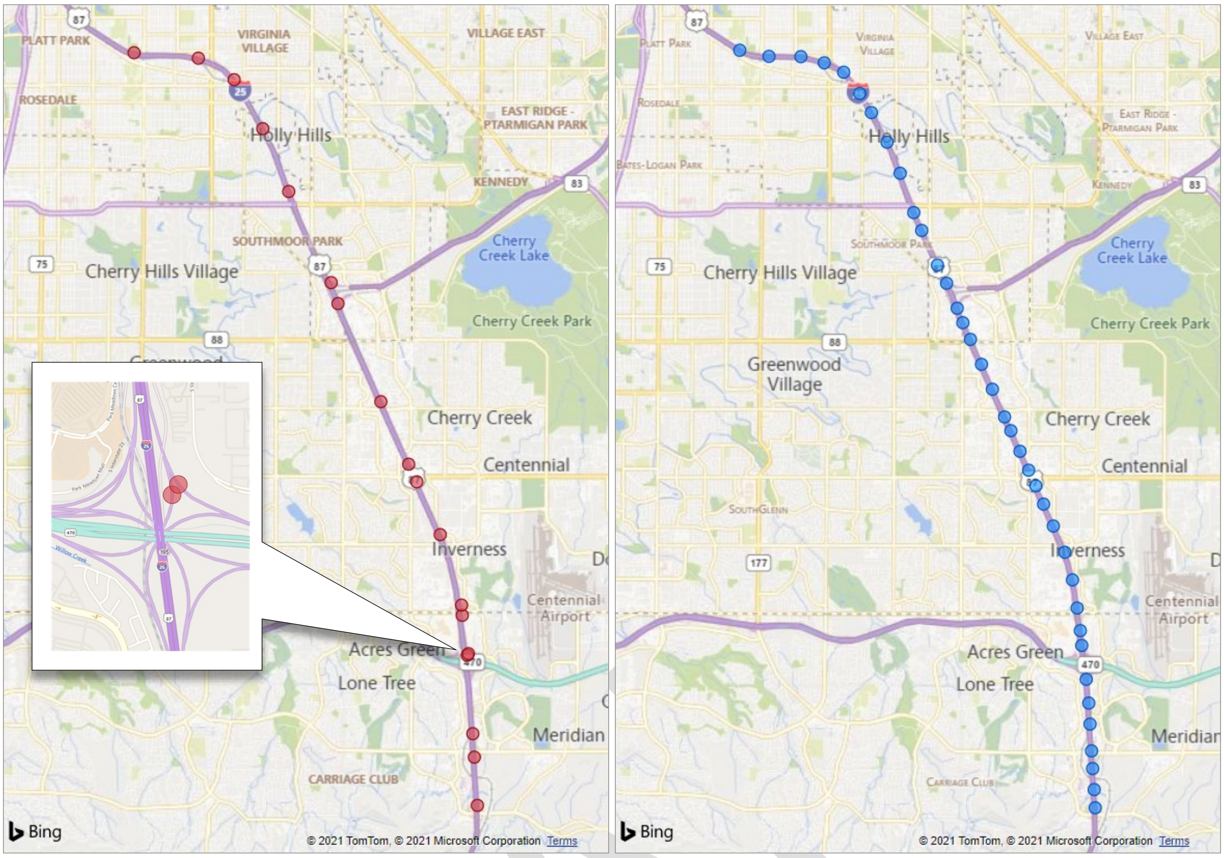


Figure 1: Ramp Signal Locations (Left) and Mainline Detector Stations (Right)

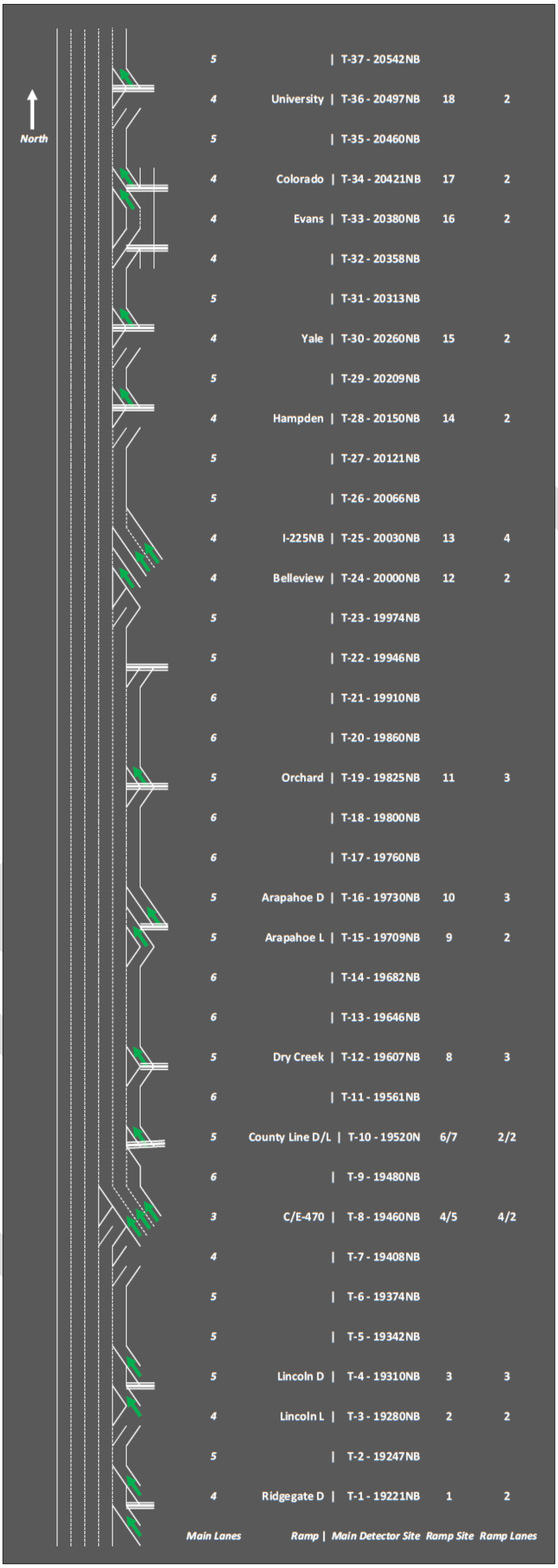


Figure 2: I-25 Pilot Section: Lane and Ramp Schematic with Summary Information (Not to Scale)

4 Pilot Section Definitions and Network Context

4.1 Pilot Section and Sub-section Definitions

Throughout this report, various measures and summaries are provided in the context of the overall pilot section and 3 sub-sections. The sections are shown in Figure 3 and summarised with additional detail in Table 2.

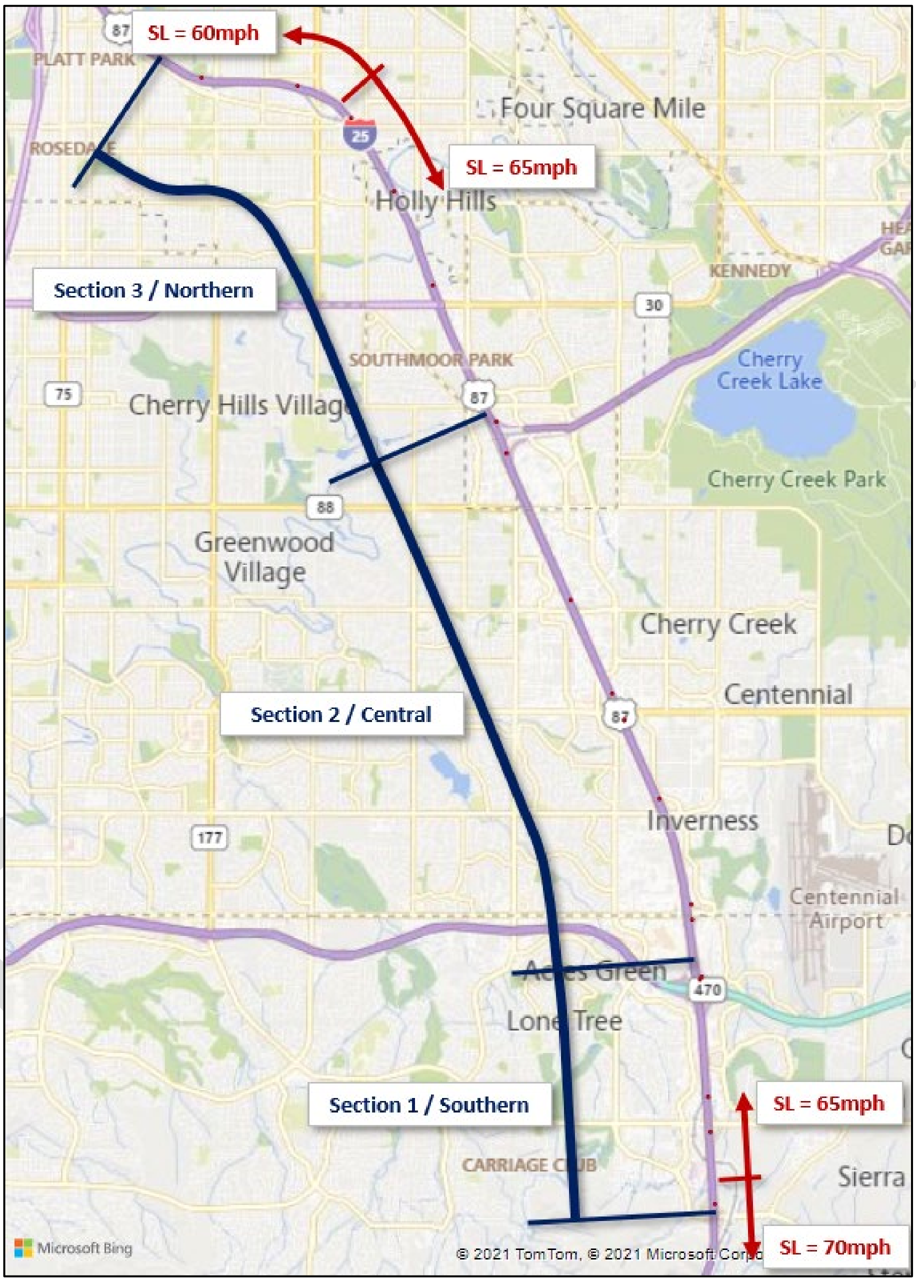


Figure 3: I-25 Section Definitions and Speed Limits

Table 2: Section Definitions for Mainline Performance Reporting

Name	Description	From	To	Length (miles)
All	*Whole Pilot Section*	*Ridgegate Parkway (South of Direct Entry Ramp) MP 192.1*	*University Boulevard (West of Entry Ramp) MP 205.6*	*13.54*
Sec 1	Section 1 / Southern	Ridgegate Parkway (South of Direct Entry Ramp) MP 192.1	C/E-470 (Northbound Entry) MP 194.7	2.65
Sec 2	Section 2 / Central	C/E-470 (Northbound Entry) MP 194.7	I-225 (Northbound Entry) MP 200.5	5.77
Sec 3	Section 3 / Northern	I-225 (Northbound Entry) MP 200.5	University Boulevard (West of Entry Ramp) MP 205.6	5.12

The pilot sections were separated largely based on the intersection with other significant freeway corridors, being the C/E-470 and the I-225. Due to the large entering and existing demands that can be facilitated at these system interchanges, there can be notable and significant changes in demands and operational discontinuities in the sections, although some conditions can overlap the section boundaries resulting in various interactions between sections as well. The section divisions are also consistent with common approaches taken to segment parts of the freeway network for performance reporting purposes (including the derivation of certain metrics such as travel time indices which are discussed later in this report).

4.2 Corridor Speed Limits

The prevailing speed limits in the pilot project section are shown in Figure 3. Most of the pilot project section has a 65mph speed limit. A 70mph limit exists to the south which changes to 65mph between the Ridgegate and Lincoln interchanges. A 60mph limit exists to the north which changes from 65mph between the Evans and Colorado interchanges. Speed limits in the corridor are static – variable speed limit signs are not present in the pilot project section of the corridor.

It is noted that the observed operating speeds, under free-flow conditions, tend to significantly exceed the speed limits within the pilot section. These observations are discussed in more detail in Section 8.6.

4.3 Peak Periods

Based on an analysis of the daily flow patterns in the corridor, the following time periods were identified for comparisons.

Table 3: Peak Period Definitions for Performance Reporting

Period	Start Time	End Time
Low Off-Peak (AM)	12:00:00 AM	6:30:00 AM
AM Peak	6:30:00 AM	9:30:00 AM
High Off-Peak	9:30:00 AM	3:00:00 PM
PM Peak	3:00:00 PM	7:00:00 PM
Low Off-Peak (PM)	7:00:00 PM	11:59:59 PM

Figure 4 below shows a typical daily profile at Site T-11 (19561_NB) in August 2021. The period definitions are overlaid which indicate the higher demand AM and PM peak and the high off-peak (daytime interpeak period) with elevated flows. The same profiles adopted for the baseline period have been used for the full evaluation comparison.

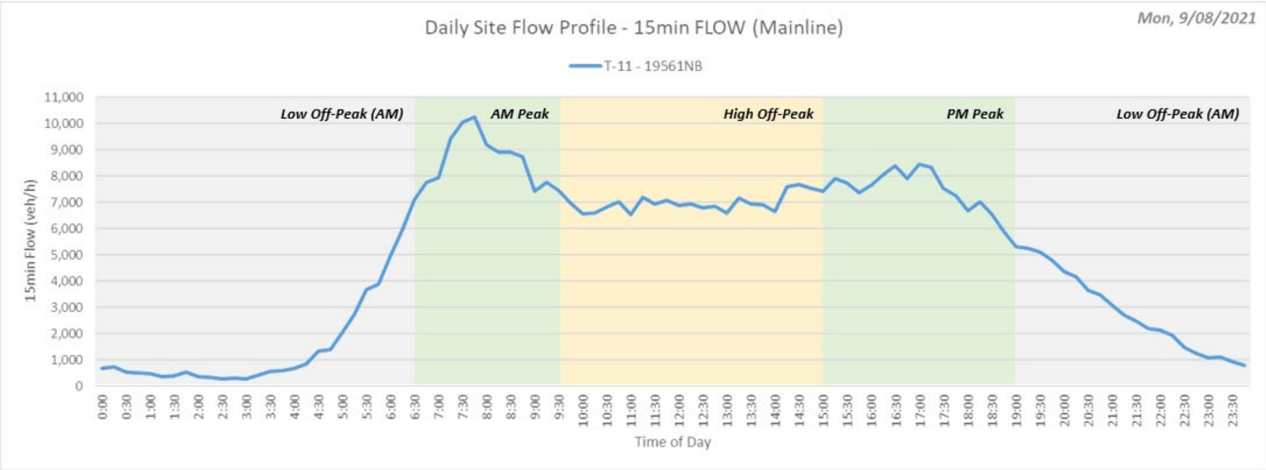


Figure 4: Indicative Daily Flow Profile with peak Period Definitions

5 Detection Technologies and Data Sources

5.1 TIRTL

Figure 1 (Right) shows the locations of the mainline detection on the northbound freeway. All mainline detector sites utilise TIRTL devices. TIRTL (The InfraRed Traffic Logger) is a side fire technology with a transmitter on one side of a freeway and receiver on the other projecting infrared beams across the traffic lanes just above the road surface. The beams of light “break” and “make” as vehicle tires interrupt the beams. Internal computations convert these beam events into axle and vehicle detection events. These events are converted to speed, volume and occupancy measures for use in real-time control and stored for further data analytics. Data is available at the lane level and aggregated across all lanes at a cross section location.

The locations of the mainline TIRTL detectors have also been used to define the road segments that are used for calculation of various metrics along the corridor. The alignment of the mainline segments with the INRIX Probe Data travel time sections is provided in Appendix A.

5.2 Sensys Pucks

Wireless Sensys Pucks are used on all entry ramps to measure and manage ramp demands and queue conditions. The detection pucks are installed in the center of each lane at three strategic locations on a ramp. Where multiple pucks are present in multiple lanes at a cross section location on a ramp, detectors are grouped to operate as a combined detector site.

The three strategic locations along each ramp are:

- Entry – upstream end of the entry ramp where vehicles first enter the ramp at a location generally clear of areas where vehicles may straddle lanes due to turning maneuvers.
- Mid-Ramp – mid-point along the entry ramp generally located at a location centered between the entry location and the ramp stopline.
- Passage (Stopline) – immediately downstream of the ramp metering stopline

Figure 5 below shows the typical locations for ramp detector sites. Data from the three sites are used in combination by the real-time control system to estimate queue lengths. Ramp flows provided later in this report are generally based on the volume measures from the passage detector, downstream of the stopline, which best represents ramp demand entering the freeway.

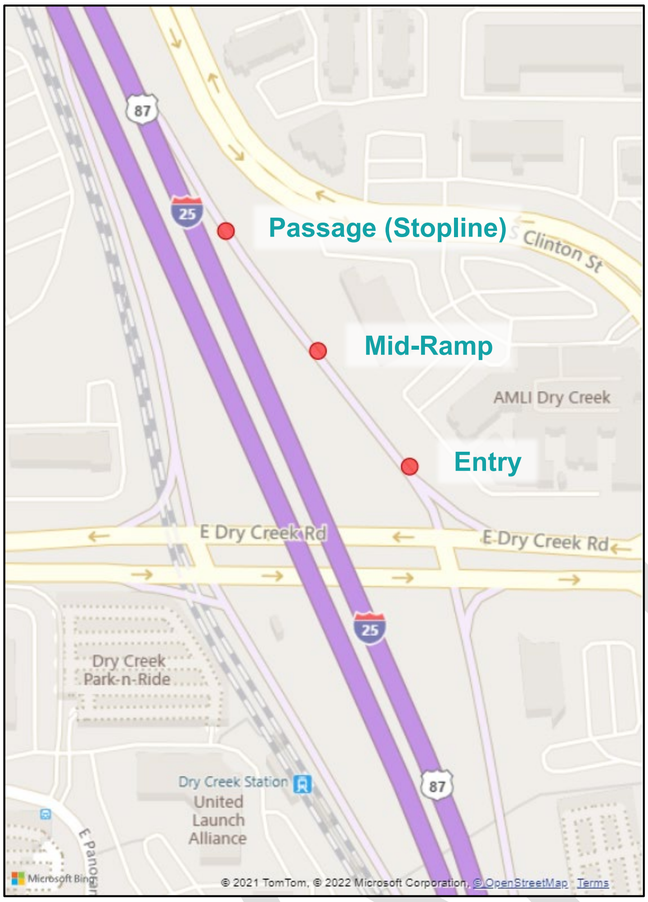


Figure 5: Entry Ramp Sensys Puck Locations (Example Location: Dry Creek Road)

5.3 System Data – STREAMS

The STREAMS control system being used for the ramp metering pilot collects and is able to export a wide variety of system information in relation to the ramp metering operations and mainline conditions. Where relevant, the data presented further in this, and associated reports will expand on the specific detail of the STREAMS data source.

Historical operational and performance data is also displayed in the Transmax Smart Motorways Dashboard. Some figures from the Smart Motorways Dashboard may be included to demonstrate historical conditions during various phases of the pilot project.

5.4 INRIX Probe Data

INRIX probe vehicle data provides real-time and historic speed and travel time data calculated from GPS probes from connected vehicles, commercial fleets and mobile GPS applications. As part of the pilot, CDOT/Apex Design have provided historic data for both the pre-pilot period and during the pilot period at regular intervals. Data has been provided for the mainline travel conditions as well as selected movements approaching and through various ramps (service and system) within the pilot area.

The INRIX Data on the mainline has been provided from the start of January 2019, which provides more than 12 months of historic travel time data that precedes traffic and travel impacts associated with the COVID-19 Stay-at-Home (Safer-at-Home) and associated public health orders and other pandemic related travel demand impacts.

Detail is provided in Appendix A showing the start and end points of each travel time section for the INRIX probe data. Alignment with the mainline road segments, used to analyse the speed and volume data from the mainline TIRTL detectors is also provided.

5.5 CDOT TDMS

The CDOT Transportation Data Management System (TDMS) was used to extract long term traffic demand data at key permanent traffic data locations on the I-25 corridor.

There are no permanent count stations (PCS) on the I-25 within the pilot project area, however, there are two stations on each end of the pilot project section. Figure 6 shows the location of the nearest count stations relative to the pilot project section.

The southern station, PCS No. 000012, is just south of the Ridgegate Parkway interchange and effectively provides a good indication of volumes entering the southern end of the pilot section with only one exit and entry ramp between the station and the pilot section. The northern station, PCS No. 000501, is to the north of West Alemeda Ave which results in 5 interchange / access locations between the northern extent of the pilot section and the count station. As a result, the northern station may be useful for changes in broad usage patterns on the I-25 although may be less reflective of the volumes leaving the pilot section due to the number of access locations which can experience varying ramp demands over extended periods. Only northbound data was extracted and utilised from this data source.

Figure 6: CDOT Permanent Count Stations (PCS) – Pilot Section shown in Orange

6 Performance Data and Metrics

6.1 Project Stages

Under the original program for the pilot demonstration project, three stages were proposed to run for the following durations:

- Baseline – Data Collection: 12 Weeks
- Arterial Ramp Only – Soft Launch: 8 Weeks
- Full Operations – Arterial + System Ramps: 4 months (~17-18 Weeks)

Throughout the project implementation, the starting dates and durations of the various stages were necessarily changed to account for various challenges that were encountered in real-world deployment. The changes were also applied to ensure appropriate time was allocated to the stages for sufficient demonstration of the system and data collected for analyses.

The sections below discuss and summarise the stages and durations that resulted across the pilot demonstration period.

6.1.1 Baseline Data Collection Period

As part of the project timeline, a Data Collection period was undertaken which preceded the soft launch (STREAMS-AHS Control) period. During the data collection period, ramp metering operations utilised local control reflective of CDOT ramp metering operations prior to the pilot project.

The live data collection period occurred between Wednesday, 14 July 2021 and Thursday, 28 October 2021. For practical reporting and comparisons, the formal data collection period, rounded out to full weeks was adopted as:

- ***Baseline Stage: Monday, 12 July 2021 to Sunday, 31 October 2021***

The full reporting of the baseline conditions are covered in the *Baseline Performance Report* although the baseline measures and metrics are also included in the comparisons made throughout this report.

6.1.2 Pilot Operations Periods

The operational period of the pilot demonstration project was separated into two stages, being the initial soft launch stage, or arterial ramps only, and the subsequent full operations stage, which added the operation of the three system (freeway-to-freeway) metered ramps within the pilot section.

With the commencement of the data collection period in mid-July 2021, the initial target date for the commencement of the STREAMS-AHS control was scheduled for around the end of September 2021. Part of the transition needed to ensure that the switch-over of operations from the 2070 local control was safe and reliable, and to also ensure that most, if not all, supporting devices for the metering operations were working and available. Throughout the data collection period, testing of the ramp meters and monitoring of the ramp and mainline detection and supporting systems was undertaken. During this period a number of device and system faults were identified that required remediation, including involvement of on-site maintenance staff. For various reasons, challenges in resolving some of the faults with the field devices resulted in the switchover to STREAMS-AHS control being delayed until the end of October 2021

The arterial ramp only operations under STREAMS-AHS control technically commenced on 29 October 2021, although for practicality purposes and to allow an initial transition to the modified control, the assessment period commenced on Monday, 1 November 2021.

With the arterial ramps only operations period commencing at the start of November, scheduled 8-week ramp up period was initially programmed to finish around the end of December 2021. However, for a number of reasons, the transition from the arterial ramp only stage to full operations was substantially delayed.

The Christmas holiday and new year period through late December impacted on resource availability to plan and commence transition processes. From mid-December through to mid-February, significant snow falls impacted the Denver area and caused a number of challenges with the TIRTL mainline detection due to blocking of the light beams that enable the detectors to function. CDOT operations staff also determined that commencing the operation of the freeway-to-freeway system ramps should ideally not occur under adverse weather conditions, since this would be the first ever application of ramp metering on systems ramps in Colorado. Throughout January-February 2022, testing of the system ramps was undertaken to ensure that all supporting devices and system functionality was in place to enable safe and reliable activation of the systems ramp meters. During this testing, issues that required on-site remediation were identified. In addition, roadside hardware, including signals lanterns were damaged by vehicle strikes which required hardware replacement before ramp metering operations could commence.

The system ramps were first switched on for live operations on Tuesday, 1 March 2022 in time for the PM Peak, although, due to the initial transition process, the formal Full Operations period commenced on Monday, 7 March 2022.

Based on the original project schedule, all live operations were scheduled to be completed by the end of April 2022. This would have resulted in only 7 weeks of the full operation stage due to the challenges discussed earlier. To enable a more representative full operations period to be completed, CDOT elected to extend the pilot demonstration to the end of July. The full operations period ended on Friday, 29 July 2022 with ramp metering operations reverting back to local control, similar to the baseline data collection period.

A summary of the stages throughout the whole pilot demonstration project is provided in the table below.

Table 4: Peak Period Definitions for Performance Reporting

<table>
<tr><th>Stage</th><th>Description</th><th>Start Date</th><th>End Date</th><th colspan="2">No. of Weeks</th></tr>
<tr><td>Baseline
(Emulated CDOT Legacy System)</td><td>Data Collection Period</td><td>Mon, 12 July 2021</td><td>Sun, 31 Oct 2021</td><td colspan="2">16</td></tr>
<tr><td>Arterial Ramps Only
(Soft Launch)</td><td>Arterial Ramps Only, No Systems Ramps</td><td>Mon, 1 Nov 2021</td><td>Sun, 6 Mar 2022</td><td colspan="2">18*</td></tr>
<tr><td>Full Operations</td><td>All Ramps, Including System Ramps</td><td>Mon, 7 Mar 2022</td><td>Sun, 1 May 2022</td><td>8</td><td rowspan="2">21</td></tr>
<tr><td>Full Operations (Ext)</td><td>All Ramps, Including System Ramps^</td><td>Mon, 2 May 2022</td><td>Fri, 29 July 2022</td><td>13</td></tr>
</table>

** While 18 weeks elapsed during the Arterial Ramp Only period, about 6-8 of these weeks were impacted by significant snow falls in the Denver area, reducing the days available for comparisons / the analysis period*

^ Although all system ramps were configured for operations during the extended full operations period, one of the system ramps (RS-4: C-470 to I-25) was disabled for an extended period due to faults of supporting devices

6.1.3 Holidays, Incidents and Adverse Weather

Holidays and significant incidents can have notable impacts on demands and travel conditions across the corridor. Throughout the pilot project, some days or periods have been excluded from the aggregation / processing and reporting to avoid significant skewing of the reported measures. For example, traffic demands on public holidays (e.g. Labor Day, Monday, 6 September 2021) and nearby days that may be significant impacted by proximity of the holiday to a weekend (e.g. Friday, 26 November 2021 after Thanksgiving). Exclusions will be noted where relevant to the measures present throughout this report.

Holiday periods are excluded due to low flow conditions, where ramp metering is unlikely to be activated. The low flow, high speed conditions skew averages towards faster travel times / lower delays. High speeds in such cases are not due to the operation of ramp metering.

Throughout the arterial ramps only and full operations periods, additional impacts from weather related events also caused significant impacts on operating conditions. In particular, significant snow falls throughout the December 2021 to February 2022 winter period impacted the performance of the mainline detection and also impacted the traffic demand and traffic operations along the corridor. In some cases, the snow conditions lead to significant crashes and incidents with the pilot section of the corridor. Periods of heavy rain have also been observed to significantly impact traffic operations.

A list of dates excluded due to holidays, significant incidents or adverse weather is provided in Appendix B, along with justification for that exclusion. Excluded dates are also highlighted in the Daily heat plot in Appendix H.

6.2 Measures from Data Collected within the Pilot Area

6.2.1 Speed

Aggregated speed measures were available from freeway vehicle detectors (TIRTLs and Sensys Pucks) in miles per hour (mph). Speed data is generally based on 1min pre-aggregated data extracted from detector sites (comprising all lanes at a motorway cross section) and further aggregated for determining and reporting measures.

A derived average speed, Space Mean Speed, is also calculated using Vehicle Miles Travelled and Vehicle Hours Travelled and takes into account the distance over which the number of vehicles travelled.

6.2.2 Volume and Flow

Aggregated volume measures were available from freeway vehicle detectors (TIRTLs and Sensys Pucks) and represents the number of vehicles detected in the collection interval. Volume data is generally based on 1min pre-aggregated data extracted from detector sites (comprising all lanes at a motorway cross section) and further aggregated for determining and reporting measures. Flow is the hourly equivalent volume for the time interval utilised.

6.2.3 Occupancy

Aggregated occupancy measures were available from freeway vehicle detectors (TIRTLs and Sensys Pucks) and represents the ratio of time detectors are occupied within the collection interval. Occupancy is expressed as a percentage – an occupancy measure of 10 (%) indicates a detector was occupied for a cumulative 10% of the time of the data interval (i.e. Occ of 10 equates to a total of 2 seconds of total occupied time in a 20 second measurement interval). Occupancy data is generally based on 1min pre-aggregated data extracted for detector sites (comprising all lanes at a motorway cross section) and further aggregated for determining and reporting measures. The average occupancy at a multi-lane detector site is the arithmetic mean of the occupancy measures from all lanes.

6.2.4 Vehicles Miles Travelled (VMT) and Vehicle Hours Travelled (VHT)

Vehicles Miles Travelled (VMT) and Vehicle Hours Travelled (VHT) were calculated based on the speed and volume measures from mainline detectors. The methods used are outlined in the report title Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies (National Academies of Sciences, Engineering, and Medicine, 2012). Appendix G of the NASEM report outlines the aggregations steps and computation of various intermediate metrics to produce VMT and VHT. VMT and VHT were calculated at a 5min intervals and aggregated further as needed.

The section definitions, aggregation steps and formula definitions for the various travel time metrics calculated are provided in Appendix C.

6.2.5 Travel Time and Travel Time Indices

Travel time measures were calculated from aggregated mainline TIRTL detector data (speed and volume) and also from aggregated travel time measures from INRIX data.

Measures derived from mainline vehicle detectors were calculated using the methods outlined in the report title Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies (National Academies of Sciences, Engineering, and Medicine, 2012). Appendix G of the NASEM report outlines the aggregations steps and computation of various intermediate metrics to produce flow adjusted travel times and associated indices. Travel times were calculated at a 5min interval.

Measures derived from the INRIX probe data used similar formulas for the metrics to those outlined in the procedure utilising mainline detection, however, due to the absence of corresponding volume data flow, travel times are not flow adjusted and associated speed measures are aggregations of time mean speed, rather than the desirable space mean speed.

It is noted that **60mph** was adopted as the **Free Flow Speed (FFS)** for calculating the various travel time indices and associated measures. Adoption of 60mph is common practice and ensures measures and indices avoid reflecting natural speeds variations in traffic flow as deterioration in conditions. It is important to ensure changes in the measures and indices reflect congestion and under performance, rather than a "credit" being assigned to high speed (or speeding) conditions.

The following metrics have been calculated for reporting or utilisation in further derivation of downstream measures:

- Average Travel Time (units as described where shown)
- Travel Time Index (TTI)
    - ratio of the experienced travel time to a nominal travel time
    - E.g. a trip that is 20% longer than travel at the free-flow speed has a TTI = 1.2
- Planning Time
    - Measure of travel time reliability represented by the 95th percentile travel time, which indicates how bad travel time was on the heaviest travel days
- Planning Index (95th Percentile TTI)
    - Ratio of near-worst case travel time to travel time in free-flow or nominal conditions – calculated as the 95th percentile travel time divided by the free-flow travel time.
- Buffer Index
    - Percentage extra buffer time (or time cushion) that road users "need to add" to their average travel time (at the planning stage) to ensure on-time arrival
    - difference between planning time and average travel time divided by the average travel time

The section definitions, aggregation steps and formula definitions for the various travel time metrics calculated are provided in Appendix C.

6.2.6 Ramp Travel Time and Delay

Travel times on ramps were made available through the provision of INRIX data. For all ramps, the probe vehicle samples were available allowing the traversal time of the ramps to be determined (generally from the ramp entry to the merge point with the freeway mainline). Data was provided in 5 minute intervals, allowing for a reasonable sample size in each period. The 5-minute data represents an average of all measured travel times within each sample period and accordingly any statistics calculated on the data available cannot take into account any of the variability within the sample periods.

Based on an analysis of the distribution of travel times measured on the ramps, a free flow travel time was able to be determined, based on the 10th percentile travel time. The 10th percentile travel time for each ramp was calculated and was generally within 0-2 seconds of the minimum 5-minute travel time. Using the free flow travel time, a relative per ramp delay was able to be calculated to understand the delay conditions on ramps throughout peak periods, when metering typically operates.

6.2.7 Average Delay

Reportable delays are incurred when the average speed on a segment is less than the adopted FFS of 60mph, which implies a segment travel time greater than the travel time at FFS. Average Delay is the difference between the average derived travel time and the travel time at FFS.

Average travel times are reported and where they differ from (are higher than) travel time at FFS, delays are incurred and therefore calculated. It is noted that causes of delays can be many and varied and overlap, including peak period congestion from flow breakdown, from speed reductions introduced to manage incidents or slower conditions due to adverse weather. Since exact causes cannot always be identified, causes of most delays are not

The section definitions, aggregation steps and formula definitions for the various travel time metrics calculated are provided in Appendix C.

6.2.8 Maximum Sustainable Flow Rates

Maximum Sustainable Flow Rates (MSFR) are representative of operational capacity, specifically in relation to individual bottleneck locations. Deriving MSFR uses an approach of developing flow breakdown risk distribution curves to understand the performance at recurrent bottleneck locations and provide a consistent and statistically sound method for measuring and comparing operational capacities. The background and methodologies for this process are outlined in the Managed Motorway Design Guide, Volume 1, Part 3, Motorway Capacity Guide (VicRoads, 2019).

Based on the derived flow breakdown risk curves (also known as the probability of flow breakdown), VicRoads has adopted the flow at a 1% probability of flow breakdown in a 15min period as a MSFR. This figure is also the equivalent of a probability of flow breakdown of 10% in a 3 hour period. This probability level was chosen as it generally aligns with the maximisation of productivity (defined below) which incorporates both speed and flow measures.

Using the same derivation methodology, sustainable occupancy targets can also be derived that can be used in operations utilising coordinated ramp metering.

Changes in MSFR that are achieved through operational improvements and flow optimisation can be measured. MSFR have been derived for the various stages of the pilot project at key recurrent bottleneck locations along the corridor.

6.2.9 Productivity

Productivity is a utilisation or efficiency measure based on the arithmetic product of speed and flow. It is calculated from the speed and flow measures from mainline detector sites. Productivity has been calculated at 5-minute aggregations (using 5-minute aggregated speed and flow data).

Productivity is best used for understanding performance at a cross-section location, such as a recurrent bottleneck. It can be best understood as a measure of VMT / unit time.

6.2.10 Utilisation – Classification

TIRTL Data collected throughout the pilot project includes classification data. Vehicles are classified according to their size and number of axles (and spacing). The classes for identifying vehicle types are defined at the federal level in FHWA documents (FHWA, November 2014) and a similar class structure has been adopted by CDOT as outlined in their Best Practice Guidebook for vehicle classification counts (CDOT, 2005).

The TIRTL detection system has used the axle patterns and definitions outlined by the FHWA to classify all detected vehicles. Data presented in this report has been extracted from the CEOS TIRTL GIS CDOT Traffic Statistics application.

7 I-25 Performance and Stage Comparisons

The following sections present the calculated metrics and measures for all stages for the I-25 pilot corridor. Comparisons are also made between the Arterial Ramps Only and Full Operations periods.

7.1 Travel Time Measures

The following tables summarise the travel time and travel time index (TTI) measures and also the changes when comparing each stage. Measures are provided across all sections and the three main time periods. The baseline measures are re-presented here to allow comparison of the project stages. Description of the measures presented are provided in Section 6.2.5.

Identified exclusions (days and relevant peak periods) apply to the measures presented in this Travel Time Measures section of the report.

Table 5: Baseline – Travel Time Measures

Peak Period & Section	Mean Travel Time (min)	Planning Time (95% Travel Time) (min)	Buffer Index (%)	Travel Time Index	Planning Index (95% Travel Time Ind.)
AM Peak					
All	**14.0**	**20.8**	**49%**	**1.10**	**1.53**
Section 1	2.9	3.7	28%	1.03	1.15
Section 2	5.7	10.0	74%	1.13	1.81
Section 3	5.4	8.1	51%	1.17	1.67
High Off-Peak					
All	**13.0**	**17.4**	**34%**	**1.04**	**1.29**
Section 1	2.8	2.9	3%	1.01	1.00
Section 2	5.3	7.4	40%	1.06	1.35
Section 3	4.9	6.9	40%	1.08	1.42
PM Peak					
All	**17.1**	**26.8**	**56%**	**1.29**	**1.98**
Section 1	3.3	5.0	53%	1.12	1.58
Section 2	7.7	13.6	77%	1.42	2.46
Section 3	6.2	9.9	60%	1.29	2.03

Table 6: Arterial Ramps Only (Soft Launch) – Travel Time Measures

Peak Period & Section	Mean Travel Time (min)	Planning Time (95% Travel Time) (min)	Buffer Index (%)	Travel Time Index	Planning Index (95% Travel Time Ind.)
AM Peak					
All	**13.8**	**21.2**	**53%**	**1.10**	**1.57**
Section 1	2.9	3.7	28%	1.03	1.16
Section 2	5.7	10.2	78%	1.13	1.85
Section 3	5.2	8.0	52%	1.14	1.64
High Off-Peak					
All	**12.3**	**14.1**	**14%**	**1.02**	**1.04**
Section 1	2.7	2.8	3%	1.00	1.00
Section 2	5.0	5.4	7%	1.02	1.00
Section 3	4.6	5.5	19%	1.03	1.13
PM Peak					
All	**16.1**	**25.5**	**59%**	**1.22**	**1.89**
Section 1	3.1	4.6	47%	1.09	1.46
Section 2	7.3	13.2	80%	1.36	2.38
Section 3	5.6	8.8	56%	1.19	1.81

Table 7 below shows a comparison of the Arterial Ramps Only stage travel time measures with the baseline conditions. Reductions in travel times are an improvement. It is noted that these are averages over all hours within the various periods analysed (refer to Section 4.3). Further detail within the peak periods is evident in the comparisons of the daily profiles of the measures shown in Figure 7.

Table 7: Arterial Ramps Only (Soft Launch) – Change in Travel Time Measures

Peak Period & Section	Mean Travel Time (min)	Planning Time (95% Travel Time) (min)	Buffer Index (%)	Travel Time Index	Planning Index (95% Travel Time Ind.)
AM Peak					
All	**-0.1**	**0.5**	**5%**	**0.00**	**0.03**
Section 1	0.0	0.0	0%	0.01	0.00
Section 2	0.0	0.2	4%	0.01	0.04
Section 3	-0.1	-0.1	1%	-0.02	-0.03
High Off-Peak					
All	**-0.6**	**-3.3**	**-20%**	**-0.03**	**-0.25**
Section 1	0.0	-0.1	-1%	0.00	0.00
Section 2	-0.3	-2.1	-33%	-0.04	-0.35
Section 3	-0.3	-1.4	-21%	-0.04	-0.29
PM Peak					
All	**-1.0**	**-1.3**	**2%**	**-0.07**	**-0.09**
Section 1	-0.1	-0.4	-6%	-0.03	-0.12
Section 2	-0.4	-0.4	3%	-0.06	-0.08
Section 3	-0.5	-1.1	-4%	-0.10	-0.22

Table 8: Full Operations – Travel Time Measures

Peak Period & Section	Mean Travel Time (min)	Planning Time (95% Travel Time) (min)	Buffer Index (%)	Travel Time Index	Planning Index (95% Travel Time Ind.)
AM Peak					
All	**13.7**	**20.2**	**47%**	**1.09**	**1.49**
Section 1	2.9	3.5	24%	1.03	1.12
Section 2	5.5	9.1	64%	1.09	1.64
Section 3	5.3	8.0	49%	1.16	1.64
High Off-Peak					
All	**12.9**	**16.7**	**29%**	**1.04**	**1.23**
Section 1	2.8	2.9	5%	1.01	1.00
Section 2	5.2	6.9	32%	1.05	1.25
Section 3	4.9	6.7	37%	1.07	1.37
PM Peak					
All	**14.7**	**21.4**	**46%**	**1.13**	**1.58**
Section 1	3.1	4.8	55%	1.07	1.50
Section 2	6.3	10.8	71%	1.19	1.95
Section 3	5.3	8.2	55%	1.13	1.69

Table 9 below shows a comparison of the Arterial Ramp Only stage travel time measures with the baseline conditions. Reductions in travel times are an improvement. It is noted that these are averages over all hours within the various periods analysed (refer to Section 4.3). Further detail within the peak periods is evident in the comparisons of the daily profiles of the measures shown in Figure 8.

Table 9: Full Operations – Change in Travel Time Measures

Peak Period & Section	Mean Travel Time (min)	Planning Time (95% Travel Time) (min)	Buffer Index (%)	Travel Time Index	Planning Index (95% Travel Time Ind.)
AM Peak					
All	**-0.3**	**-0.6**	**-1%**	**-0.02**	**-0.04**
Section 1	0.0	-0.1	-3%	0.00	-0.03
Section 2	-0.2	-0.9	-10%	-0.03	-0.17
Section 3	-0.1	-0.2	-1%	-0.01	-0.03
High Off-Peak					
All	**-0.1**	**-0.7**	**-5%**	**0.00**	**-0.06**
Section 1	0.0	0.1	1%	0.01	0.00
Section 2	-0.1	-0.5	-8%	-0.01	-0.09
Section 3	0.0	-0.2	-3%	0.00	-0.05
PM Peak					
All	**-2.5**	**-5.4**	**-10%**	**-0.16**	**-0.40**
Section 1	-0.2	-0.3	2%	-0.05	-0.08
Section 2	-1.4	-2.8	-6%	-0.22	-0.51
Section 3	-0.9	-1.6	-5%	-0.16	-0.34

The following figures present the daily profiles of average travel times and planning times. These presentations of the travel time results provide additional detail to the tables above which average the measures across the pre-defined time periods across the day. The profiles provide good further understanding of where travel times and planning times have changed across the day and also how the travel times experienced vary across the day.

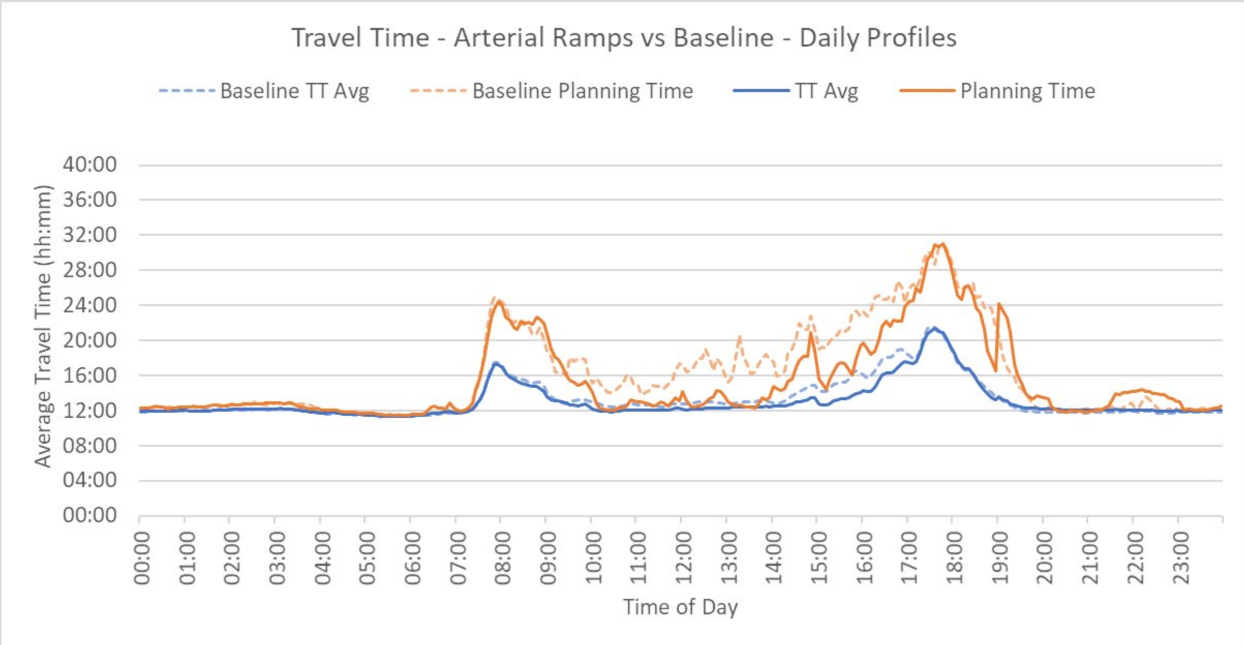


Figure 7: Travel Time Comparison – Arterial Ramps Only vs Baseline Daily Profiles (Whole Pilot Section)

During the arterial ramps only stage of the project, most of the reductions in travel time were observed in the high off-peak period and also in early shoulder of the PM peak. During this stage the early onset conditions that could result in flow-breakdown and would then continue into the PM Peak periods were potentially better managed, however, the heavier flows from both the metered ramp and the unmetered system ramps likely overwhelmed the system resulting in similar long travel times at the height of the peak periods. It is noted in further sections of this report that the average demands along the corridor were marginally lower than the baseline stage which may also contribute to a portion of the reduced congestion observed. The profiles indicate that flow recovery at the end of the Am and PM peak periods required a similar easing of corridor demand as experienced in the baseline stage.

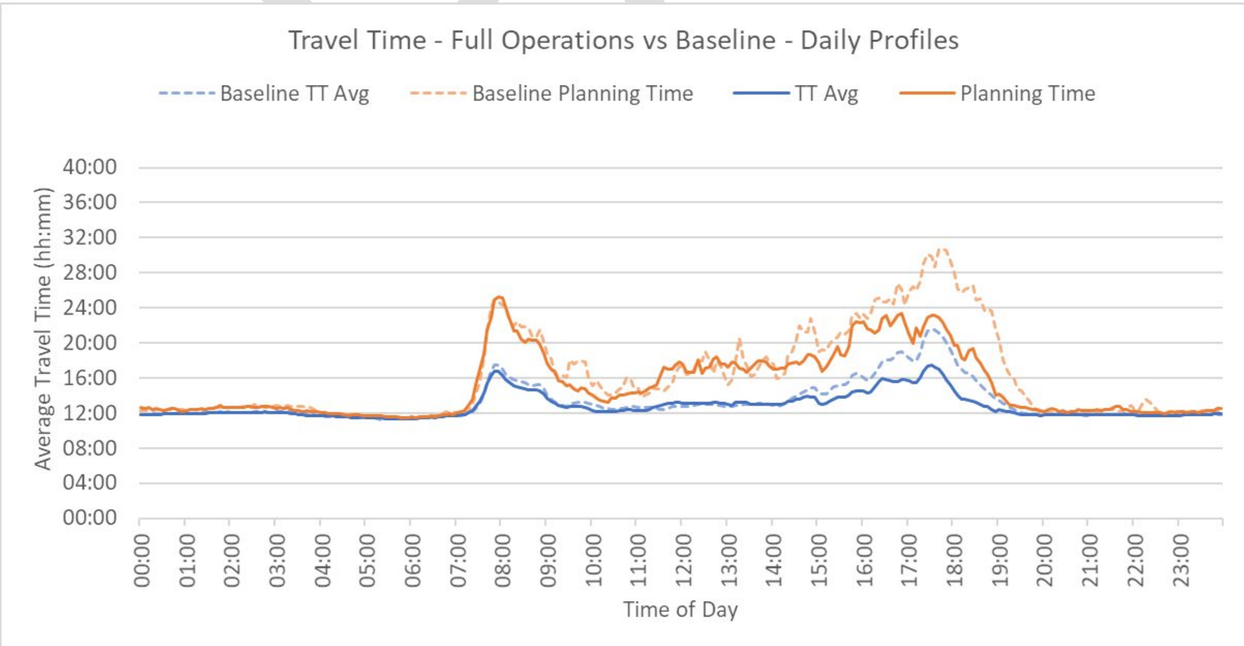


Figure 8: Travel Time Comparison – Full Operations vs Baseline Daily Profiles (Whole Pilot Section)

During the full operations stage, the reductions in average travel times and planning times are more evident especially during the broader PM peak period. In addition to congestion starting later than the baseline stage, travel time also remained significantly lower throughout the PM peak and also recovered significantly earlier. The variability of travel time was also substantially reduced through the busier parts of the PM peak. It is also noted (and discussed later in this report) that the demands within the corridor were generally similar or in some locations higher than those observed during the baseline period, which likely eliminates demand variations as a primary cause of any reduced congestion and travel times.

The table below provides the percentage change in travels times across the operational stages, compared with the baseline, across the peak periods during the day and across the various sub-sections of the pilot section. Consistent with the table and figures discussed above, significant reductions in travel times can be seen during the PM peak, especially during the full operations stage. It is noted that the right most column provides summary results for a limited part of the Full Operations stage (ending 9 May 2022).

Table 10: Average Travel Time – Percentage Change (vs. Baseline)

Peak Period	*Section*	*Arterial Ramps Only (vs Baseline)*	*Full Operations (vs Baseline)*	*Full Operations to 09 May 2022 (vs Baseline)*
AM Peak	**All**	**-0.9%**	**-2.0%**	*1.8%*
	Section 1	0.3%	-0.3%	*1.7%*
	Section 2	-0.1%	-3.7%	*1.0%*
	Section 3	-2.4%	-1.0%	*2.7%*
High Off-Peak	**All**	**-5.0%**	**-0.7%**	*-2.9%*
	Section 1	-1.5%	0.7%	*0.7%*
	Section 2	-5.5%	-1.3%	*-3.7%*
	Section 3	-6.4%	-0.7%	*-4.1%*
PM Peak	**All**	**-6.0%**	**-14.3%**	*-17.1%*
	Section 1	-3.7%	-6.3%	*-11.8%*
	Section 2	-4.8%	-18.0%	*-22.8%*
	Section 3	-8.7%	-14.0%	*-12.9%*

An expanded version of Table 10 is provided in Appendix D which also includes partial results during the full operations period. As discussed in other sections, the C-470 ramp was disabled from 10 May 2022 onwards (until the end of pilot operations) due to device faults. Accordingly, the first portion of the full operations period, from early March to early May was a key period when all 18 metered ramps in the pilot section were operating together.

Figure 9 and Figure 10 below show the average daily profiles for travel time and planning time, enabling a more direct comparison of the three main stages of the pilot project. Figure 11 below summarises the peak periods average travel times and planning times across the project stages.

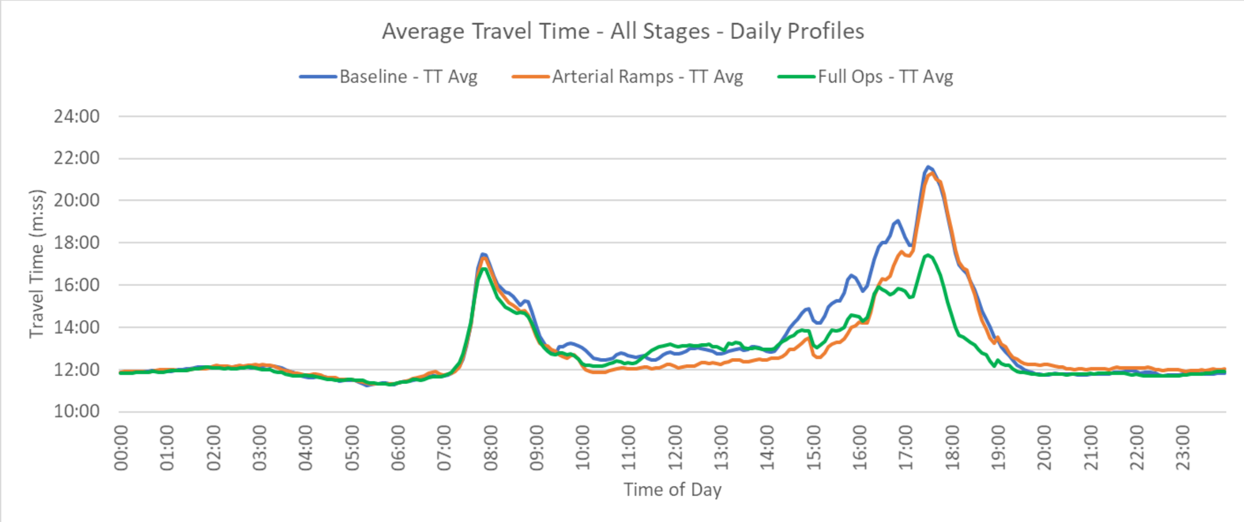


Figure 9: Average Travel Time Comparison – All Stages Daily Profile (Whole Pilot Section)

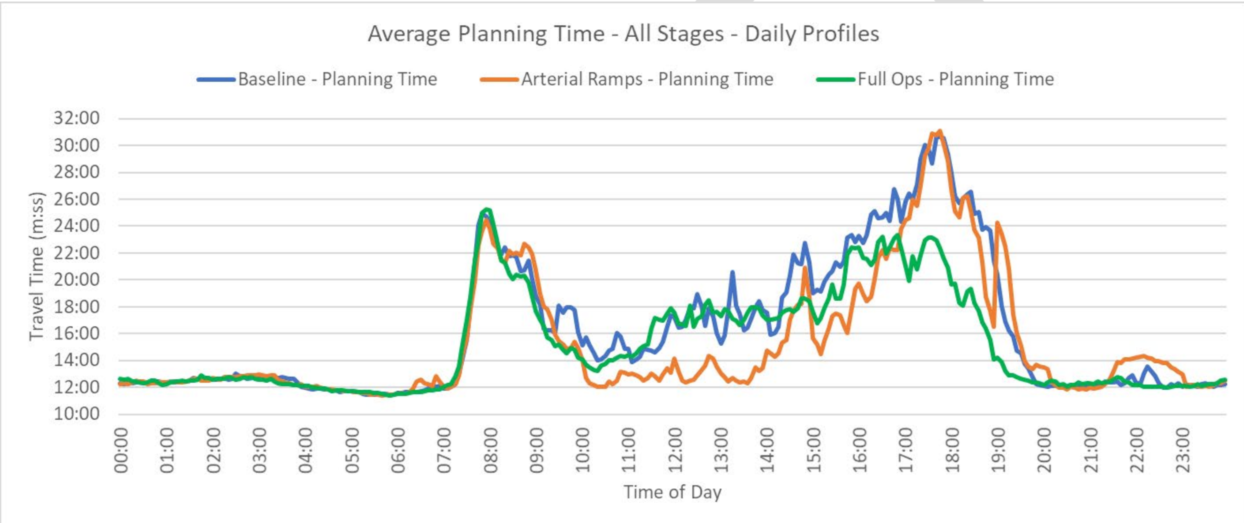


Figure 10: Average Planning Time Comparison – All Stages Daily Profile (Whole Pilot Section)

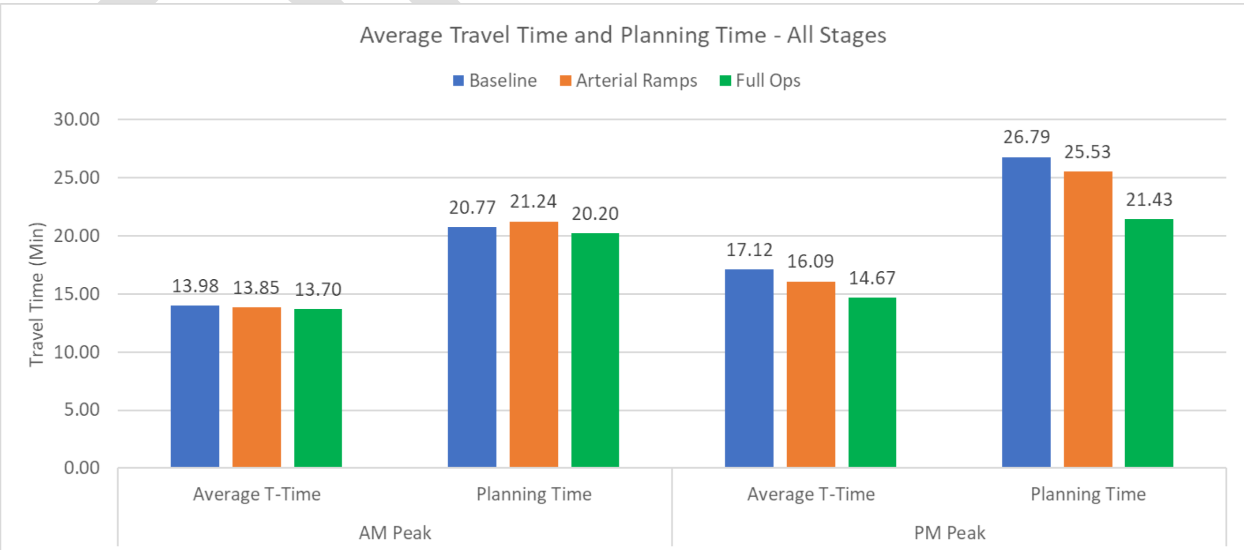


Figure 11: Average Travel Time Comparison – All Stages Daily Profile (Whole Pilot Section)

Reductions in travel times through the pilot section and the sub-sections was one of the key objectives of the project due to the high travel times and variability of travel times previously experienced in the corridor. From the measures presented above, it can be seen that there have been significant reductions in travel times, particularly during the PM Peak after application of the AHS ramp metering operations. The 14.3% improvement in the PM Peak period average represents a 2.5 minute reduction in travel time for vehicles driving the full length of the pilot section. When comparing the maximum average travel times at the height of the PM peak of the baseline and full operations stages, a reduction of up to 4.1 minutes (or 19%) was measured.

Although the whole peak period averages don't show a significant change during the AM peak, it is evident from the daily profile plots that some improvement in the AM peak was experienced.

The variability indicated by a reduction in the planning time was observed across all periods although the PM peak saw the biggest average reduction of 5.4 minutes (20%) across the whole peak period and up to 7.3 minutes (24%) at the height of the PM peak.

While changes in travel times provided a useful understanding of the benefits for individual road users, in order to better appreciate the broader cumulative improvements in the corridor, consideration of total delay reduction is needed, which accounts for the volume of traffic utilizing each segment of the corridor. Changes in total delay are discussed in Section 7.3.

The conditions that contribute to congestion and delays in the corridor are discussed in more detail in Section 8.

7.2 Average Ramp Delays

As discussed in Section 6.2.6, ramp travel times and resulting delays are based on INRIX data provided for each ramp. The ramp section with travels times reported were dependent on the pre-defined way-points within the INRIX reporting system. (The average ramp delay information is presented here as it utilises the same data source as the travel time measures in the preceding section.)

Figure 12 shows examples of travel time sections for entry ramps. The travel time sections generally start at the arterial road ramp terminal intersection and extend to the merge point with the freeway mainline. In order to capture delays on ramps that can be predominantly assigned to ramp metering operations, the travel time under relatively free-flow conditions is subtracted from the reported travel times. The free-flow travel time was calculated for all ramps individually based on the 10^{th} percentile travel time. This also accounts for a nominal travel time between the stopline and the freeway merge being excluded from any delay measures.

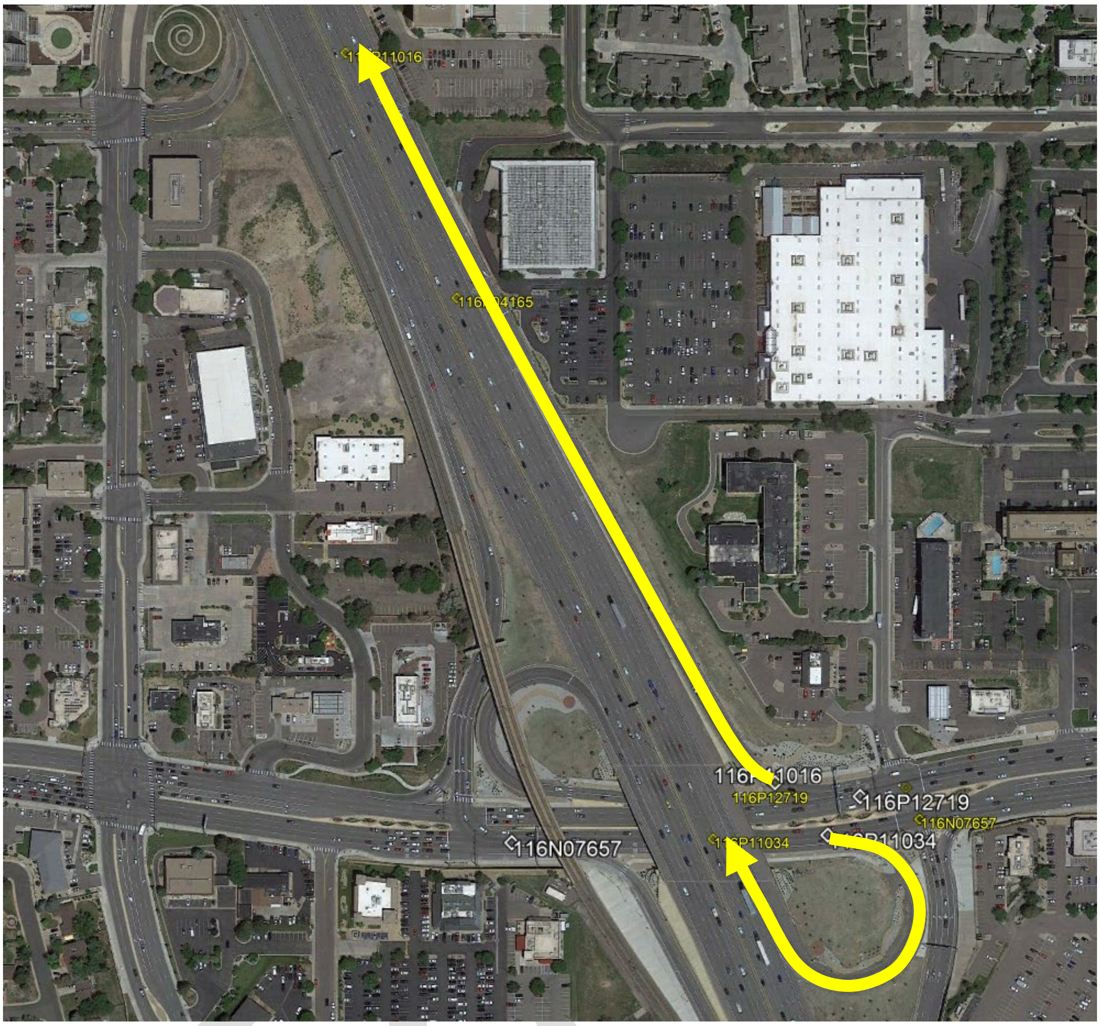


Figure 12: Example Travel Time Section associated with Entry Ramps (E. Arapahoe Road)

Table 11 below summarises the maximum and 95th percentile delays experienced during the baseline data collection period. The measures represent weekdays only and exclusions are applied (to align with the travel times and delays reported in other sections).

Table 11: Baseline Stage – Ramp Delays (Maximum and 95th Percentile) by Ramp

Ramp Name	Baseline Ramp Delays (sec)			
	AM Peak Max	AM Peak 95%	PM Peak Max	PM Peak 95%
Ridgegate Direct	164	17	100	16
Lincoln Loop	105	23	206	44
Lincoln Direct	70	30	189	51
C-470 Storage	33	3	141	4
E-470 Storage	7	2	6	2
County Loop	23	10	241	17
County Direct	17	8	52	16
Dry Creek Direct	31	17	76	31
Arapahoe Loop	34	13	41	21
Arapahoe Direct	79	34	111	49
Orchard Direct	37	19	83	48
Belleview Direct	72	38	254	89
I-225 Storage	130	14	112	22
Hampden Direct	67	23	34	19
Yale Direct	135	35	67	33
Evans Direct	40	21	36	19
Colorado Direct	97	48	156	51
University Direct	41	17	40	23

Review of the 95th percentile delays is most useful when reviewing the tabled data, as maximums can be misleading due to outlier events and averages can be strongly skewed towards parts of the peaks when there is relatively low demand and little queuing on ramps due to metering.

During the Baseline stage, it can be seen that in general delays on most ramps were fairly low, all being less than 1-minute, except for Belleview in the PM peak. It is observed that delays on the Belleview ramp can be due to queues extending back onto the ramp, between the mainline merge and the metering stopline, due to mainline congestion. The strong bottleneck north of the I-225 entry can regularly cause significant mainline congestion in the vicinity of the Belleview entry ramp merge.

With the introduction of the changed ramp metering operations in the corridor, increased ramp wait times and therefore increased average delays on metered entry ramps was to be expected. The approach to managing queues and delays on the metered ramps under AHS control is to restrain entering flows sufficiently to manage mainline conditions but not create extensive queues or delays for entering road users. In general, wait time settings in the ramp metering operations were set to 4 minutes. If wait times approached or reached this threshold, the metering operations would increase ramp flows in a managed way to ensure wait times did not get excessive.

Table 12 below shows the peak period ramp 95th percentile ramp delays during the arterial ramps only stage and the change from the baseline stage. It is observed that all ramps have relatively acceptable 95th percentile delays, mostly less than 2 minutes. While shorter portions of peak periods may experience higher spikes in delays, the general experience indicated by the derived ramp delays indicates a good level of service (with no excessive delays) being achieved for road users utilising the metered ramps. Although the system ramps (shown in **bold**) are not metered during this stage, there is some increased delay experienced which is most likely due to slowing near the mainline and ramp merge portion of the travel time sections utilized.

Table 12: Arterial Ramps Stage - Ramp Delays (95th Percentile and Change from Baseline) by Ramp

Ramp Name	Arterial Ramps Only Stage - Ramp Delays (sec)			
	AM Peak 95%	AM Peak Change	PM Peak 95%	PM Peak Change
Ridgegate Direct	53	(+36)	43	(+27)
Lincoln Loop	44	(+20)	67	(+23)
Lincoln Direct	84	(+54)	99	(+48)
C-470 Storage	**5**	**(+2)**	**24**	**(+20)**
E-470 Storage	**2**	**(+1)**	**6**	**(+4)**
County Loop	16	(+7)	37	(+20)
County Direct	14	(+5)	33	(+17)
Dry Creek Direct	34	(+17)	52	(+20)
Arapahoe Loop	27	(+14)	37	(+16)
Arapahoe Direct	73	(+39)	94	(+45)
Orchard Direct	39	(+20)	62	(+14)
Belleview Direct	63	(+25)	119	(+30)
I-225 Storage	**37**	**(+23)**	**66**	**(+44)**
Hampden Direct	68	(+45)	58	(+40)
Yale Direct	73	(+37)	50	(+17)
Evans Direct	29	(+8)	31	(+12)
Colorado Direct	124	(+76)	120	(+69)
University Direct	30	(+13)	35	(+11)

Table 13 below shows the peak period ramp 95th percentile ramp delays during the full operations stage and the change from the baseline stage. It is observed that all ramps have relatively acceptable 95th percentile delays, again all less than 2 minutes. While shorter portions of peak periods may experience higher spikes in delays, the general experience indicated by the derived ramp delays indicates a good level of service (with no excessive delays) being achieved for road users utilising the metered ramps. The system ramps (shown in **bold**) are metered during this stage, and so delays on these ramps are more likely due to the delays imposed by the ramp meters, although minor delays at the ramp merge in the event of flow breakdown may still be possible.

Table 13: Full Operations Stage- Ramp Delays (95th Percentile and Change from Baseline) by Ramp

Ramp Name	Full Operations Stage - Ramp Delays (sec)			
	AM Peak 95%	AM Peak Change	PM Peak 95%	PM Peak Change
Ridgegate Direct	49	(+31)	52	(+35)
Lincoln Loop	44	(+20)	73	(+29)
Lincoln Direct	34	(+4)	56	(+5)
C-470 Storage	**28**	**(+25)**	**32**	**(+28)**
E-470 Storage	**19**	**(+17)**	**13**	**(+11)**
County Loop	19	(+9)	40	(+22)
County Direct	16	(+7)	32	(+17)
Dry Creek Direct	38	(+21)	50	(+19)
Arapahoe Loop	34	(+20)	41	(+20)
Arapahoe Direct	77	(+44)	100	(+51)
Orchard Direct	40	(+22)	55	(+7)
Belleview Direct	62	(+23)	104	(+16)
I-225 Storage	**71**	**(+57)**	**71**	**(+49)**
Hampden Direct	70	(+47)	61	(+42)
Yale Direct	80	(+44)	53	(+20)
Evans Direct	32	(+11)	32	(+13)
Colorado Direct	*	*	*	*
University Direct	35	(+18)	40	(+16)

** Note: Poor Data from source system for the Colorado Boulevard entry ramp from March 2022*

Figure 13, Figure 14 & Figure 15 below show the 95th percentile average ramp delays as daily profiles for each stage of the pilot project. Ramps are presented in north, central and south groups. Additional plots are provided in Appendix E which show daily profiles for individual ramps enabling comparison of the project stages.

In general, assessment of the ramp delays was undertaken primarily to ensure that excessive delays were not being experienced by most users accessing the I-25. The analysis of the INRIX travel times on the ramps and calculated delays indicates the ramps did not experience excessive delays across the operational periods. This does not mean that there were no periods where some long queues or longer delays were experienced, but that overall most users experienced a good level of service.

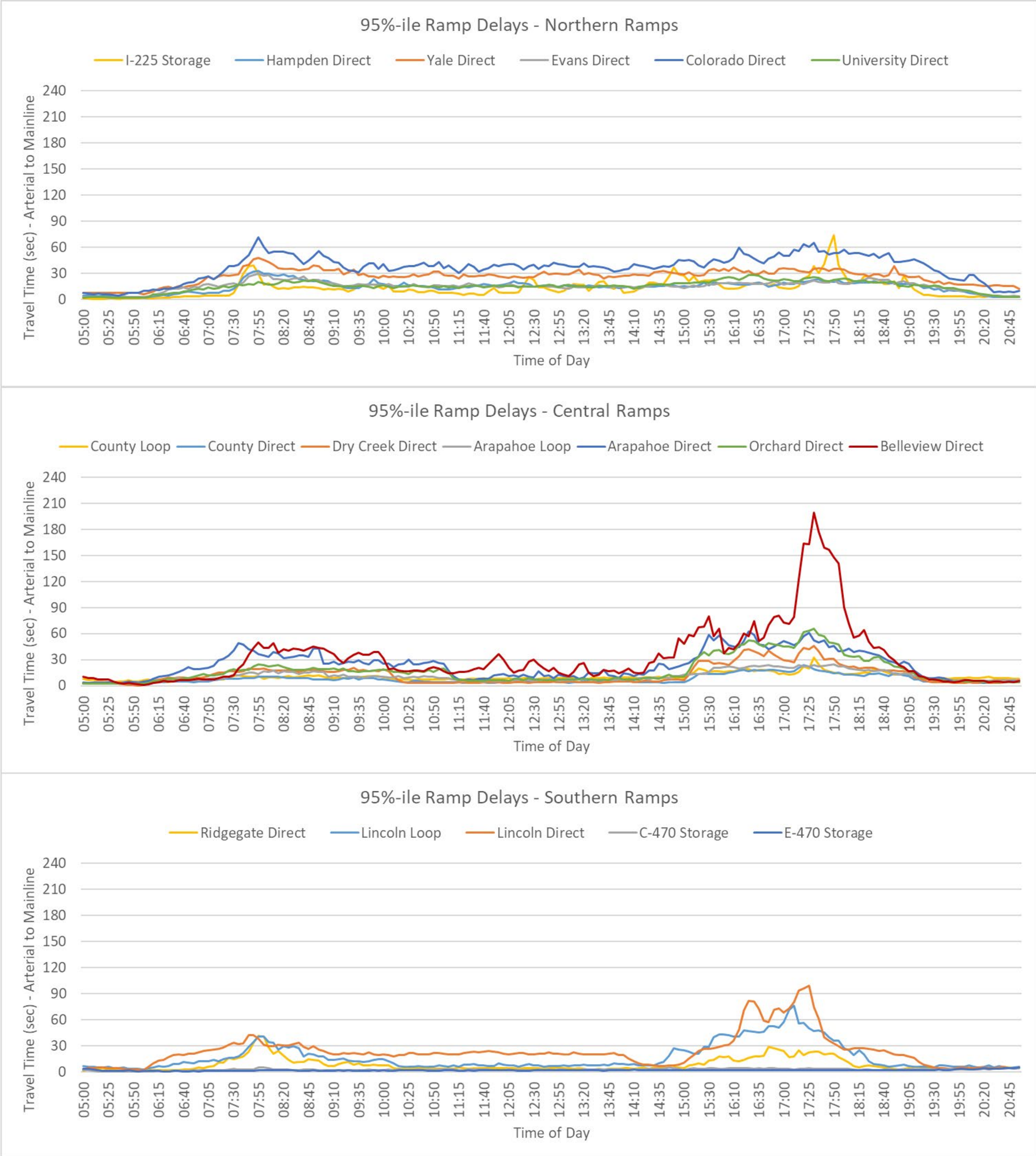


Figure 13: Baseline 95th Percentile Ramp Delays – North, Central and Southern Groups

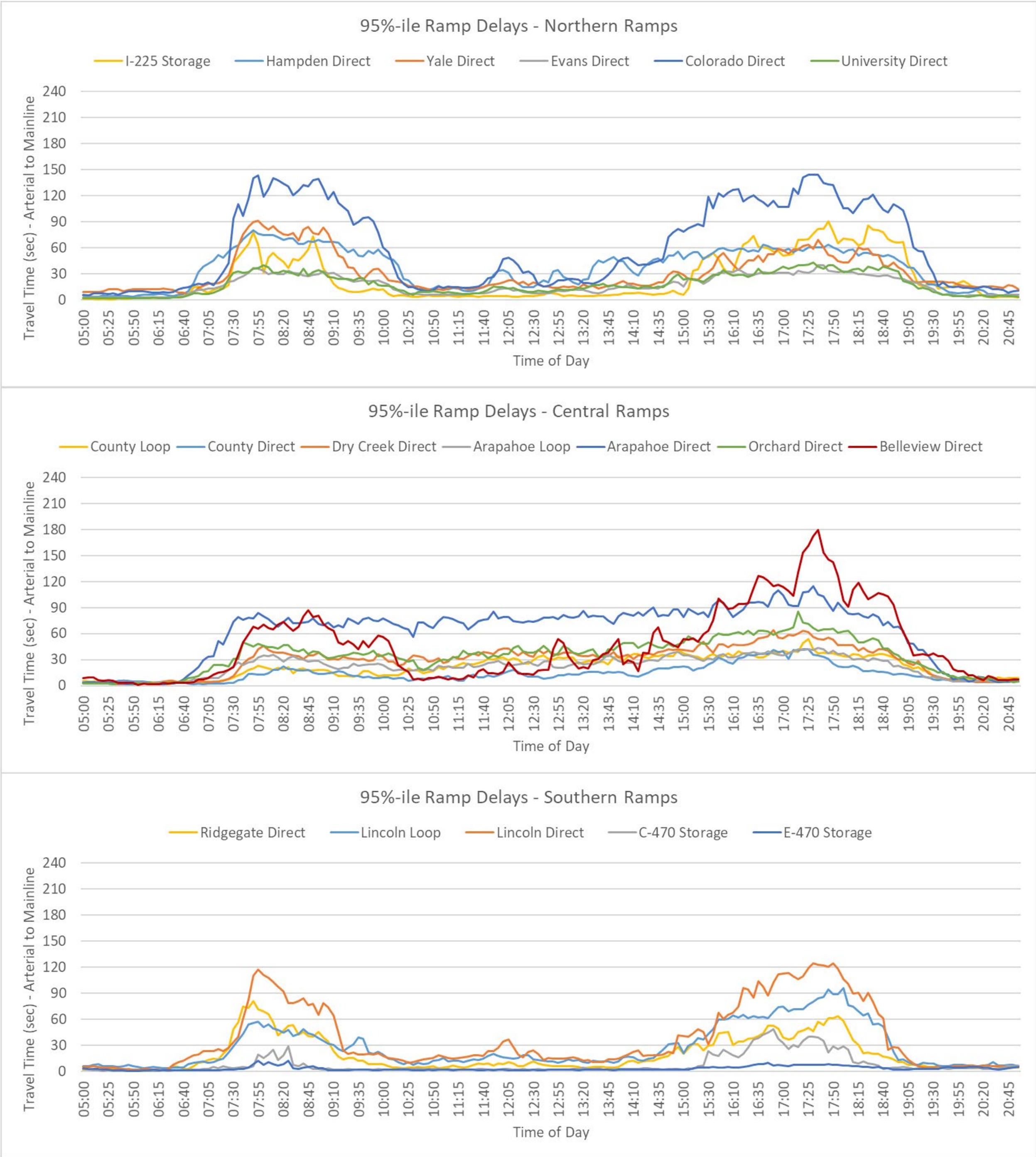


Figure 14: Arterial Ramps Only Stage 95th Percentile Ramp Delays – North, Central and Southern Groups

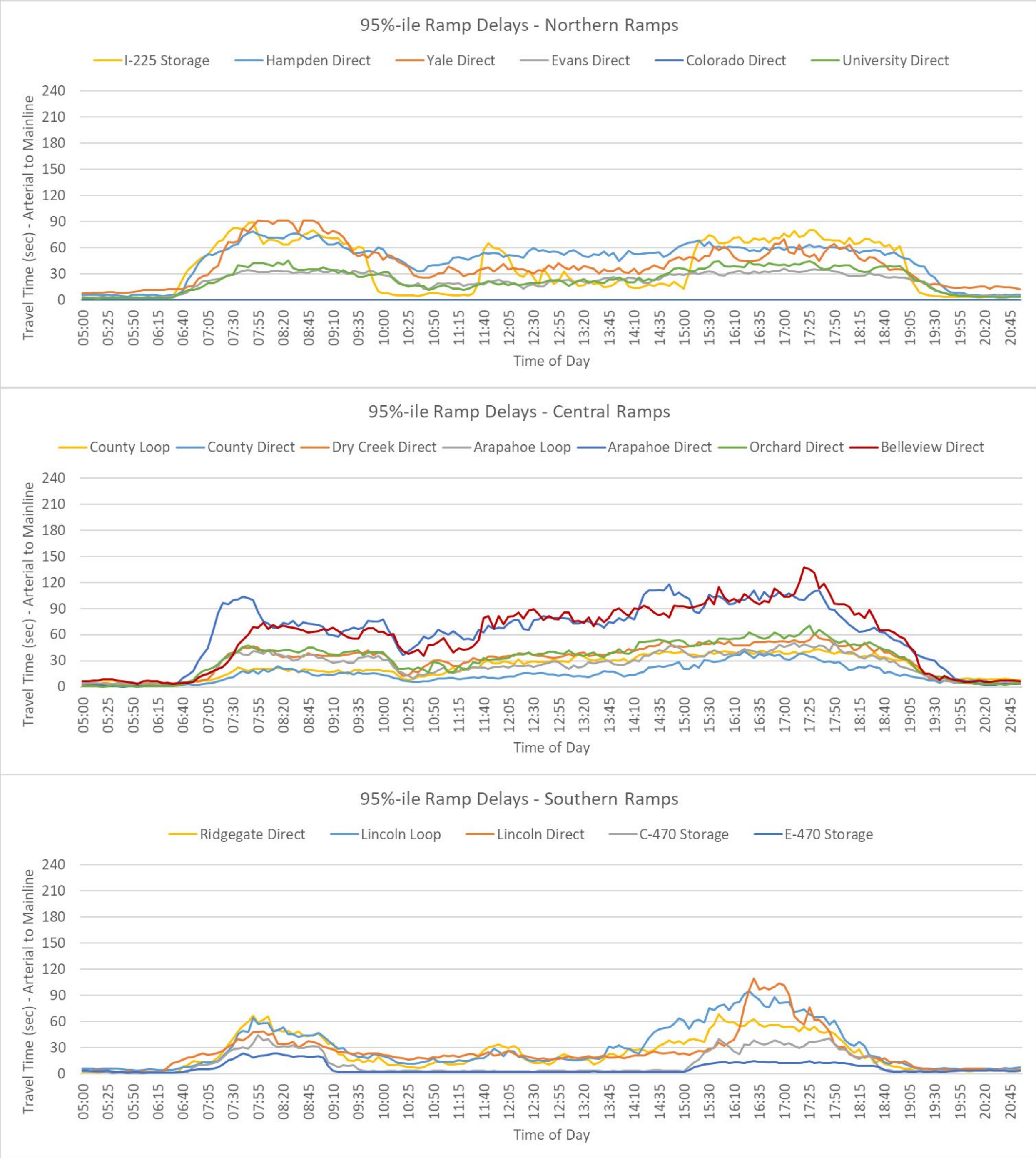


Figure 15: Full Operations Stage 95th Percentile Ramp Delays – North, Central and Southern Groups

7.3 Total Mainline Delays

Delays are calculated as the difference between the measured or derived travel time and the travel time at nominal speed along the corridor or each section. As discussed in Section 6.2.5, a free-flow speed of 60mph has been used to determine reference travel times (i.e., there is no negative delay or delay "saving" due to high speeds). Delays are calculated at 5-minute intervals then aggregated as appropriate.

Identified exclusions (days and relevant peak periods) apply to the measures presented in this Mainline Delays section of the report.

The average daily total delay (average of all weekdays during the respective stages) is provided in the tables below while the histograms show the daily total delays by section. The tables also includes a summary of the proportional split of delays by section of the pilot corridor. It can be seen that the total delays are disproportionate to the length in each section. The higher delays, by distance occur in Section 2 – the central section between C/E-470 and the I-225. This higher proportion of delays within Section 2 of the pilot section remained across both operational stages, although there was a very minor redistribution of delays across the sections.

Table 14: Baseline – Average Daily Total Delay by Section

Section	*Average Daily Total Delay (All Weekdays)*	*Delay Proportion by Section*	*Section Length Proportion by Section*
All	*1,958*		
Section 1	86	4%	20%
Section 2	997	51%	43%
Section 3	874	45%	38%

Table 15: Arterial Ramps Only – Average Daily Total Delay by Section

Section	*Average Daily Total Delay (All Weekdays)*	*Delay Proportion by Section*	*Section Length Proportion by Section*
All	*1,462*		
Section 1	81	5%	20%
Section 2	817	56%	43%
Section 3	573	39%	38%

Table 16: Full Operations – Average Daily Total Delay by Section

Section	*Average Daily Total Delay (All Weekdays)*	*Delay Proportion by Section*	*Section Length Proportion by Section*
All	*1,131*		
Section 1	70	6%	20%
Section 2	521	46%	43%
Section 3	549	48%	38%

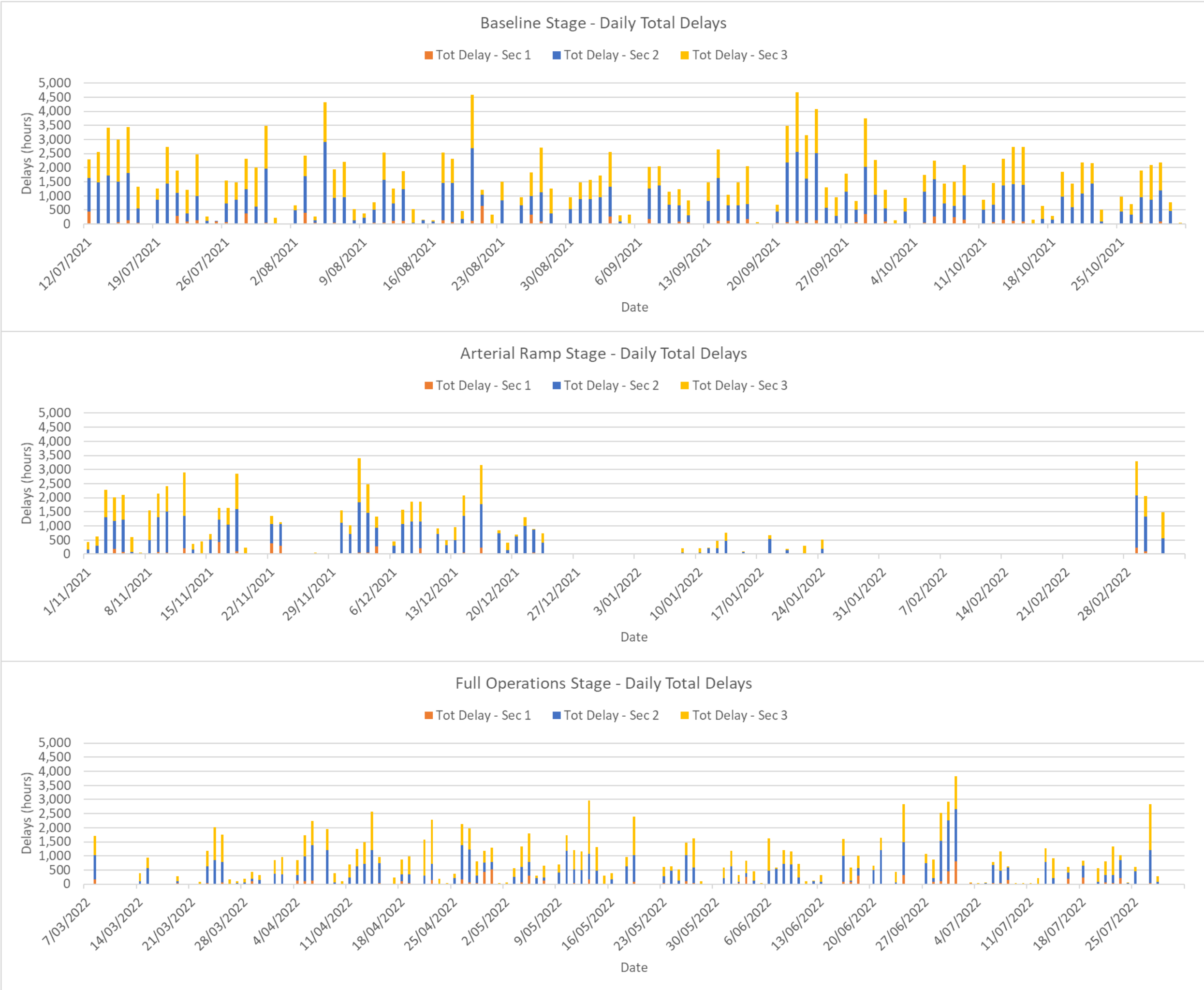


Figure 16: Histograms of Daily Total Delays by Section for Project Stages

Table 17 below shows the absolute and proportional changes in delay, compared with the baseline data collection stage. Changes are shown for daily and peak time periods and are also broken down by section.

The results presented in the table below generally shows significant reductions in average daily total delays across both operational periods. Most reductions in delays were experience in the central and northern sections of the pilot corridor.

It is noted that some increased delays were measured in the southern section (Section 1) of the pilot corridor. It is important to note that the proportional change figures shown in these cases are compared to a low baseline delay and so the absolute change is more relevant for consideration. Factors that have potentially contributed to the increased delays in Section 1 are:

- Increased flows in the southern section of the corridor, concentrated in Section 1 (refer to further sections that discuss the changes in flows in the pilot sections).
- Insufficient storage in the Ridgegate Parkway entry ramp, limiting the amount of flow that can be restrained during the height of the AM peak period.
- Extended periods of time that the Lincoln Direct Ramp was required to operate in a fixed time operating state due to ramp detector faults, allowing more traffic into the downstream bottleneck area than desirable.

Table 17: Average Daily Total Delay – Comparison Across Project Stages by Period and Section

Section	Baseline	Arterial Ramps Only			Full Operations		
	Daily Tot Del	Daily Tot Del	Change from Baseline		Daily Tot Del	Change from Baseline	
All Day							
All Sections	*1,958*	*1,462*	*-495*	*-25.3%*	*1,131*	*-827*	*-42.2%*
Section 1	86	81	-6	-6.4%	70	-16	-18.9%
Section 2	997	817	-180	-18.1%	521	-476	-47.8%
Section 3	874	573	-301	-34.5%	549	-325	-37.2%
AM Peak							
All Sections	*424*	*305*	*-119*	*-28.1%*	*401*	*-23*	*-5.3%*
Section 1	25	27	1	5.4%	26	1	3.0%
Section 2	203	153	-50	-24.5%	172	-31	-15.2%
Section 3	231	180	-51	-21.9%	235	4	1.6%
PM Peak							
All Sections	*1,374*	*1,112*	*-262*	*-19.1%*	*713*	*-661*	*-48.1%*
Section 1	75	73	-2	-2.7%	69	-6	-7.4%
Section 2	772	695	-77	-10.0%	415	-357	-46.2%
Section 3	530	355	-175	-33.0%	248	-282	-53.2%

7.4 Maximum Sustainable Flow Changes

VicRoads / Victorian Department of Transport adopted the approach of developing flow breakdown risk distribution curves to understand the performance at recurrent bottleneck locations and provide a consistent and statistically sound method for measuring and comparing operational capacities. The background and methodologies for this process are outlined in the Managed Motorway Design Guide, Volume 1, Part 3, Motorway Capacity Guide (VicRoads, 2019).

As outlined in Section 6.2.8, MSFR is based on derivation of the 1% probability of flow breakdown (15 minute) at bottleneck locations.

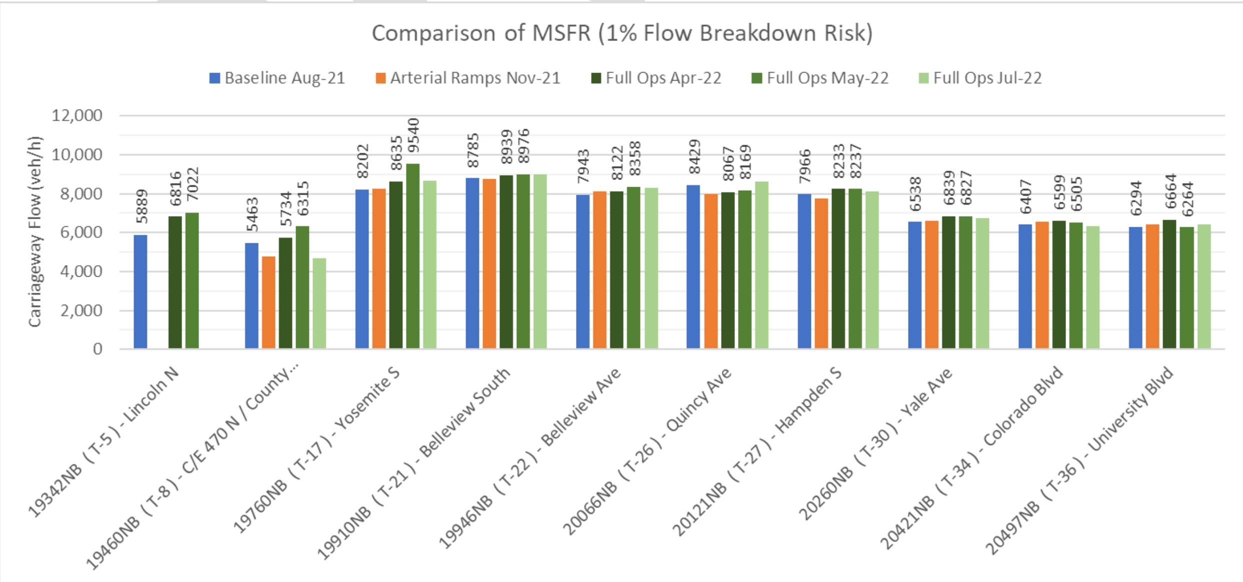


Figure 17: Comparison of MSFR at recurrent bottleneck sites across project stages

The figure above shows a comparison of MSFR at a number of selected locations that are in the proximity of recurrent bottlenecks in the pilot section (measured at the nearest vehicle detection location). It can be seen in the figure that across most of the recurrent bottleneck sites there has been an increase in the MSFR. It is also evident from the locations shown that a greater change was able to be achieved where there was less impact downstream queuing impacts. Where downstream queue impacts were observed (I-225 and the northern end of the pilot section), changes were more limited although increases were still observed. It is also noted that general demand levels and flows restricted by upstream bottlenecks can limit how much the MSFR can increase.

The two figures below show the flow breakdown risk curves derived for two locations. These curves demonstrate a notable shift to the right, indicating that higher flows are achieved and can be sustained prior to flow breakdown occurring. Generally, the green curves (Full Operations) shift to the right of the blue and orange curves (Baseline and Arterial Ramps Only) particularly at the low Probability of Flow Breakdown ranges. Further plots for these and additional sites are provided in Appendix F.

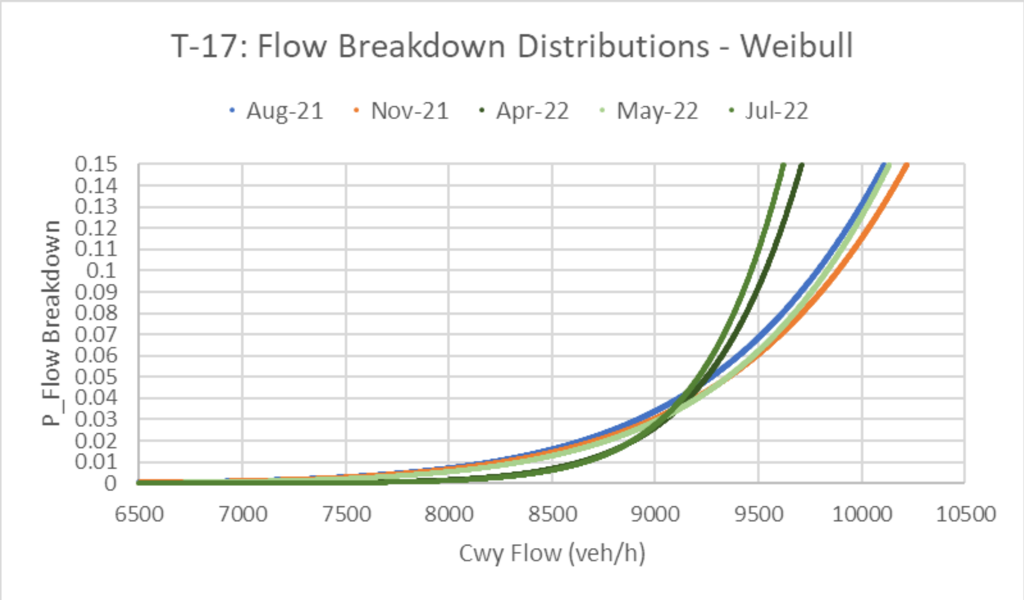


Figure 18: Comparison of Flow Breakdown Distributions for Site T-17 (Arapahoe to Orchard)

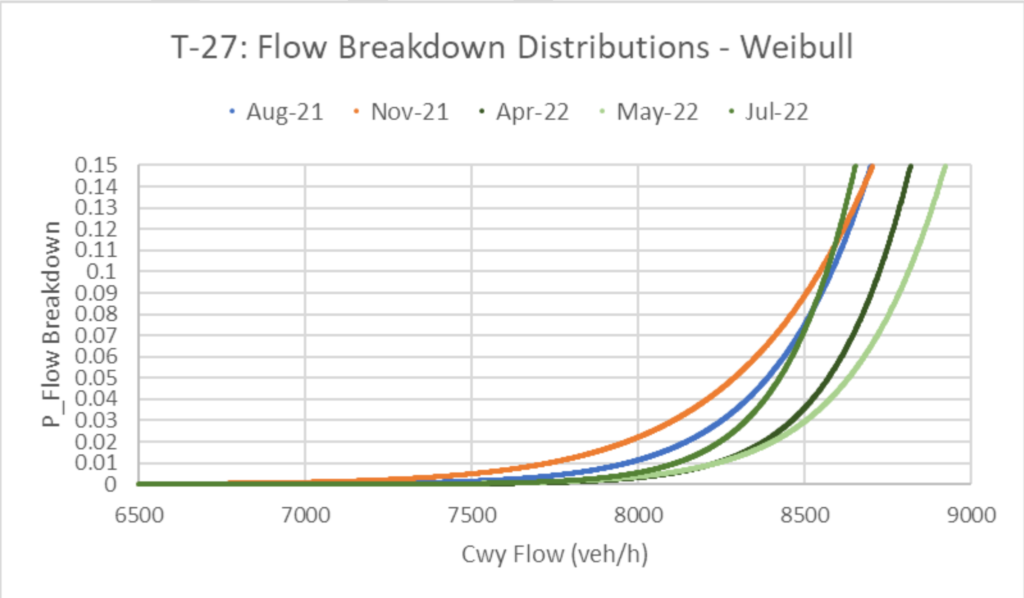


Figure 19: Comparison of Flow Breakdown Distributions for Site T-27 (I-225 to Hampden)

7.5 Bottleneck Productivity, Speed and Flow – Profiles and Distributions

In freeway traffic flow, higher operating speeds are typically possible when demand is below capacity and lower speeds are typically experienced when congestion and flow breakdown occur. Lower flows can be experienced due to lower demands; however, lower flows can also be a result of the freeway flows exceeding capacity and transitioning to a forced flow, or flow breakdown state. Under forced flow conditions lower speeds and lower flows are experienced. Assessing speed and flow in isolation can limit the full understanding of operational performance due to the impacts of demands in the corridor. In order to assess the combination of both speed and flow, Productivity, which is the mathematical product of speed and flow can be calculated and assessed. Per lane flows are used to calculate per lane productivity.

In this section, speed, flow and productivity are presented in two ways.

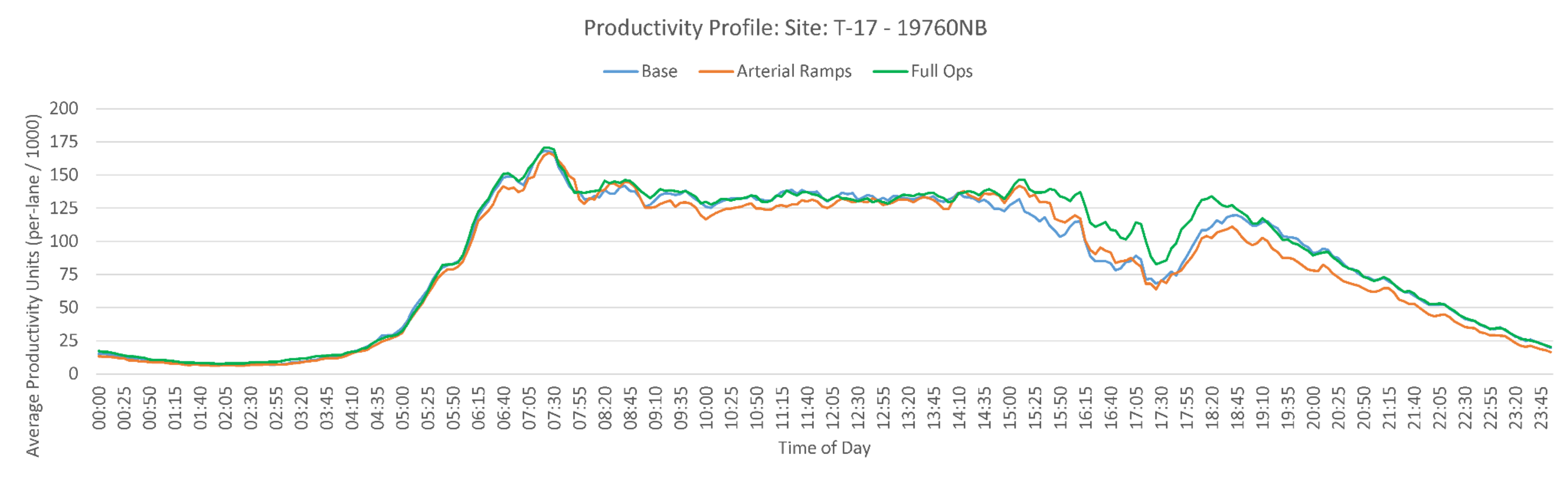
- Profiles of averages by time of day (5 minute intervals) of each measure comparing the three project stages
  - Averages are based on the weekday measures from the same time of day across the relevant project stage.
  - Improved performance can generally be interpreted as the daily profiles being higher than the baseline for speed and productivity. This can be the case for flow as well, however, flows that are too high can be detrimental to performance through capacity exceedance – therefore careful interpretation of high flows is required.
- Proportional Frequency Distributions of the three measures comparing the three stages
  - This form of analysis determines the number (count) of 5min periods where measures were within bins (fixed ranges). To enable comparison across project stages of different lengths (with different amounts of reportable days and 5 minute periods), the counts are converted to proportions of the total counted periods across the frequency bins.
  - Improved performance is generally indicated by a shift of an increasing frequency of values in higher ranges – shift to the right in the distribution plots, especially for both speed and productivity. This is preferred for flows as a well, although appropriate interpretation is required as excessively high flows are not necessarily indicative of improvement.

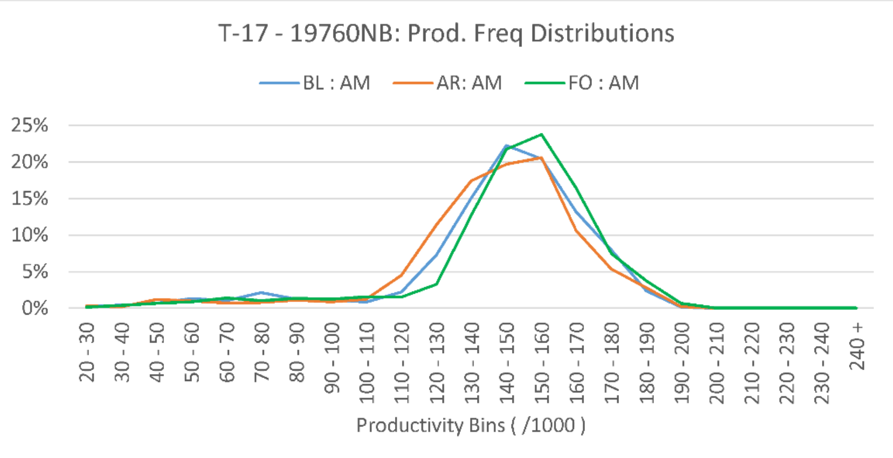
The measures described are provided for key bottleneck locations along the corridor. Identified exclusions (days and relevant peak periods) apply to the measures presented in this section of the report.

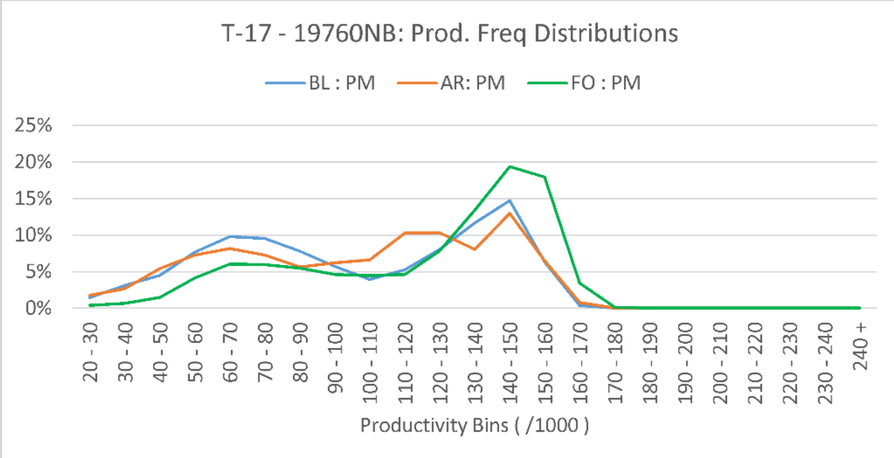
The two figure sequences provided below show profiles and distributions for productivity, speed and flow. The sequence of figures shows the measures from Sites T-17 and T-26, located north of Arapahoe Road and I-225 entry ramps respectively. Plots for other key bottleneck locations are provided in Appendix G.

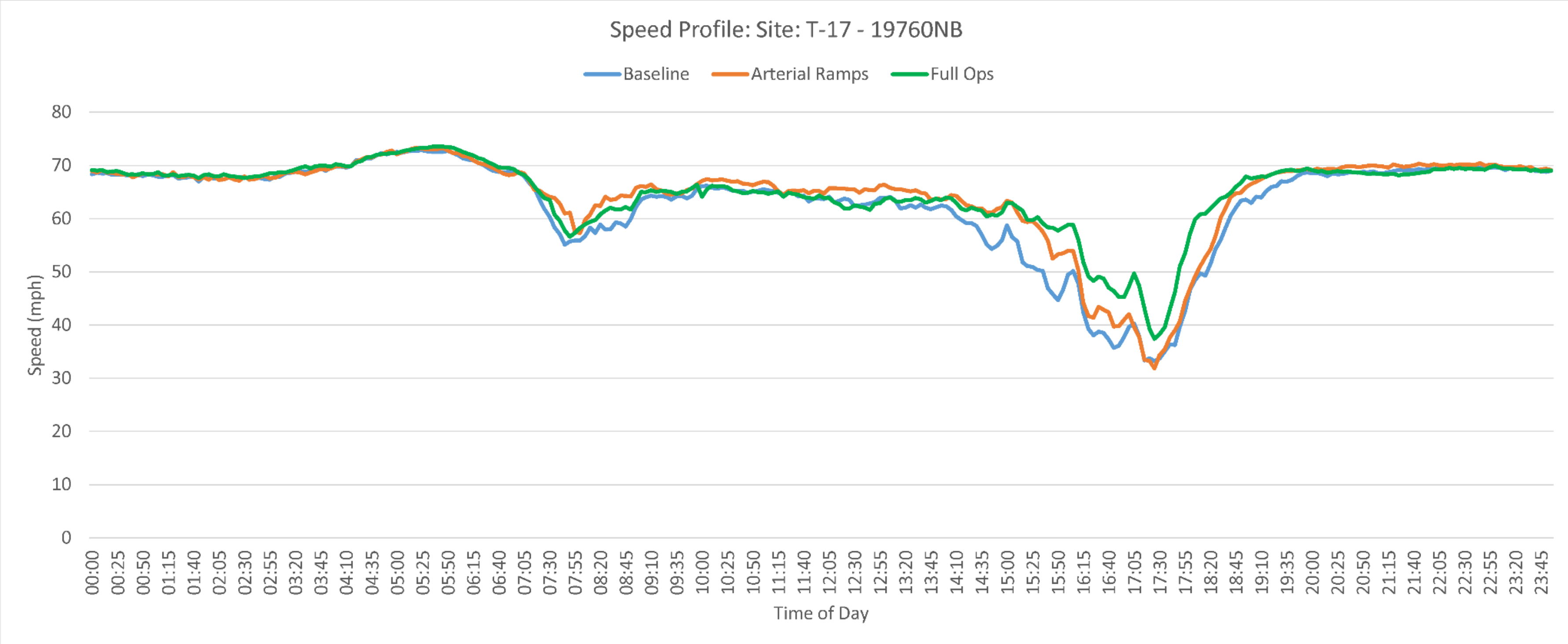
The figure sequence below for Site T-17 – north of the Arapahoe Road direct entry ramp – shows an improvement in operating conditions, evident in both the profiles and frequency distributions, for productivity and both the contributing speed and flow components. Although the daily profile shows similar productivity outcomes during the AM peak, the corresponding AM peak frequency distribution for the full operations stage shows a small shift to the right and minor increase. The PM peak improvement is more substantial with a distinct lift in the profile and a significant rightward shift and rise in higher values in the frequency distribution. The positive component shifts are also evident in both speed and flow figures, although the improvement in speed is more dominant, although the ability to hold flows higher during the latter part of the PM peak (16:00 onwards) is noted.

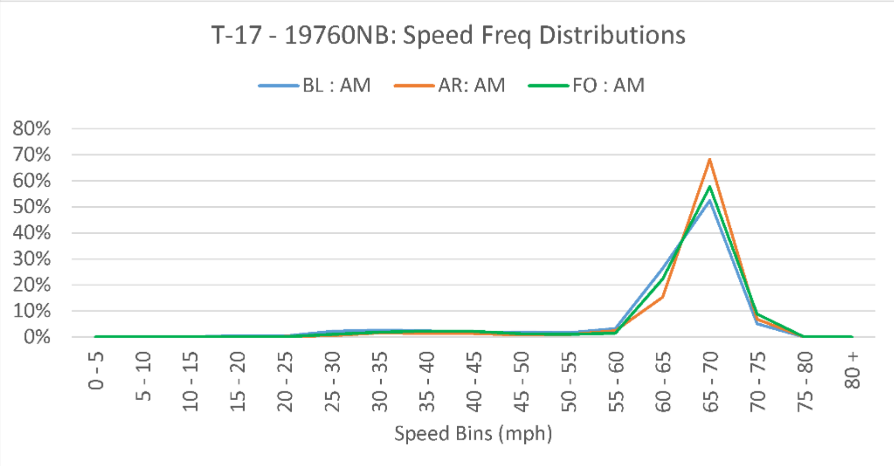
The figure sequence below for Site T-26 – north of the I-225 system entry ramp – also shows an improvement in operating conditions, evident in both the profiles and frequency distributions, for productivity. At this site the speed component improvement is more dominant, and changes are more distinct in the PM peak. Comparing the flow between the baseline and full operations stages, conditions are fairly similar. It's worth noting that the flow profiles across the project stages at this site potentially indicate that there was not a significant flow loss at this bottleneck location and so the main gains to be achieved were more likely to be speed improvements.

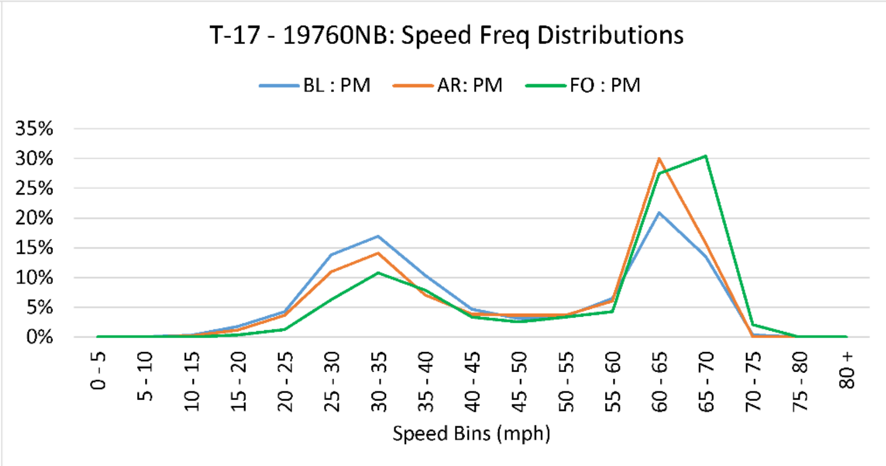

Productivity Profile: Site: T-17 - 19760NB
Base
Arterial Ramps
Full Ops
Average Productivity Units (per-lane / 1000)
200
175
150
125
100
75
50
25
0
Time of Day


T-17 - 19760NB: Prod. Freq Distributions
BL : AM
AR: AM
FO : AM
25%
20%
15%
10%
5%
0%
Productivity Bins (/1000)


T-17 - 19760NB: Prod. Freq Distributions
BL : PM
AR: PM
FO : PM
25%
20%
15%
10%
5%
0%
Productivity Bins (/1000)


Speed Profile: Site: T-17 - 19760NB
Baseline
Arterial Ramps
Full Ops
Speed (mph)
80
70
60
50
40
30
20
10
0
Time of Day


T-17 - 19760NB: Speed Freq Distributions
BL : AM
AR: AM
FO : AM
80%
70%
60%
50%
40%
30%
20%
10%
0%
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55
55 - 60
60 - 65
65 - 70
70 - 75
75 - 80
80 +
Speed Bins (mph)


T-17 - 19760NB: Speed Freq Distributions
BL : PM
AR: PM
FO : PM
35%
30%
25%
20%
15%
10%
5%
0%
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55
55 - 60
60 - 65
65 - 70
70 - 75
75 - 80
80 +
Speed Bins (mph)

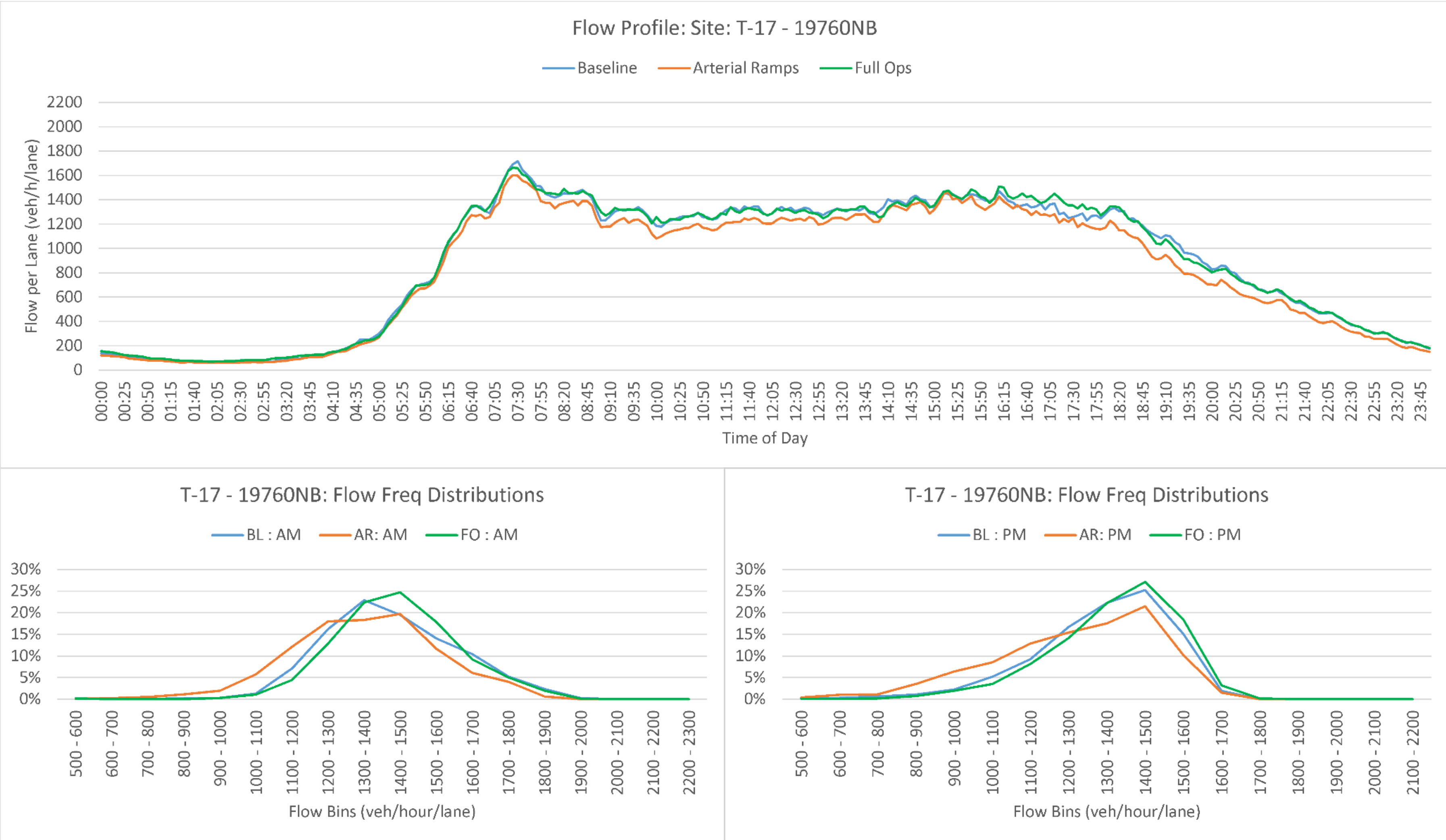
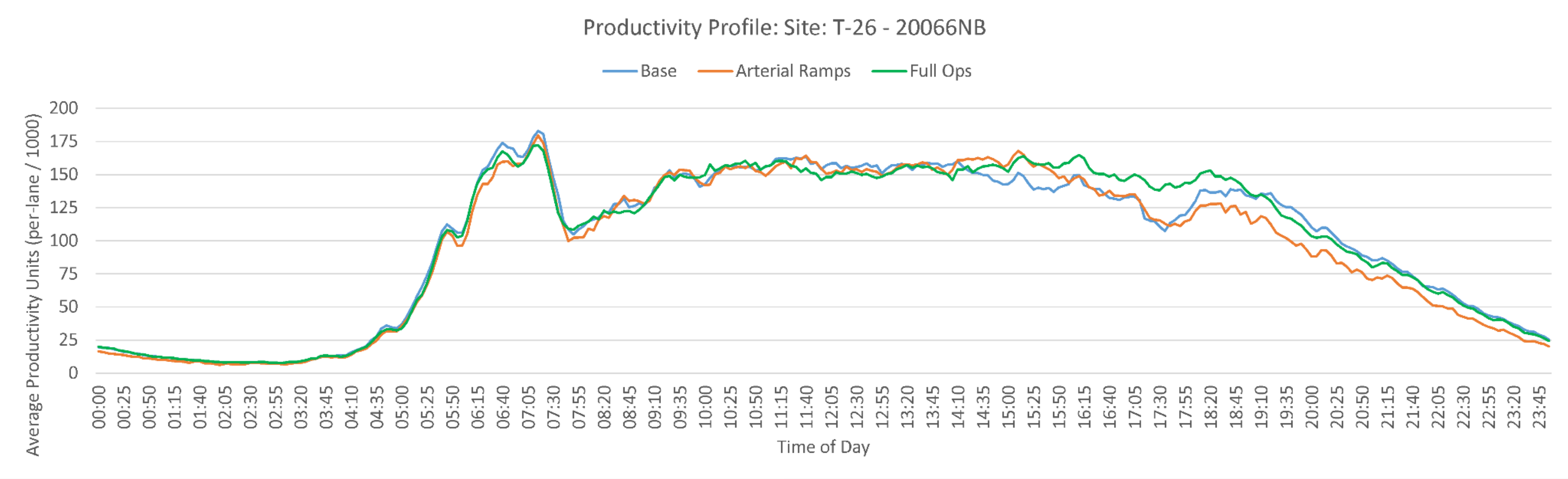
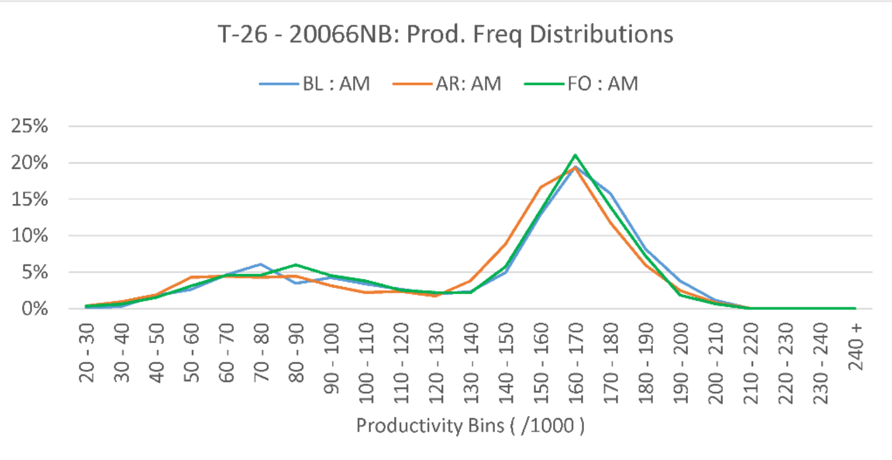
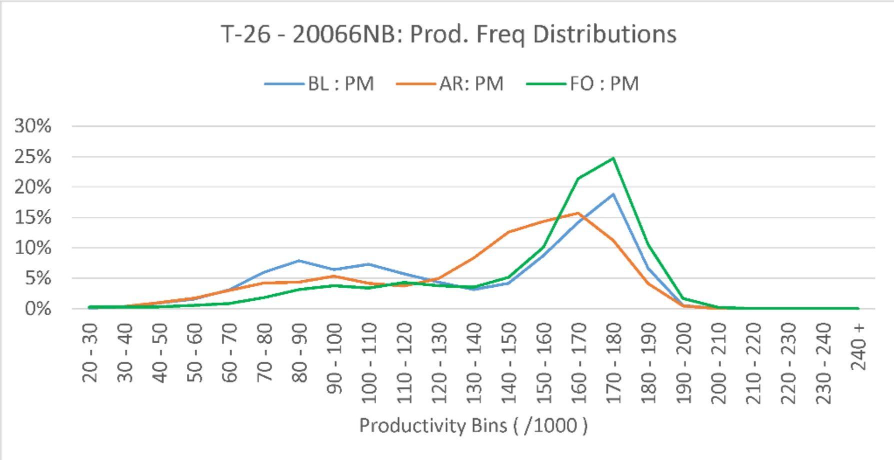
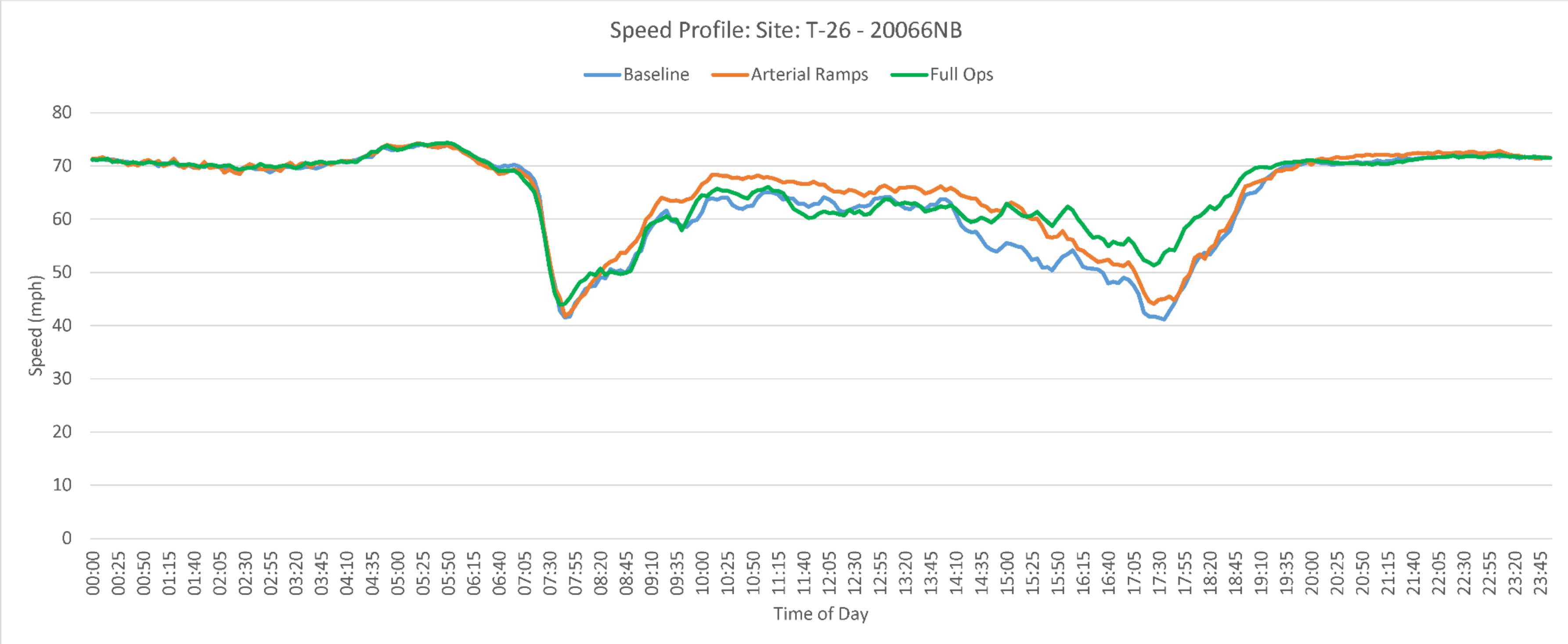


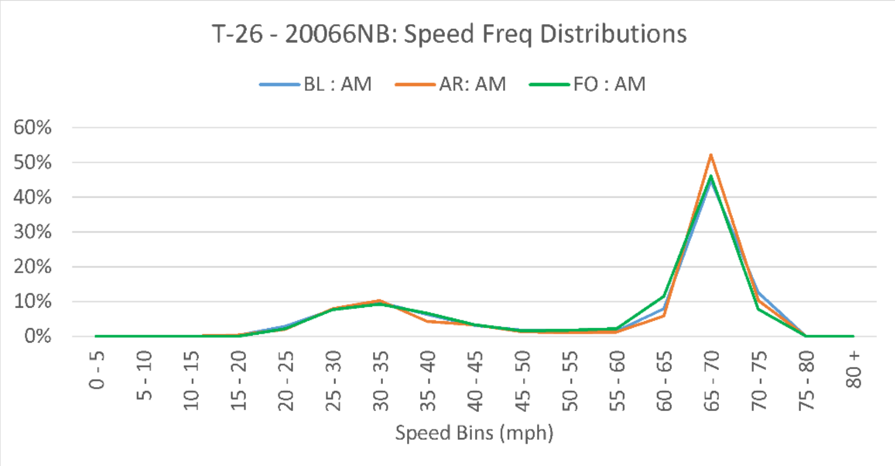
Figure 20: Comparison of Stages Site T-17 – Daily Profiles and Proportional Frequency Distributions for Productivity, Speed and Flow

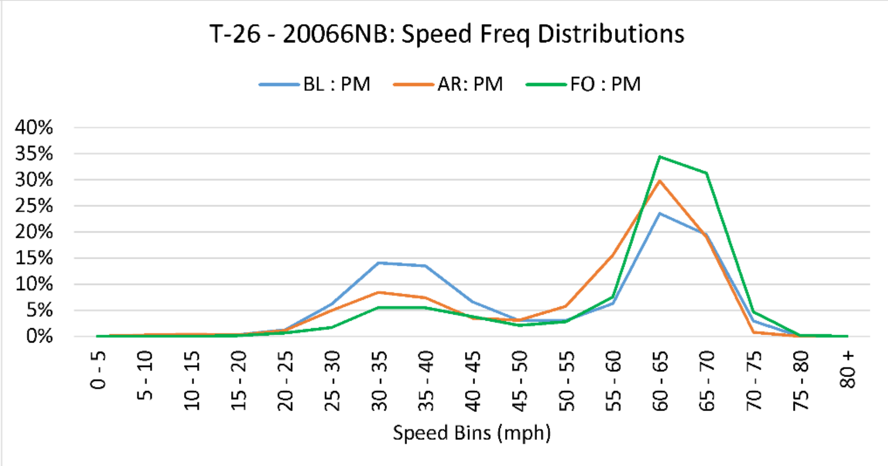

Productivity Profile: Site: T-26 - 20066NB
Base
Arterial Ramps
Full Ops
Average Productivity Units (per-lane / 1000)
Time of Day


T-26 - 20066NB: Prod. Freq Distributions
BL : AM
AR: AM
FO : AM
Productivity Bins (/1000)


T-26 - 20066NB: Prod. Freq Distributions
BL : PM
AR: PM
FO : PM
Productivity Bins (/1000)


Speed Profile: Site: T-26 - 20066NB
Baseline
Arterial Ramps
Full Ops
Speed (mph)
0
10
20
30
40
50
60
70
80
Time of Day
00:00 00:25 00:50 01:15 01:40 02:05 02:30 02:55 03:20 03:45 04:10 04:35 05:00 05:25 05:50 06:15 06:40 07:05 07:30 07:55 08:20 08:45 09:10 09:35 10:00 10:25 10:50 11:15 11:40 12:05 12:30 12:55 13:20 13:45 14:10 14:35 15:00 15:25 15:50 16:15 16:40 17:05 17:30 17:55 18:20 18:45 19:10 19:35 20:00 20:25 20:50 21:15 21:40 22:05 22:30 22:55 23:20 23:45


T-26 - 20066NB: Speed Freq Distributions
BL : AM
AR: AM
FO : AM
0%
10%
20%
30%
40%
50%
60%
Speed Bins (mph)
0 - 5 5 - 10 10 - 15 15 - 20 20 - 25 25 - 30 30 - 35 35 - 40 40 - 45 45 - 50 50 - 55 55 - 60 60 - 65 65 - 70 70 - 75 75 - 80 80 +


T-26 - 20066NB: Speed Freq Distributions
BL : PM
AR: PM
FO : PM
0%
5%
10%
15%
20%
25%
30%
35%
40%
Speed Bins (mph)
0 - 5 5 - 10 10 - 15 15 - 20 20 - 25 25 - 30 30 - 35 35 - 40 40 - 45 45 - 50 50 - 55 55 - 60 60 - 65 65 - 70 70 - 75 75 - 80 80 +

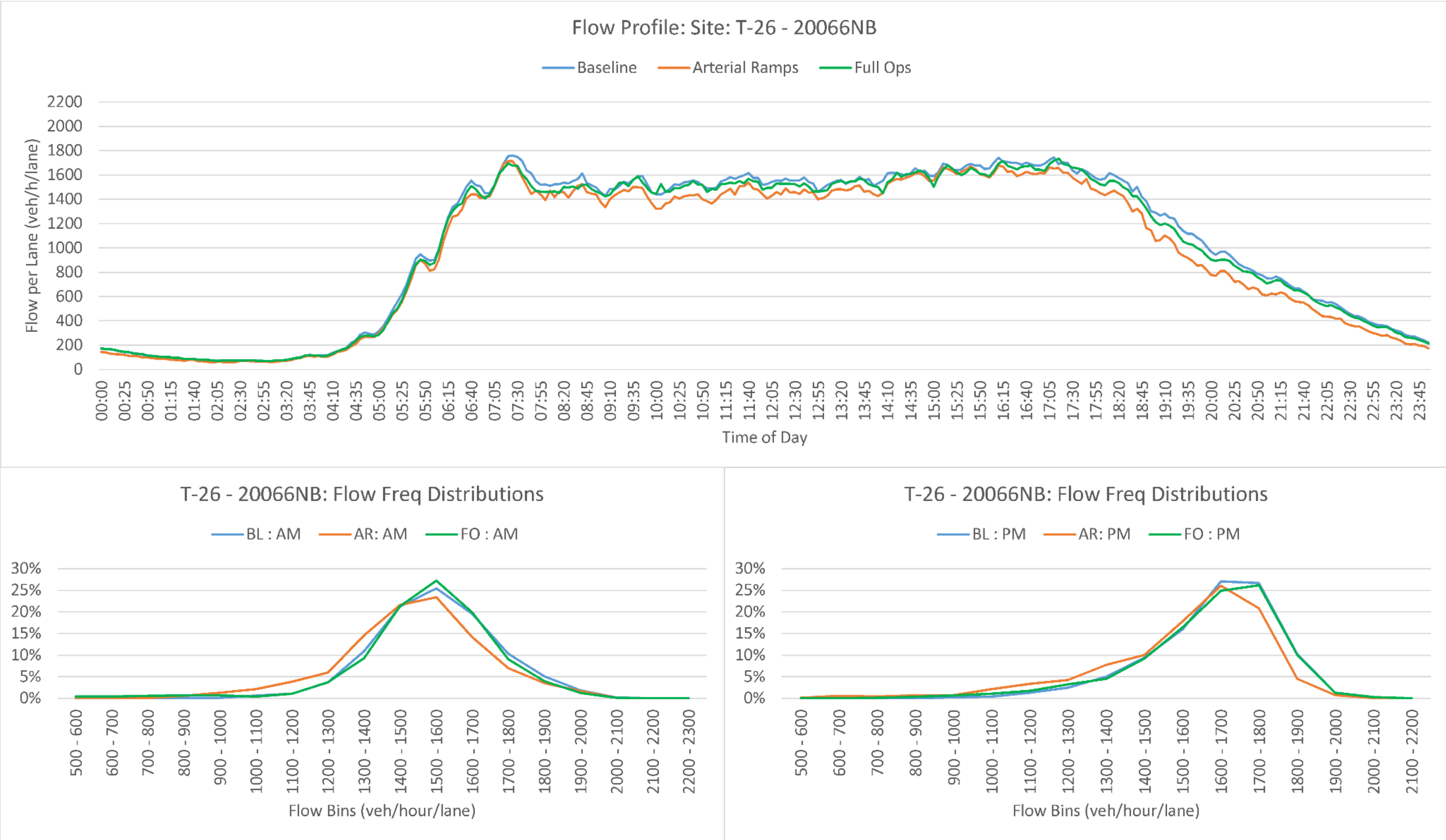


Figure 21: Comparison of Stages Site T-17 – Daily Profiles and Proportional Frequency Distributions for Productivity, Speed and Flow

7.6 Vehicle Miles Travelled (VMT)

Vehicle Miles Travelled (VMT) is a useful measure to understand the utilization of road segments, corridors or networks. VMT is being reported to communicate the scale of travel occurring along the main carriageway in the pilot section of the corridor across the baseline period and also during the operational phases. VMT is calculated at 5-minute intervals then aggregated as appropriate.

Changes in VMT alone are not necessarily an indicator of improvement or decline in performance, but rather can be an indicator of whether there has been a notable change in utilization of the corridor. The causes of change can be varied and may or may not be directly due to changes in operational regimes, however, deeper analysis in due course may indicate whether VMT may have been impacted by operational changes. VMT can be influenced by both overall demand in the corridor and also by the origin and destination patterns that take place over time and changes to these contributors can occur in isolation of operational control.

The average daily VMT (average of all weekdays during the respective stages) is provided in the tables below while the histograms shows the daily total VMT by section. The tables also includes a summary of the proportional split of VMT by section of the pilot corridor. It can be seen that VMT is not completely proportional to the length of each section. The VMT are proportionally higher in Sections 2 (Central) and 3 (Northern), although this to some degree consistent with the number of lanes in these sections and also reflects the higher demands that are likely to enter, exit and proceed through these sections.

Identified exclusions (days and relevant peak periods) do not apply to the measures presented. Including all days is on the basis that although delays may occur in the sections, VMT are more a reflection of demand as opposed delays experienced.

Table 18: Average Daily Vehicle Miles Travelled by Section – Baseline Stage

Section	Average Daily VMT (All Weekdays)	VMT Proportion by Section	Section Length Proportion by Section
All	*1,419,739*		
Section 1	203,277	14%	20%
Section 2	648,897	46%	43%
Section 3	567,566	40%	38%

Table 19: Average Daily Vehicle Miles Travelled by Section – Arterial Ramps Only Stage

Section	Average Daily VMT (All Weekdays)	VMT Proportion by Section	Section Length Proportion by Section
All	*1,315,741*		
Section 1	200,118	15%	20%
Section 2	603,306	46%	43%
Section 3	512,317	39%	38%

Table 20: Average Daily Vehicle Miles Travelled by Section – Full Operations Stage

Section	Average Daily VMT (All Weekdays)	VMT Proportion by Section	Section Length Proportion by Section
All	*1,424,389*		
Section 1	214,728	15%	20%
Section 2	653,525	46%	43%
Section 3	556,136	39%	38%

Table 21: Average Daily Vehicle Miles Travelled – Comparison Across Project Stages by Section

Section	Baseline	Arterial Ramps Only			Full Operations		
	Daily VMT	Daily VMT	Change from Baseline		Daily VMT	Change from Baseline	
All Sections	1,419,739	1,315,741	-103,998	-7.3%	1,424,389	4,650	0.3%
Section 1	203,277	200,118	-3,158	-1.6%	214,728	11,451	5.6%
Section 2	648,897	603,306	-45,590	-7.0%	653,525	4,629	0.7%
Section 3	567,566	512,317	-55,249	-9.7%	556,136	-11,430	-2.0%

Figure 22 shows there was a reasonably consistent trend in the VMT throughout the pilot project stages. A marginally declining trend is evident through the baseline and early arterial ramps only stages. Gaps in the data are a result of poor data during winter snow falls and blocking of detector beams. (To maintain reasonably comparative data, days with partial data were also removed from the figures – these removals differ from the condition based exclusions discussed in other sections.) During the full operations stage, VMT returns to levels similar to the start of the baseline period, indicating similar levels of utilization and helps to validate comparisons of other measures.

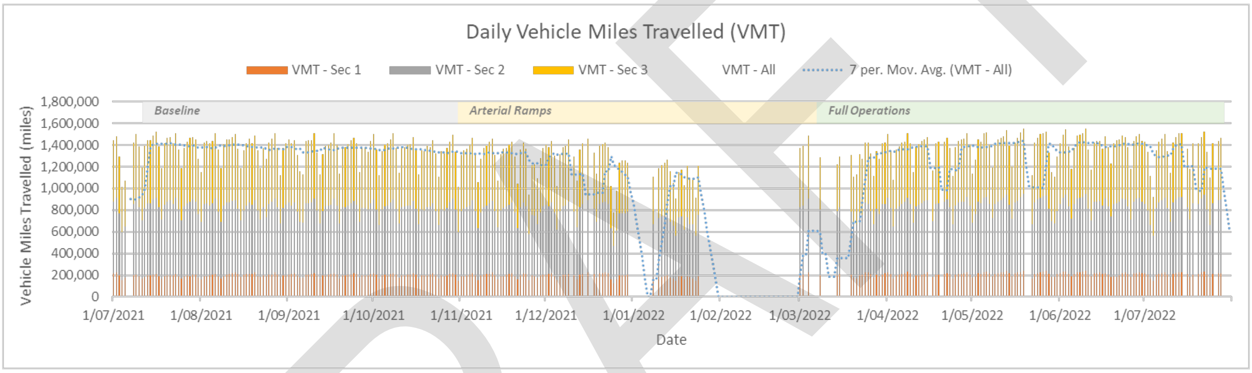


Figure 22: Histogram of Daily Vehicle Miles Travelled by Section for All Project Stages

7.7 Vehicle Hours Travelled

Vehicle Hours Travelled (VHT) is a measure of time spent by all vehicles utilizing the mainline freeway of the pilot section. The calculated VHT has not been capped using the free-flow speed so as to reflect the actual total time spent by vehicles in the corridor and ensure that the impacts of operations in the subsequent phases of the project can be fully reflected by the overall VHT changes, not just the differences in congested conditions. VHT are calculated at 5-minute intervals then aggregated as appropriate.

The average VHT (average of all weekdays during the respective stages) is provided in the tables below while the histogram shows the daily VHT by section. The table also includes a summary of the proportional split of VHT by section of the pilot corridor. The VHT are proportionally higher in Sections 2 (Central) and 3 (Northern), although this to some degree consistent with the number of lanes in these sections and also reflects the higher demands that are likely to enter, exit and proceed through these sections, although is it noted that the total delays outlined above are proportionally different to the VHT indicating that excess delays are more concentrated.

Identified exclusions (days and relevant peak periods) apply to the measures presented since excessive delays caused by incidents and other events can substantially skew the calculated averages.

Table 22: Average Daily Vehicle Hours Travelled by Section – Baseline Stage

Section	*Average Daily VHT*	VMT Proportion by Section	Section Length Proportion by Section
VHT - All	*23,749*		
VHT - Sec 1	3,009	13%	20%
VHT - Sec 2	10,905	46%	43%
VHT - Sec 3	9,835	41%	38%

Table 23: Average Daily Vehicle Hours Travelled by Section – Arterial Ramps Only Stage

Section	*Average Daily VHT*	VMT Proportion by Section	Section Length Proportion by Section
VHT - All	*21,754*		
VHT - Sec 1	2,978	14%	20%
VHT - Sec 2	10,065	46%	43%
VHT - Sec 3	8,711	40%	38%

Table 24: Average Daily Vehicle Hours Travelled by Section – Full Operations Stage

Section	*Average Daily VHT*	VMT Proportion by Section	Section Length Proportion by Section
VHT - All	*22,504*		
VHT - Sec 1	3,129	14%	20%
VHT - Sec 2	10,268	46%	43%
VHT - Sec 3	9,108	40%	38%

Table 25: Average Daily Vehicle Miles Travelled – Comparison Across Project Stages by Section

Section	Baseline	Arterial Ramps Only			Full Operations		
	Daily VHT	Daily VHT	Change from Baseline		Daily VHT	Change from Baseline	
All Sections	23,749	21,754	-1,995	-8.4%	22,504	-1,245	-5.2%
Section 1	3,009	2,978	-31	-1.0%	3,129	119	4.0%
Section 2	10,905	10,065	-840	-7.7%	10,268	-637	-5.8%
Section 3	9,835	8,711	-1,124	-11.4%	9,108	-727	-7.4%

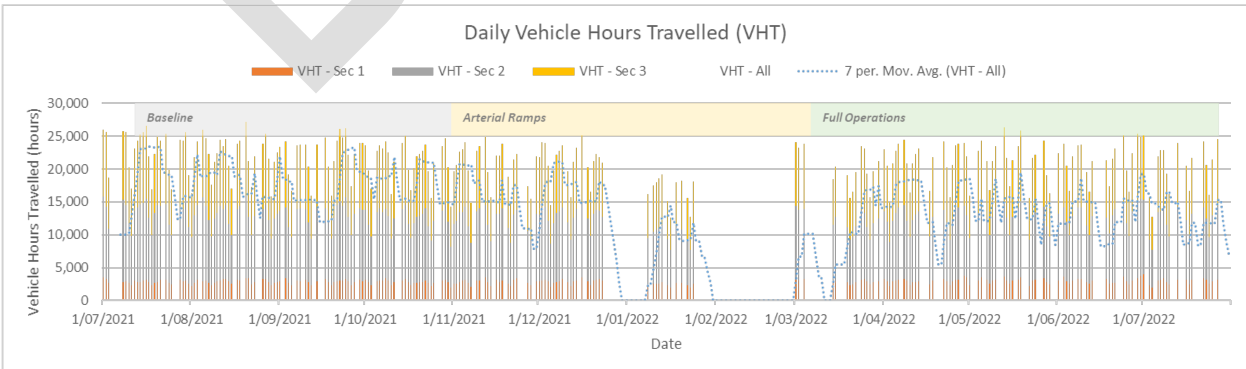


Figure 23: Histogram of Daily Vehicle Hours Travelled by Section for All Project Stages

7.8 Average Speed (Space Mean Speed)

Average Speeds, based on Space Mean Speed (SMS, derived from VMT and VHT), is a speed measure that takes into account the speed over of length of road, not just the measurement at a point. SMS is calculated at 5-minute intervals for all individual measurement sections and also for the groups of sections described within the pilot corridor. Measures provided below are shown for the overall corridor and also for the three smaller sections.

As speeds can vary across the day due to varying conditions, measures are reported relative to time periods rather across the whole day. This avoids the lengthy periods of the overnight off-peak period skewing the averages too much towards higher speeds.

It is noted that the average SMS in the tables below are relatively high, even during the peak periods when lower speeds would be experienced by individual road users. Since the aggregation process combines speeds from all road segments and 5-minute time periods, it is usually the case that high speeds can prevail in road segments within a section of the corridor, even when specific locations experience congestion and conditions significantly slower that free-flow conditions.

Identified exclusions (days and relevant peak periods) apply to the measures presented.

Table 26: Average Speed (mph) by Section, Stage and Peak Period

Section	AM Peak		High Off-Peak		PM Peak	
Baseline						
All	*62.4*		*64.1*		*52.7*	
Sec 1	69.5		70.5		64.9	
Sec 2	64.3		65.4		51.7	
Sec 3	58.8		61.4		52.2	
Arterial Ramps Only		***Change from Baseline***		***Change from Baseline***		***Change from Baseline***
All	*64.1*	*1.7*	*67.1*	*3.0*	*55.1*	*2.3*
Sec 1	69.9	0.4	71.4	0.9	65.5	0.6
Sec 2	66.4	2.1	67.9	2.5	53.4	1.7
Sec 3	60.0	1.3	65.1	3.6	55.1	2.9
Full Operations		***Change from Baseline***		***Change from Baseline***		***Change from Baseline***
All	*63.2*	*0.8*	*65.2*	*1.1*	*59.2*	*6.4*
Sec 1	69.2	-0.3	70.0	-0.5	66.3	1.5
Sec 2	65.4	1.1	66.7	1.3	58.8	7.1
Sec 3	59.2	0.4	62.4	1.0	58.6	6.4

The daily profile plots provided below demonstrate the variability of SMS across the day and also provide a comparison of the various stages of the project and the impact of metering operation on average speeds. Plots are provided for the whole length of the pilot corridor and also by southern, central and northern sections.

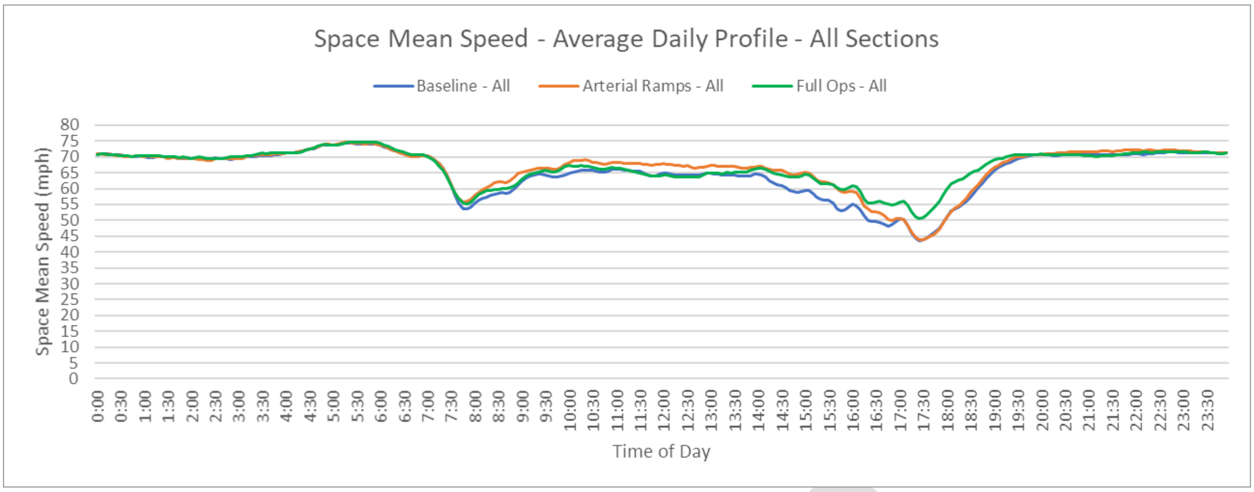


Figure 24: Average Speed Daily Profile (mph) – Full Pilot Length, All Stages

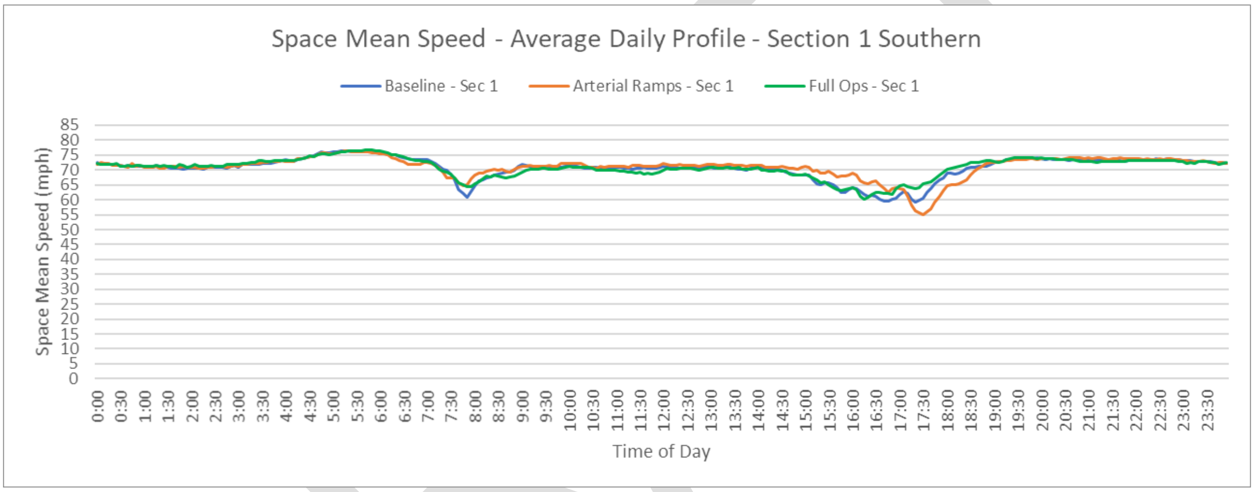


Figure 25: Average Speed Daily Profile (mph) – Section 1 – Southern, All Stages

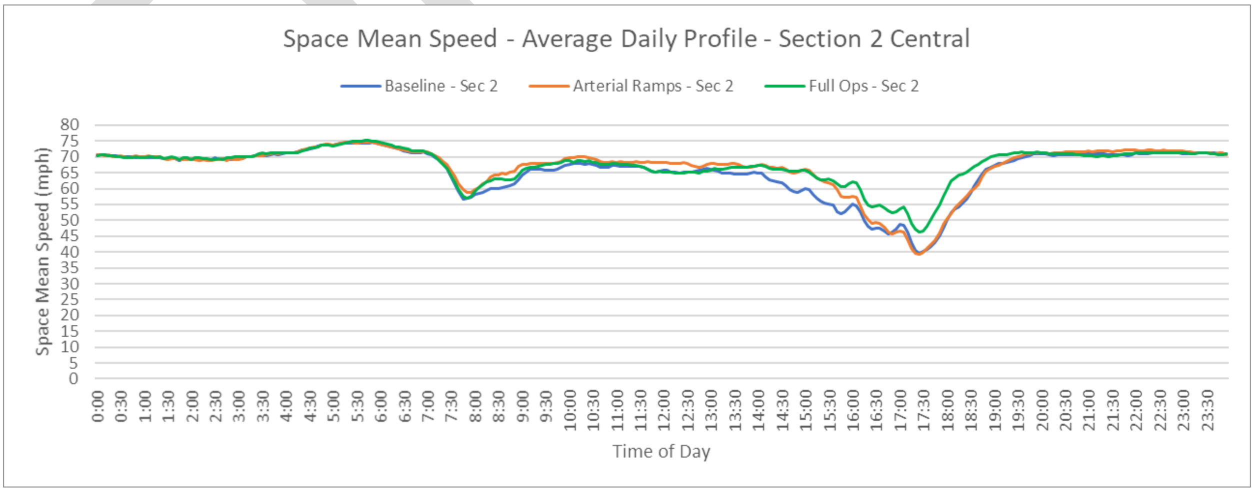


Figure 26: Average Speed Daily Profile (mph) – Section 2 – Central, All Stages

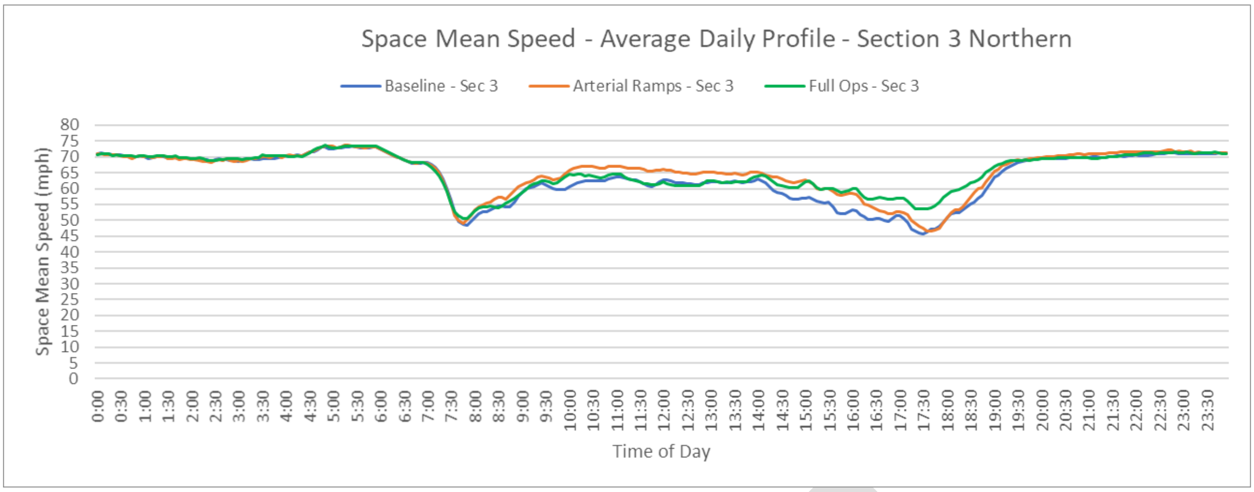


Figure 27: Average Speed Daily Profile (mph) – Section 3 – Northern, All Stages

8 Operating Conditions – Data Collection Period

8.1 Heat Plots

Heat plots, or time-distance diagrams, of traffic measures are useful to understand the time and extent of traffic disruption in motorway carriageways. In the diagrams below, the time of day is represented on the x-axis (from left to right increasing) and the distance along the corridor is shown on the y-axis (from bottom to top in the direction of flow).

When speed measures are displayed on a heat plot, locations of congestion form as darker colours at a location due to reduced speeds. If shockwave (or wide moving jams) start to form, diagonal bands can be observed propagating down and to the right as the slowed condition moves backwards, against the direction of flow. Areas of reduced speed can be used for identifying bottleneck locations where congestion forms, how far queuing and slowed conditions extend upstream of the bottleneck and how long the congestion impacts conditions.

The following figures show a sample of heat plots at various time and aggregation periods that can be useful for understanding conditions in the pilot section of the corridor. A full set of monthly 15-minute resolution and weekly 5-min resolution plots across all project stages is included in Appendix H. Plots for individual days have also been produced at 1-minute resolution and are used within this report as needed to demonstrate relevance to the discussion.

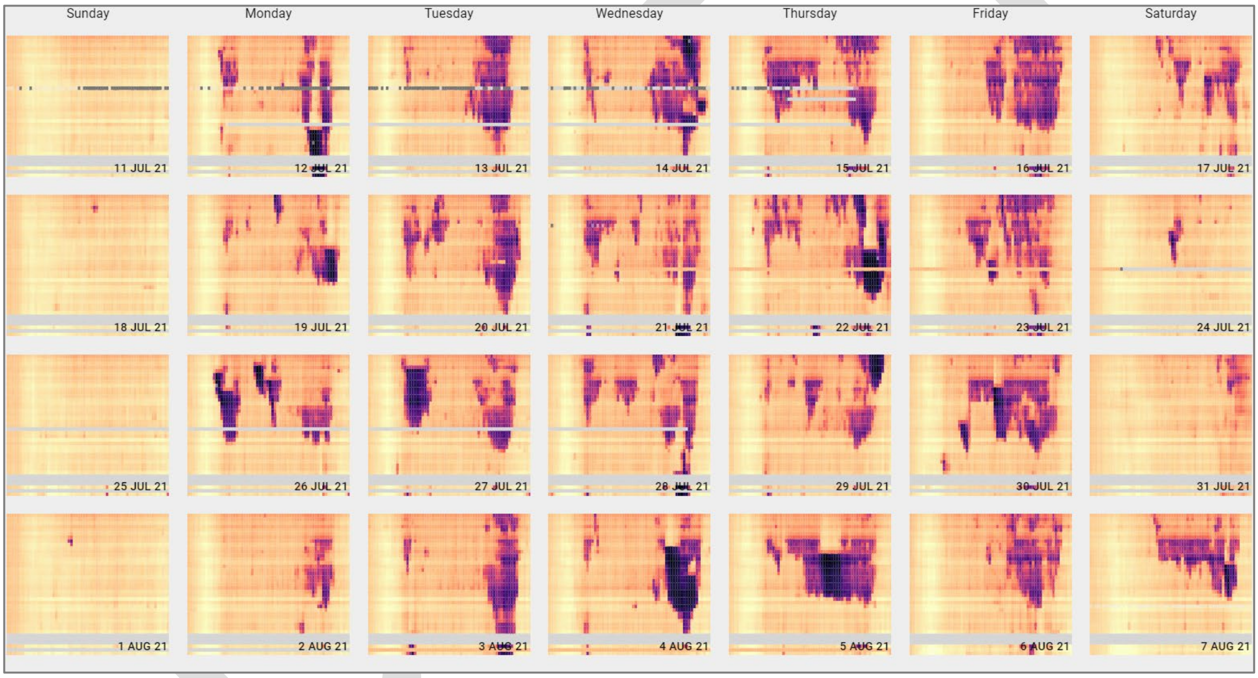


Figure 28: Sample of 4 Weeks of Daily Heat Plots colored by Speed (mph) – 15 Minute Data

8.1.1 Visual Comparison of Project Stages through Heat Plots

An inspection of the Baseline and Full Operations stages can be useful to highlight some high level changes in operating conditions. Since the same color scaling is used across the figures, observing less dark shading is a reasonable indicator of reduced congestion and improved speeds in the pilot corridor section.

Generally, it can be observed that there are less occurrences, and also less severe occurrences of peak period congestion with the darker perk period congestion patches being narrower horizontally (occurring over a shorter time period), shorter vertically (impacting shorter lengths of the freeway) and to some degree lighter in color overall (speeds did not reduce to the same levels as experienced prior).

An observation relevant to the Arterial Ramps Only stage is the impact of data loss (blank lines or solid shading), weather impacts (slower periods indicated by a general darker shading that differs for congestion patterns) and low demand days (days with little speed reduction evident, similar to most Sundays).

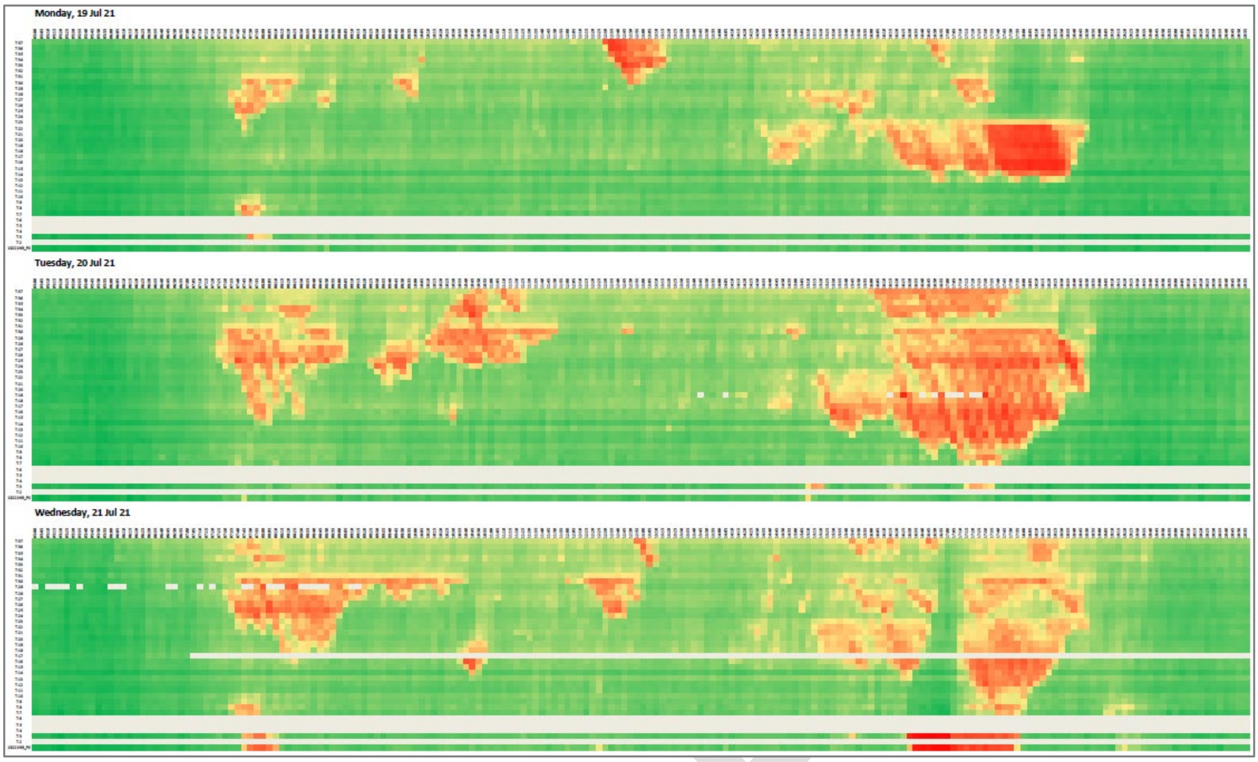


Figure 29: Sample of 3 Days of Heat Plots Colored by Speed (mph) – 5 Minute Data (5AM-9PM)

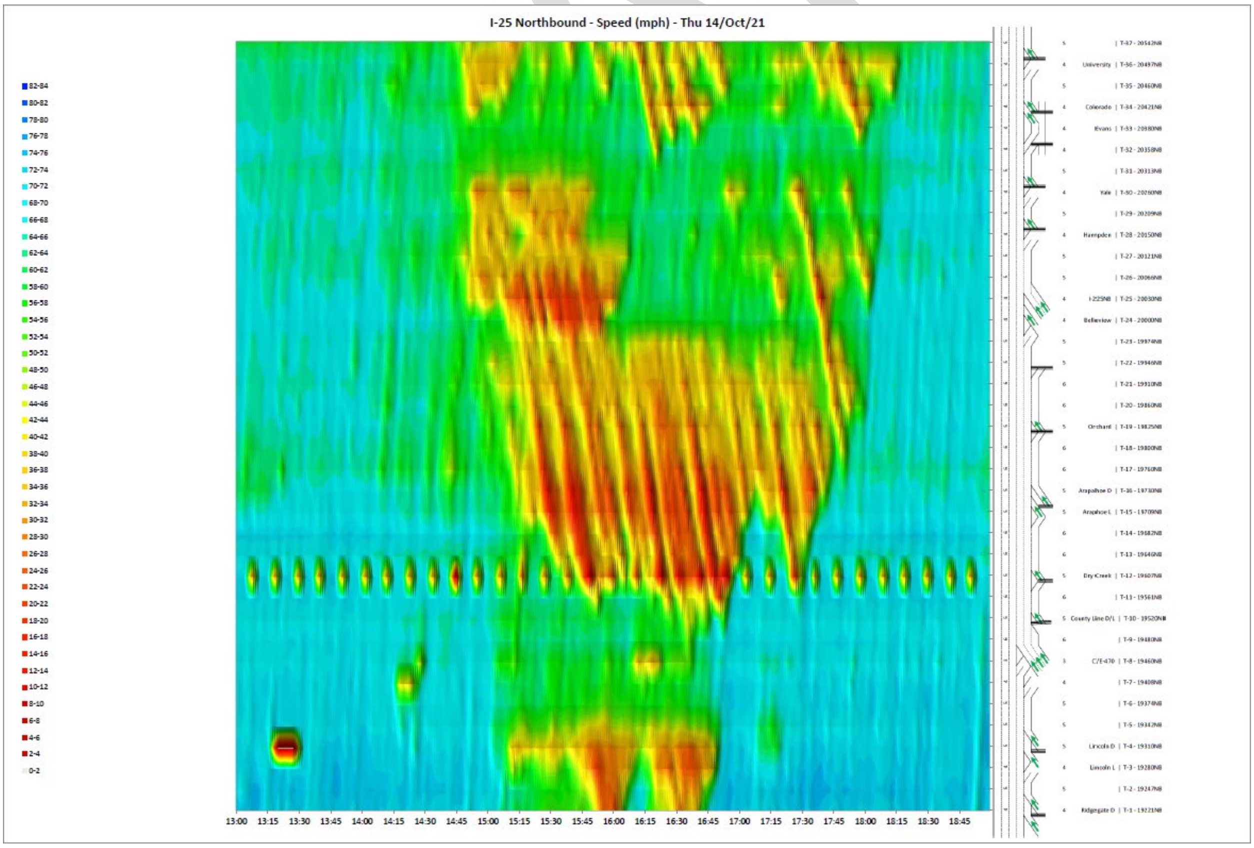


Figure 30: Sample of a 6 Hour Heat Plot Colored by Speed (mph) – 1 minute Data (PM Peak)

8.2 Recurrent Bottlenecks and Causes

Based on a review of the available data and inspection of heat plots across the data collection period, it was evident that there are a number of bottleneck locations where recurrent (or reoccurring) congestion forms and spreads.

The following sites were identified during the Baseline Data Collection period as locations of recurrent flow breakdown:

- **Site T-34 (204.21)** – Merge from Evan/Colorado C-D
    - High left lane density and clustered entering traffic from ramp/collector-distributor entry
- **Site T-30 (202.60)** – near Yale
    - Geometric and demand/capacity imbalance
- **Site T-25/26 (200.30-200.66)** – North of I-225 Entry
    - High volume merge causing turbulence
- **Site T-21/22 (199.10-199.46)** – North of Orchard
    - Exit to I-225 - vehicles aligning with exiting and through lanes as needed
- **Site T-17 (197.60)** – North of Arapahoe
    - Merging and weaving
- **Site T-6/8 (193.74-194.60)** – Lincoln to South approach to E/C-470
    - Merging and weaving for vehicles to align with exiting and through lanes as needed

The heat plots in the figures below shows the locations of the recurrent bottlenecks. A sample from each period is provided to demonstrate there is some consistency in the bottleneck locations across the pilot project stages. In general, the bottleneck locations remain consistent with the baseline period, however, it can be seen – and was observed through the operations stages – that the bottleneck locations "behaved" differently due to the influence of the coordinated ramp metering control.

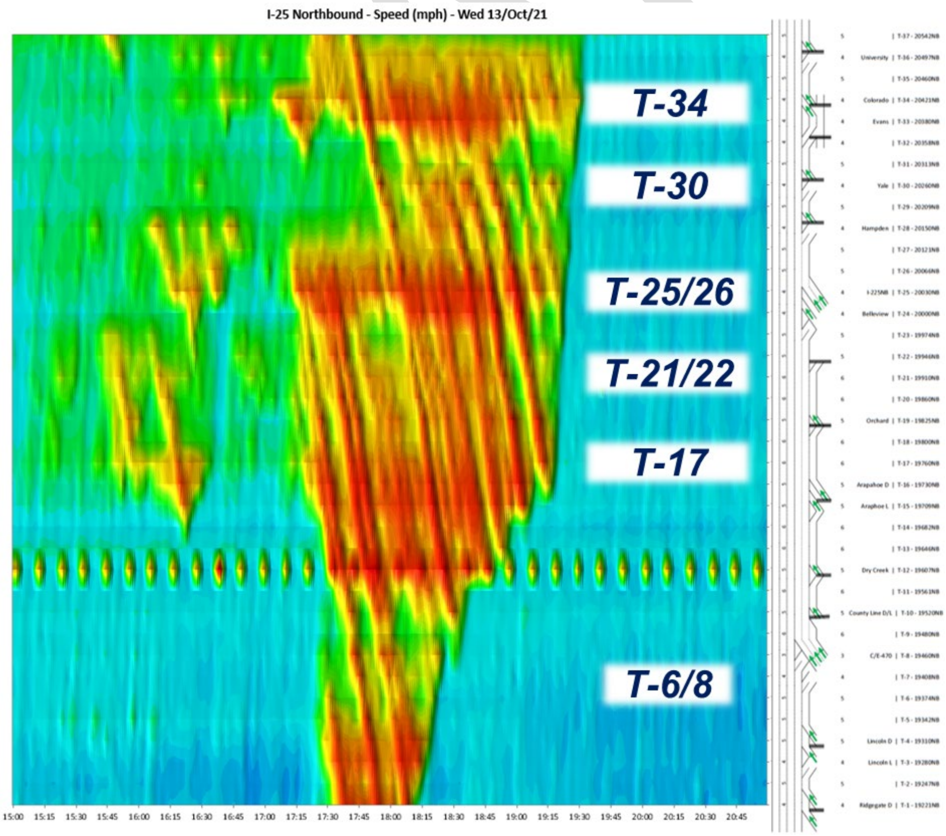


Figure 31: Baseline Stage – Heat Plot indicating recurrent bottleneck locations and congestion

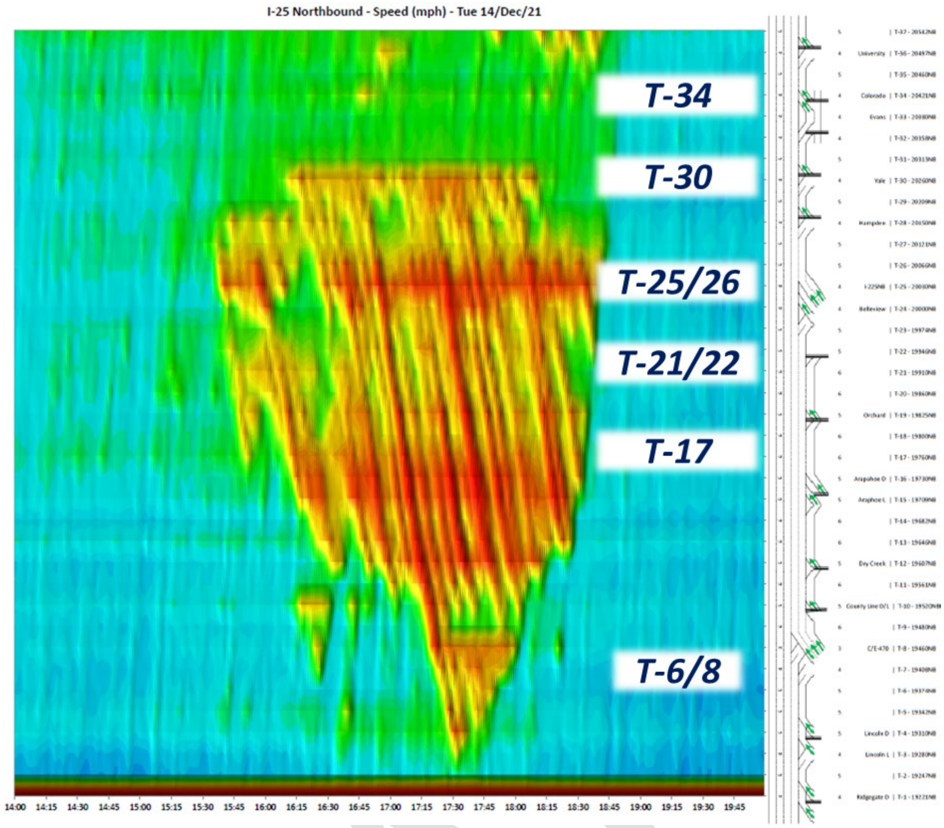


Figure 32: Arterials Ramps Only Stage – Heat Plot indicating recurrent bottleneck locations

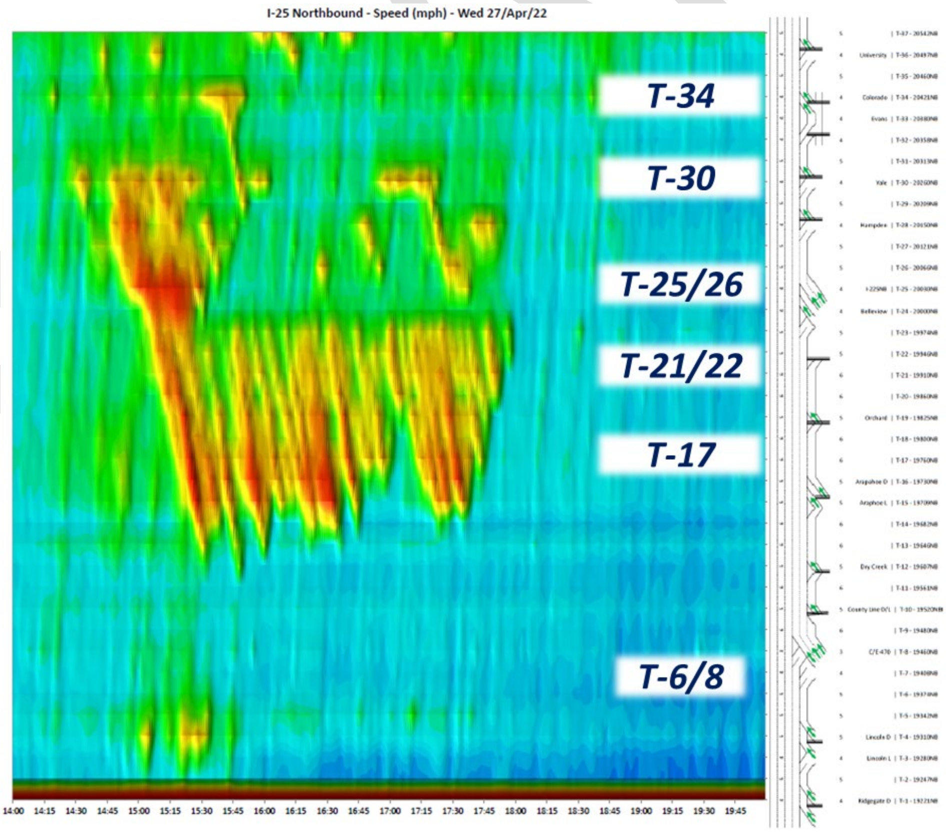


Figure 33: Full Operations Stage – Heat Plot indicating recurrent bottleneck locations

Inspection of the heat plots throughout the operations stages and from observations during operations, it is possible to see the impacts of better managed bottlenecks allowing increased flows to downstream locations during peak periods. This release of previously held back demand creates further pressure on downstream recurrent locations or triggers new bottleneck locations that may not have previously been evident.

The availability and performance of detection and ramp meters along the corridor can also impact how recurrent bottlenecks behave and also influence the emergence of other bottleneck locations.

Through the operations stages of the pilot demonstration, additional minor operational bottlenecks were observed although they were not always present. The following additional locations experienced minor flow breakdown from time to time although impacts were generally localised.

- **Site T-9/10 (194.8-195.2)** – Branch Connection from C/E-470 Ramps
  - High entry demand and weaving of traffic streams downstream of system interchange
  - During periods of effective metering south of the C/E-470 interchange, higher flows were able to progress to this location which also likely contributed to the increased chance for flow breakdown to occur.
- **Site T-4/5 (193.1-193.42)** – Lincoln Avenue Loop and direct Ramp Merges
  - High entering demands from the Lincoln ramps and also from the upstream Ridgegate ramp results in significant entering demand around Lincoln Avenue
  - For an extended period within the operations stages, the Lincoln Direct entry ramp had ramp detector faults that prevent adaptive operations. Fixed time metering was used, however, without the ability effectively manage ramp queues, higher than desired flows were able to enter resulting in inefficient management of the Lincoln entry ramp merge locations which triggered flow breakdown.

8.3 Mainline Flows

The following plots show the mainline total flows and also per lane flows at each detector location along the pilot section. The calculated flows are based on all weekdays within the Full Operations stage. (Plots for Baseline flows are provided in the *Baseline Performance Report*.) Mainline flows of this nature are calculated to understand where high flows occur in the corridor. Changes in flows are best shown at the individual site level or in a times series for a site. Changes in section flows can indicate changing utilisation and demand patterns but can also be impacted by upstream and downstream bottleneck and congestion patterns so direct comparison, especially within peak periods needs to be done with caution.

The mainline flows shown in the following plots should not be interpreted as being representive of capacity as they are purely statisical measures from the measured data. The process for determining meaningful capacity at bottleneck locations is based on undertaking an appropriate flow breakdown risk analysis and comparison of Maximum Sustainable Flow Rates (MSFR).

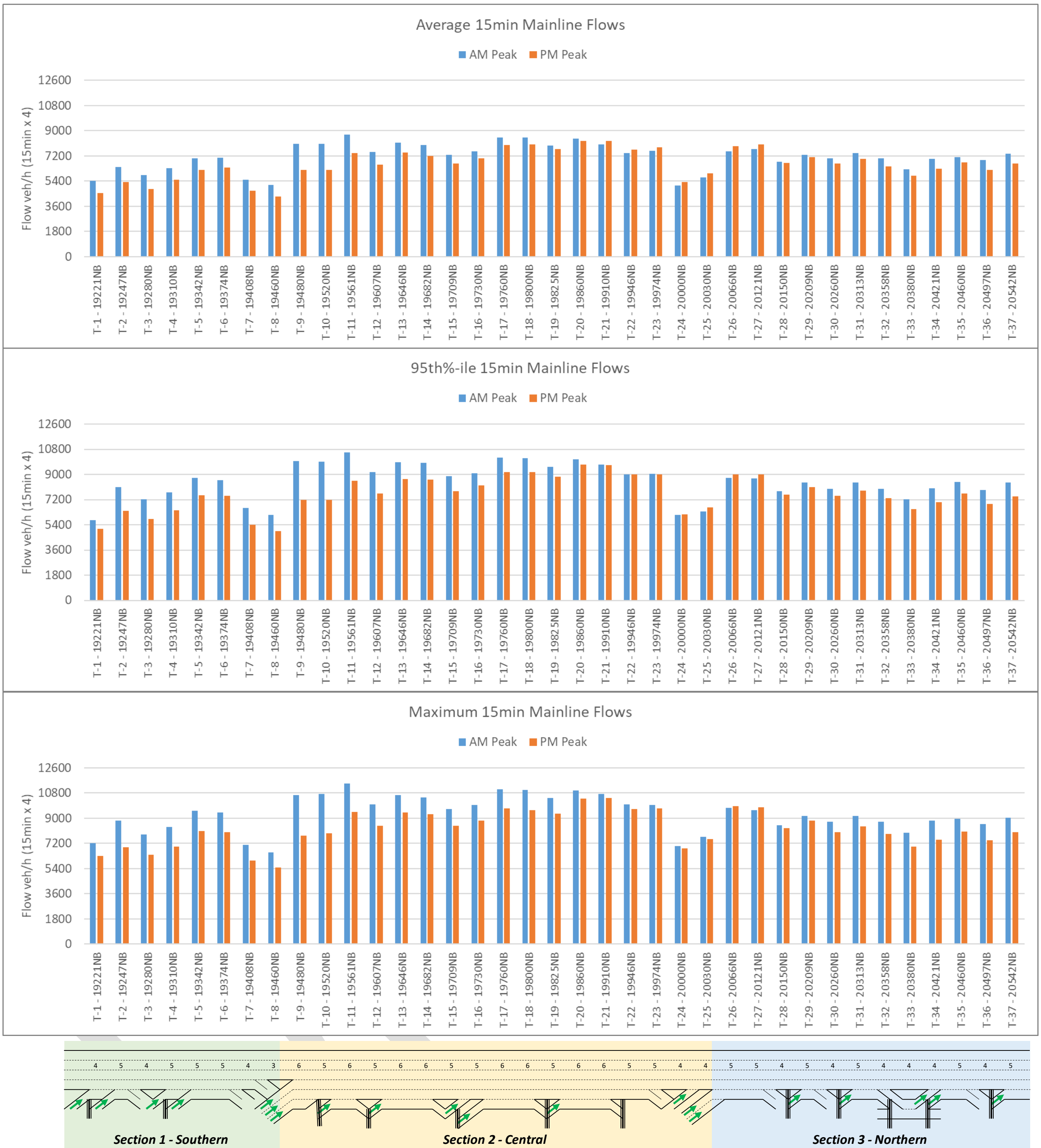


Figure 34: Histograms of Mainline Total Carriageway Flows by Detector – Peak Period Averages, 95th Percentiles and Maximums (Full Operations Stage)

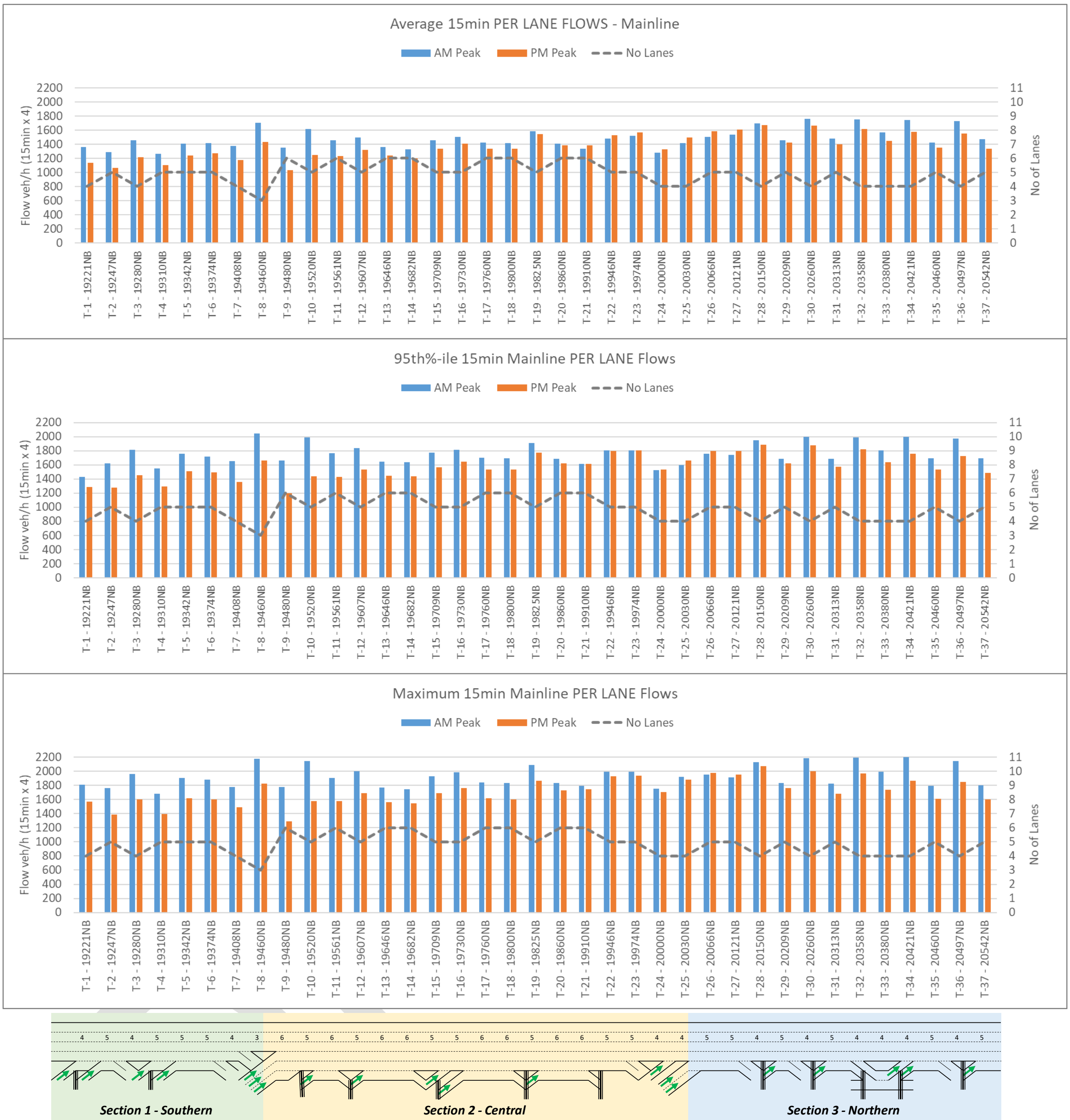


Figure 35: Histograms of Mainline per lane Flows by Detector – Peak Period Averages, 95th Percentiles and Maximums (Full Operations Stage)

8.3.1 Changes in Mainline Flows

The following figures compare the 95th percentile and average carriageway volumes during the Full Operations stage with the Baseline stage. When interpreting the data, readers should be aware that various detection faults or data anomalies can influence the aggregations presented in these figures.

A known detector configuration error (highlighted in the figures) at Sites T-4 and T-5 shows a significant change in measured volumes. This was primarily due to a configuration error of one lane being omitted from the carriageway detector site during the data collection phase. This configuration error was corrected around the start of the arterial ramp only operations stage. It is also known that Site T-1 experienced intermittent communication issues throughout the project resulting in likely undercounting in some periods and potentially anomalous changes.

Aside from data anomalies, the changes in flows can be influenced by a range of different factors through the pilot project period, including but not limited to:

- Road network demand and related external factors including work from home restrictions,
- Seasonal changes,
- The daily conditions in the corridor (congestion etc.),
- Changes in travel by time of day,
- Weather events, or
- Incidents and events both on the corridor and the broader surrounding road network.

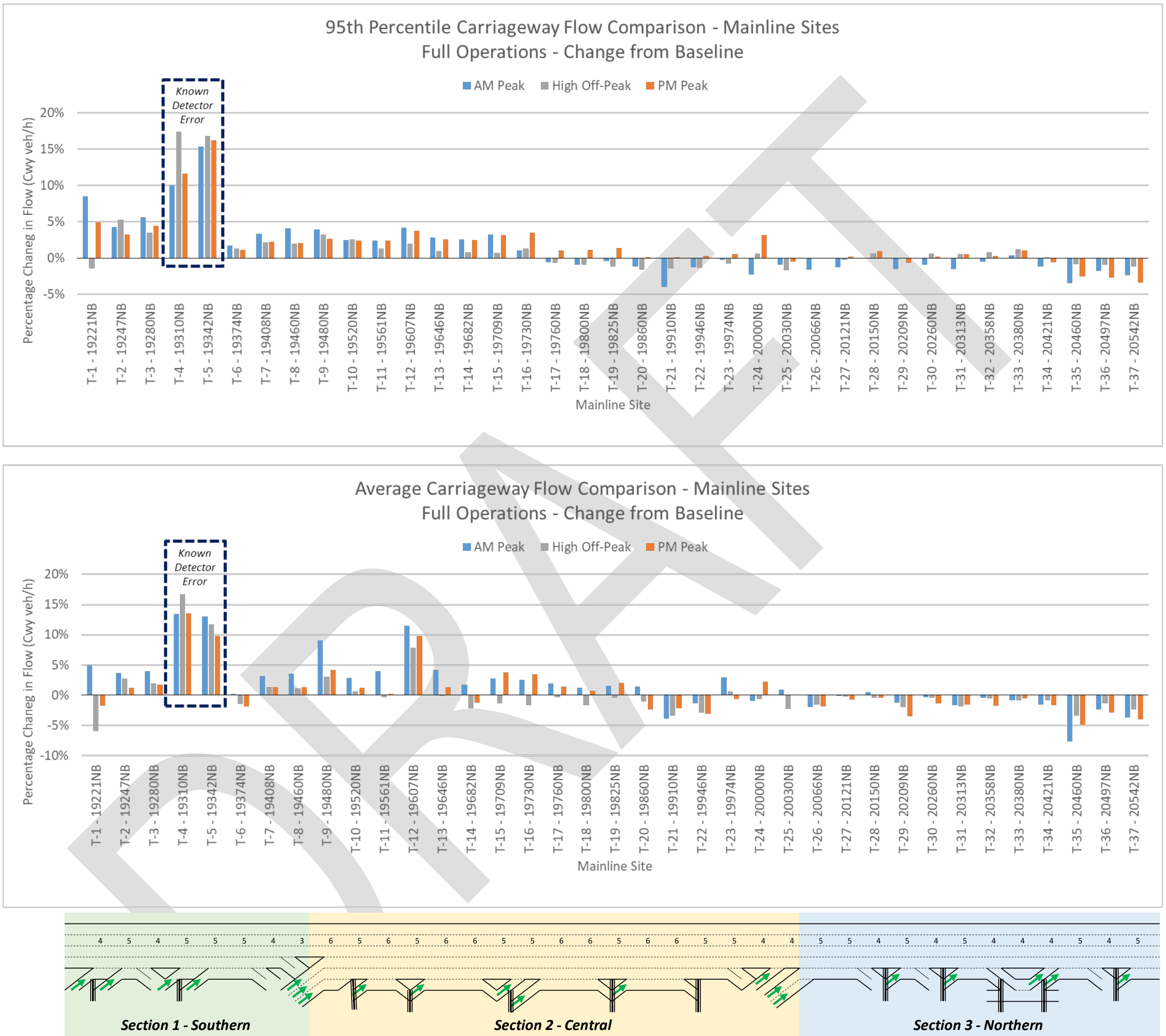


Figure 36: Change in Mainline Flows by Detector – Peak Period 95th Percentiles and Averages (Full Operations Stage vs Baseline)

Changes in flows between Baseline and Full Operations stages are to be expected on an urban freeway corridor to some degree. This is all the more the case given the broader context of changing travel patterns due to the recovery from COVID-19 Pandemic impacts and related restrictions. Understanding the scale of any changes, both over time and spatially (along the corridor) is needed to assist in interpreting changes in operating conditions.

In terms of understanding the scale of change along the I-25 mainline, it is valuable to review the changes from Sites T-6 to T-34 in Figure 36. In most cases (with the exception of a few outliers), the changes are less than 5% and generally within the 1-3% range. When considering an approximate average carriageway flow of 8,000 veh/h, a 1-3% change is the equivalent of a change in 20-60 veh/h/lane across 4 lanes which is relatively small and can be considered not too significant overall.

It is evident from the plotted changes, especially in the 95th percentile plot, that there is a general and marginal increase in flows south of Site T-16 and a general and marginal decrease in flows north of Site T-16. It is noted that this location is coincident with the Arapahoe Road interchange. A review of similar ramp flow changes (refer to Section 8.4.1) shows corresponding reductions on the Arapahoe, Orchard and Belleview entry ramps. This may be an indicator of changes in activity and access to the Denver Tech Center area. It is also possible that as demands and conditions have changed, some road users may be using other parts of the road network to navigate broader road network conditions (e.g. I-225 Congestion or congestion further downstream on the I-25).

It is also notable in the flow change plots that there is a more noticeable reduction at the northern end of the corridor. This may be due to changes in broader road network utilisation as there is also a corresponding reduction in ramp flows at the three northern most ramps. Congestion occurring further downstream on the I-25 may also be deterrent as well as causing a direct flow reduction during periods of congestion and queueing back into the pilot section, as discussed further in Section 8.8.2.

To further understand the changes in mainline flows at sites along the corridor, a full set of plots showing the Daily, Maximum AM and maximum PM flows across the whole project period are provided in Appendix I.

It is noted that gaps exist in the data which is due to detector damage, power / communications faults or weather conditions (snow) or debris blocking the TIRTL beams for varying periods. It is also noted that the configuration of Sites T-4 and T-5 were modified to update the number of lane detectors on the mainline to ensure all lanes were being monitored – this occur just after the start of the Arterial Ramps Only stage.

8.4 Ramp Flows

The observed entry ramp demands were calculated from the recorded measures. The statistics shown in the histograms below represent the average, 95th percentile and maximum hourly flow equivalents. The statistics were calculated on a 15min basis and converted to an hourly equivalent flow (veh/h). The figures are based on data from weekdays within the data collection period.

Analysis of the ramp flows provides useful information for the operational stages of the pilot as they indicate the level of demand that needs to be managed by the coordinated ramp metering system. The ramp demands also indicate where significant flows may impact mainline operations.

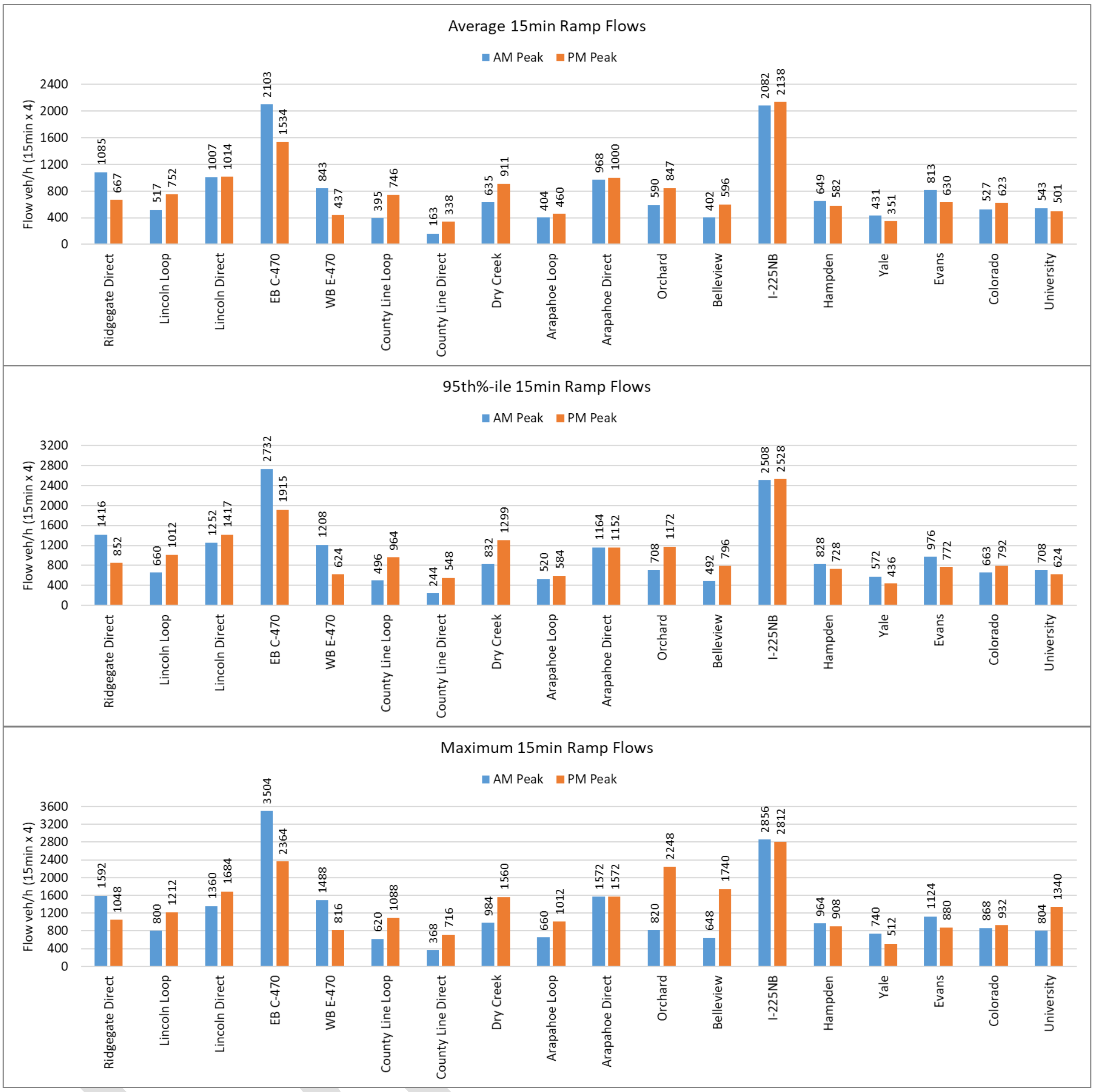


Figure 37: Histograms of Entry Ramp Flows – Peak Period Averages, 95th Percentiles and Maximums (Full Operations Stage)

8.4.1 Changes in Ramp Flows

The following figures compare the 95th percentile and average peak period ramp flows during the Full Operations stage with the Baseline stage. When interpreting the data, readers should be aware that various detection faults or data anomalies can influence the aggregations presented in these figures.

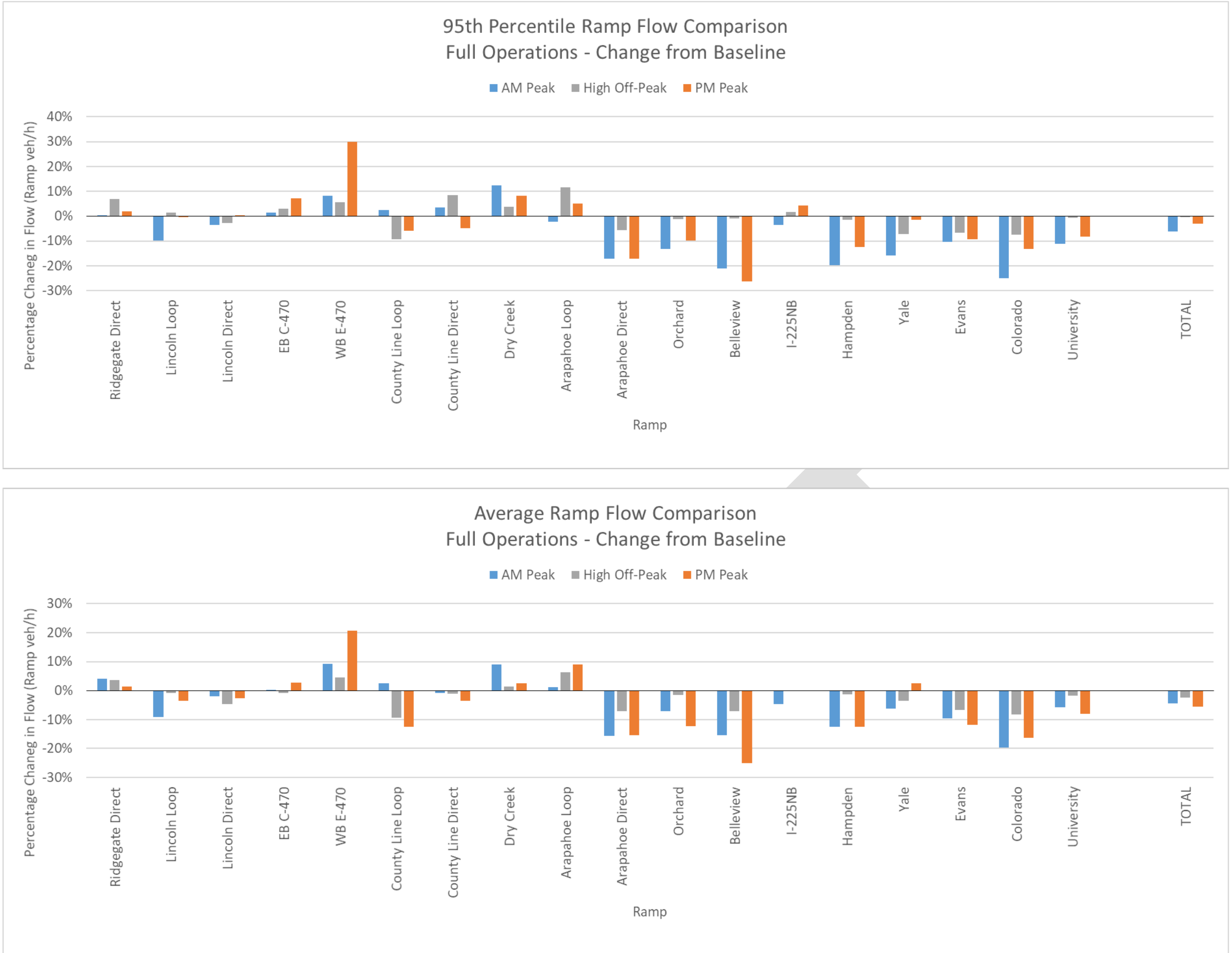


Figure 38: Change in Ramp Flows – Peak Period 95th Percentiles and Averages (Full Operations Stage vs Baseline)

To further understand the changes in ramp flows at sites along the corridor, a full set of plots showing the Daily, Maximum AM and maximum PM flows across the whole project period are provided in Appendix I.

Some ramp sites experienced loss of data for odd days or in some cases extended periods of time due to detector faults or problems with the supporting infrastructure (repeater / access point failures or power / communications dropouts). It is also noted that for part of the Baseline data collection stage, the County Line Loop ramp and I-225 system ramp the incorrect number of detectors were configured, and this was corrected, resulting in an increase in counts. Where this data has been used for analysis, appropriate adjustments have been made to the data for correctness.

8.4.2 Ramp Capacity and Design Discharge Assessment

The following table summarises the entry ramp flows measures during the data collection period. When the Smart 25 Project was originally scoped, data from 2015-16 was utilised to inform operation ramp designs for stopline discharge and storage capacity. With the newly collected data from July to October 2021, it is important to assess the provisioned capacity of the ramps, based on the current demands. Based on the guidance provided in the VicRoads Managed Motorway Design Guide (MMDG), Vol 2, Part 3 (VicRoads, 2019), the table below highlights the number of lanes and total storage lengths required for design demand volumes. The 95th percentile ramp flows were principally used for the analysis. Highlights are provided in the table to indicate where the ramp provisions fall below the recommended quantities recommended in the MMDG.

Understanding where ramps are below desired capacity assists in informing where challenging operating conditions may emerge during real-time operations. Importantly, high demand ramps with a significant under-provision of storage will require careful tuning to ensure queue are appropriately managed. Although not shown in this report, it is also noted that all ramps have varying profiles through the day and within peak periods.

It is noted that the overall system storage along the corridor is also analysed and shows that the total storage is close to the overall required storage. Although this in the case, it needs to be recognised that the locations where excess storage exists may not necessarily contribute to the overall corridor capacity due to a mismatch in the ramp demands that can and do access the various ramps along the corridor.

Table 27: Ramp Demand Assessment – Discharge and Storage Capacity

Ramp	AM Flow (veh/h)		PM Flow (veh/h)		Discharge Capacity		Storage Capacity		
	95th	Max	95th	Max	Lanes required	Lanes Available	Required (ft)	Available (ft)	% Diff.
RS-1: Ridgegate Direct	1412	1556	836	1076	3	2	2,627	1,263	-52%
RS-2: Lincoln Loop	732	848	1016	1220	2	2	1,890	1,903	1%
RS-3: Lincoln Direct	1300	1524	1416	1524	3	3	2,634	4,035	53%
RS-4: EB C-470	2696	2944	1784	2012	4	4	5,015	3,871	-23%
RS-5: WB E-470	1116	1368	480	636	2	2	2,076	1,837	-12%
RS-6: County Line Loop	480	704	1008	1136	2	2	1,875	1,102	-41%
RS-7: County Line Direct	236	320	576	888	2	2	1,071	1,115	4%
RS-8: Dry Creek	740	860	1200	1840	3	3	2,232	2,362	6%
RS-9: Arapahoe Loop	532	676	556	752	2	2	1,034	1,050	2%
RS-10: Arapahoe Direct	1404	1536	1392	1588	3	3	2,612	3,281	26%
RS-11: Orchard	816	1444	1300	1608	3	3	2,418	1,772	-27%
RS-12: Belleview	624	1380	1072	1668	2	2	1,994	4,199	111%
RS-13: I-225NB	2524	2816	2368	2744	4	4	4,695	4,183	-11%
RS-14: Hampden	1032	1232	832	1304	2	2	1,920	1,969	3%
RS-15: Yale	680	972	440	688	2	2	1,265	1,247	-1%
RS-16: Evans	1088	1232	852	1012	2	2	2,024	853	-58%
RS-17: Colorado	884	1164	912	1052	2	2	1,697	1,969	16%
RS-18: University	796	988	680	828	2	2	1,481	1,690	14%
						Total	***40,561***	***39,701***	***-2%***

During the operational stages, it is noted that poor operating conditions were observed on some ramps which required intervention to mitigate queueing impacts on the adjacent arterial roads. Of particular note is the Ridgegate Direct ramp which in addition to having insufficient storage, also had insufficient number of lanes at the stopline to be able to run effective discharge flows during high demand peak periods. Excessive queuing on Ridgegate Boulevard required high, undesirable flow rates during the AM peak period to mitigate queues, however, this likely had impacts on the mainline conditions downstream with too much demand able to enter the mainline and disrupt downstream bottleneck locations.

An inspection of the ramp flow changes from the Baseline to the Full Operations stage shows increase for a limited number of ramps and decreases for most ramps. These demand reductions can assist operational flexibility where storage and discharge capacity were previously below desirable.

It is noted that the demand increases at the Dry Creek and Arapahoe Loop ramps coincide with the critical peak which brings these ramps closer to both operating at capacity of the available storage and discharge.

8.5 Classes of Vehicles in the Corridor

The following figures show various aspects of the proportion of different vehicles classes in the pilot section. There are many factors that impact the proportion of various vehicle classes across various time scales. There are at least 13 standard classes of vehicles identified in FHWA and CDOT classification standards. While information is available across all classes, in order to better understand utilisation of the corridor by function, the classes have been grouped into the following three groups.

- Passenger Vehicles and Motorcycles
- Pickups / Vans and Buses
- Trucks – Rigid 2-Axle vehicles and larger (representing commercial vehicles)

It is acknowledged that many different trip purposes can be associated with vehicle types across the classes. What the classification information does assist in understanding is the potential influence of light vehicles and larger longer vehicles in the traffic stream.

For brevity, most of the figures that follow are based on all vehicles detected during July 2022 as a representation of the vehicle mix during the Full Operations stage. This updates the September 2021 information provided in the _Baseline Performance Report_.

Figure 39 shows the proportion of the three vehicle groupings along the corridor. Sites / mile post references from left to right represent travel from south to north. It can be seen that the vehicles mix does not change or vary significantly along the pilot section, although there is a gradual reduction of the proportion of pickups / vans and trucks from south to north, with a corresponding increase in the smaller passenger cars, although the change is by less than 10%. Locations of the reduction in commercial vehicles are generally aligned with the system interchanges.

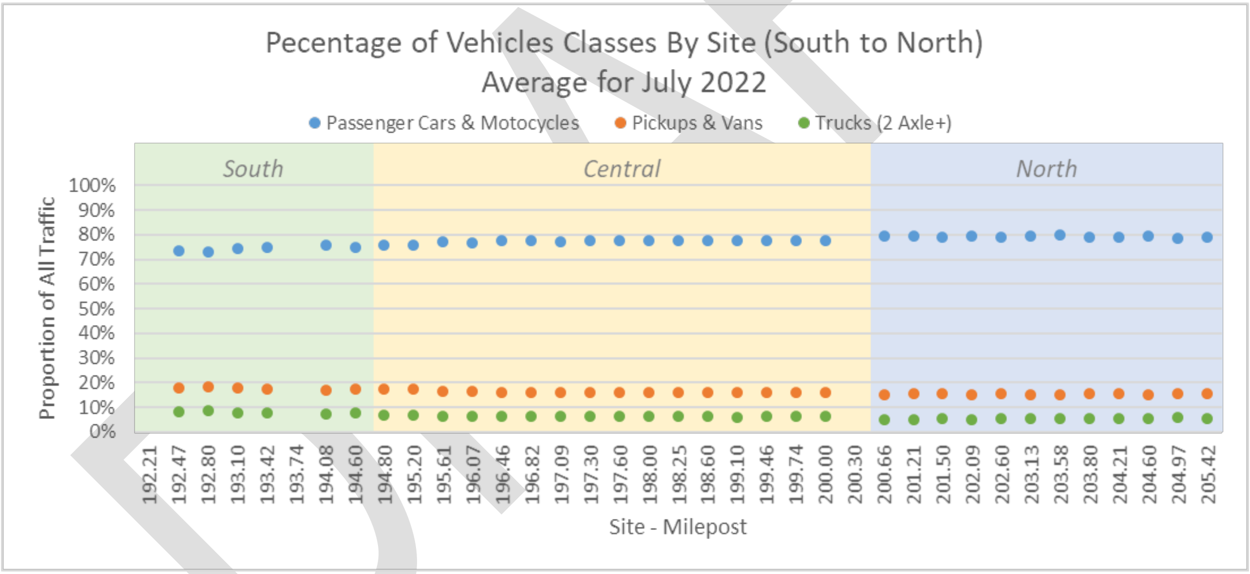


Figure 39: Percentage of Vehicle Classes by Site Along the I-25 Pilot Section (June 2022)

The proportions shown in Figure 39 above have not changed significantly from the September 2021 data previously provided. Figure 40 below shows the percentage change in the three vehicle class groupings by site along the pilot section, comparing July 2022 with September 2021. The comparison generally indicates an increased proportion of passenger cars and motorcycles with a corresponding reduced proportion of pickups, vans and trucks. It is noted though that the change is minor, being 1% or less across all sites. When considering the change in volumes along the corridor discussed in Section 8.3.1, the changed proportion of vehicle classes is likely most heavily influenced by changes in passenger cars, as opposed to a notable reduction or change in the other classes.

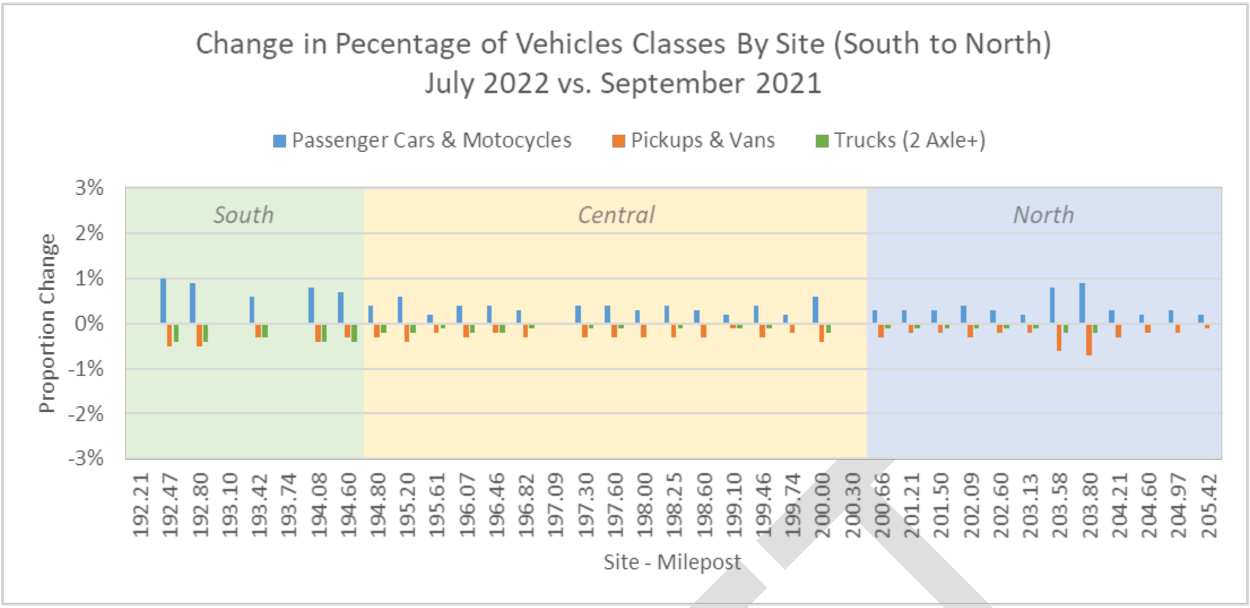


Figure 40: Change I the Proportion of Vehicle Classes by Site Along the I-25 Pilot Section (June 2022 vs. September 2021)

Figure 41 to Figure 43 shows the variation of the vehicle mix across the day and replaces the September 2021 information previously provided. Only weekdays were included in these figures and the overall traffic volume for the corresponding site is also included to assist with context (i.e. high proportions of trucks are present during the hours before the AM peak period, however, this coincides with very low overall traffic volumes). Comparison with the September 2021 baseline data shows little change in class proportions across the day with the exception of a higher proportion of passenger cars (and lower proportions of pickups, vans and trucks) during the overnight period, although it is acknowledged that this does not impact the main operational times being considered across the pilot project.

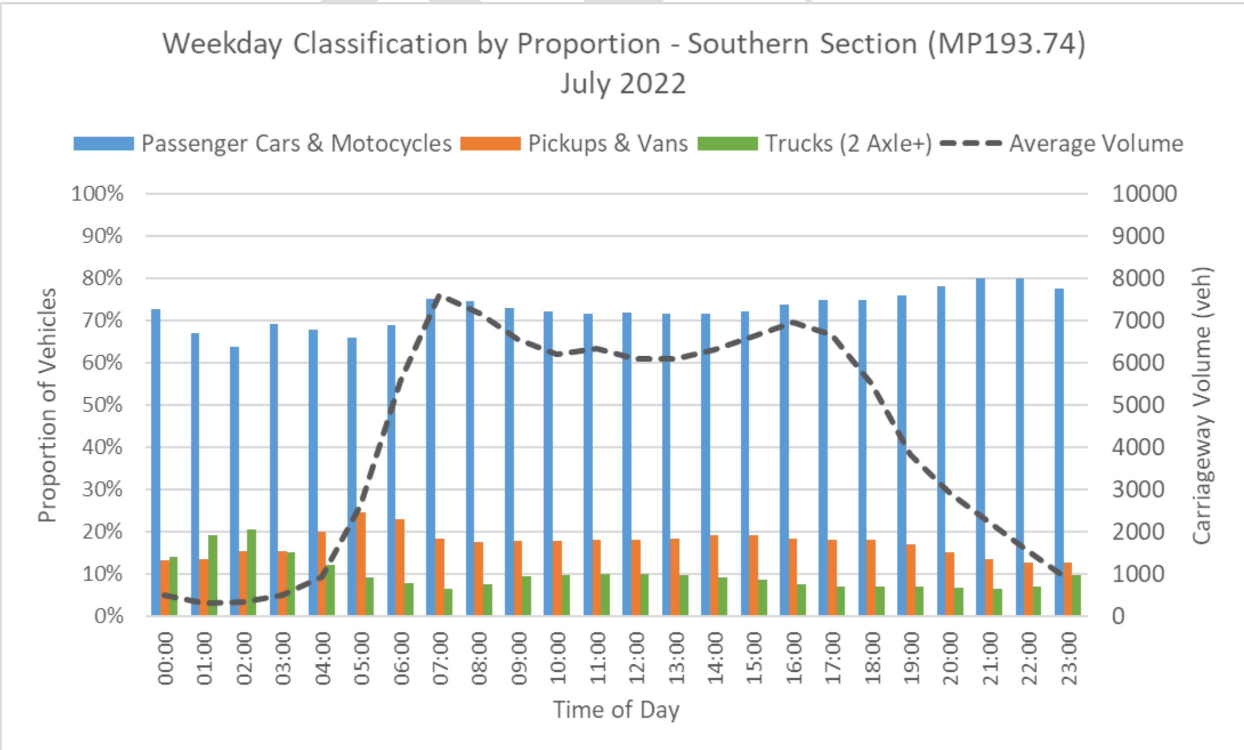


Figure 41: Proportion of Vehicle Classes by Time of Day – Southern Section (Site 193.74)

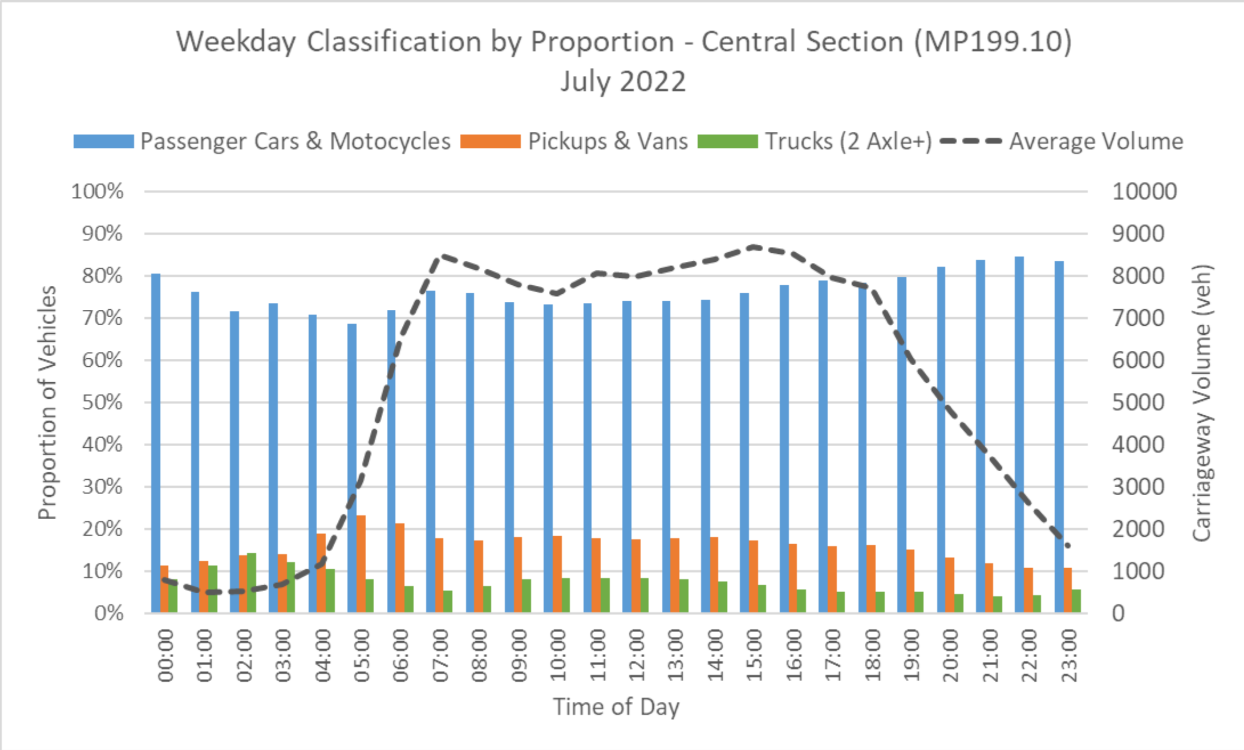


Figure 42: Proportion of Vehicle Classes by Time of Day – Central Section (Site 199.10)

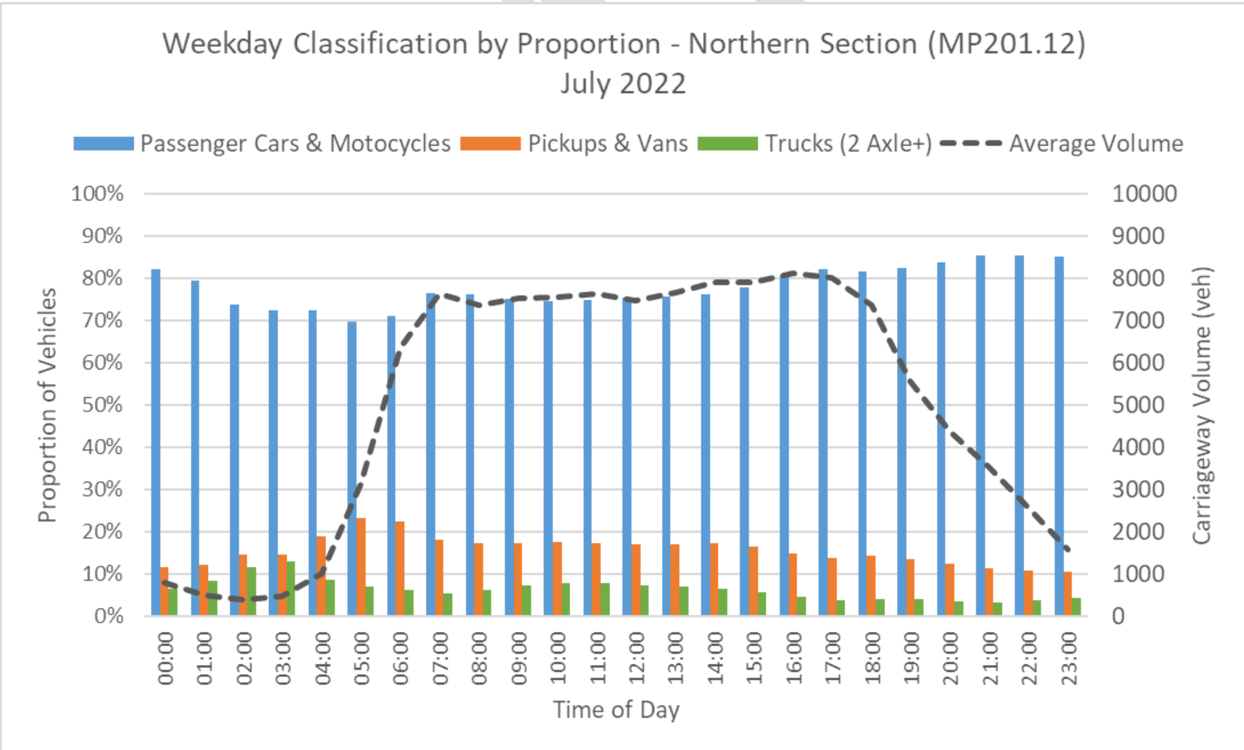


Figure 43: Proportion of Vehicle Classes by Time of Day – Northern Section (Site 201.12)

8.6 Operating Speeds in the Corridor

8.6.1 Average Speeds in relation to Posted Speed Limit

It is observed that operating speeds are quite high in the corridor, including very high proportions of drivers exceeding the posted speed limit. Figure 44 below shows the proportional speed distributions from 4 sites along the corridor, on from each of the 70 and 60mph speed zones and 3 from the 65mph speed zone. Data was previously provided for all vehicles observed during September 2021 with additional corresponding data from July2022 included for comparison.

It is evident that the modal speeds (peaks of the distributions) are about 5mph greater that the corresponding posted speed limits. The additional information in the figures below shows the proportion of vehicles that exceed the speed limit at each of the 5 sites sampled.

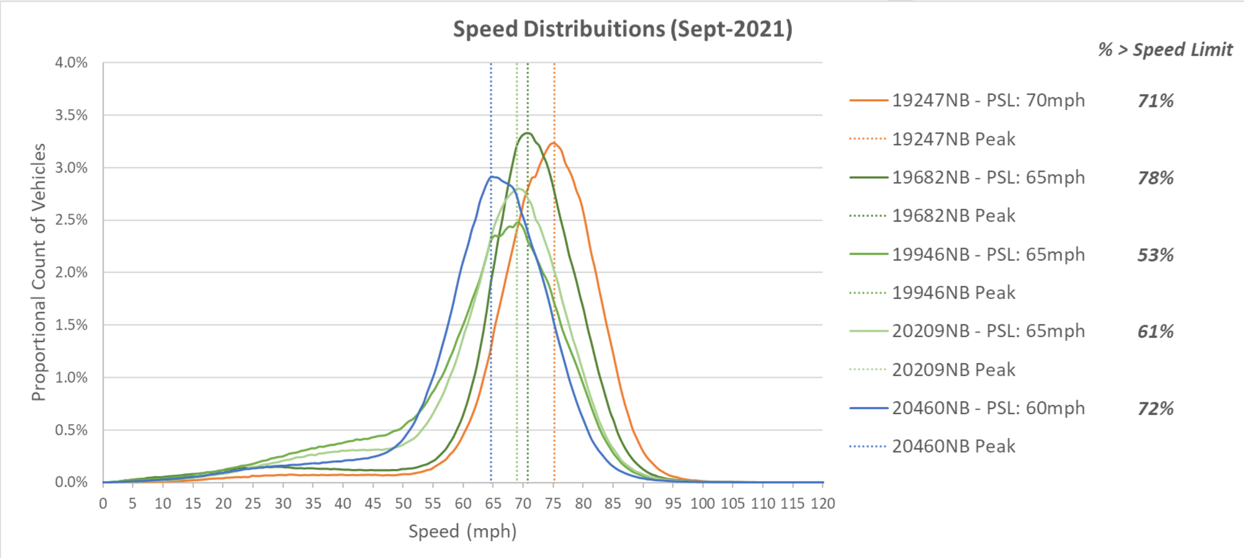


Figure 44: Proportional Distributions of Vehicles Speeds at Locations in the Pilot Section (September 2021)

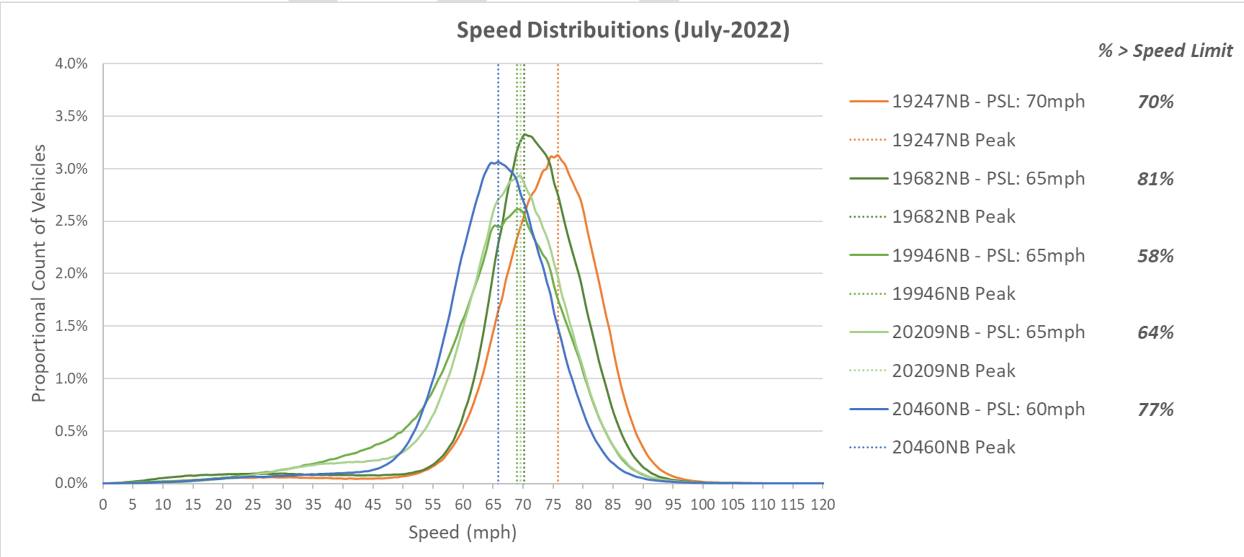


Figure 45: Proportional Distributions of Vehicles Speeds at Locations in the Pilot Section (July 2022)

A comparison of the before and after figures show that the high speeds evident before the pilot project continue to be observed in the corridor. This is not unexpected as there has not been any known change to the enforcement of posted speed limits or any other broader actions to address free-flow speed related behaviours.

It is interesting to note that the proportion of vehicles exceeding the posted speed limit has increased. While this could, to a small degree, be associated with improved operating conditions due to the pilot project operations, there are also likely to be other factors, such as seasonality and varying weather and environmental conditions that influence speeding behaviours to a greater extent.

A change in the speed distributions that can likely be linked to the pilot project operations is the reduced proportions of slower speeds measured across the five sites presented. There is a distinct reduction in the proportion of vehicles travelling at speeds between 25mph and 40mph in July 2022 compared with September 2021. Experience with improved motorway control in other jurisdictions has demonstrated a reduced proportion of lower speeds experienced, even when congestion does still occur. It is noted that days influenced by incidents and weather are not excluded in the distributions shown above.

8.6.2 Variation of Speed in the Freeway Carriageway

A further observation concerning speed in the corridor is the variability of speed in the carriageway. This implies, and is supported by observations, of high differential speeds both within and across lanes. The speed / flow plots in the two figures below cover approximately a full month data and are provided to demonstrate the high variability in speed, in traffic conditions clear of flow breakdown, where significant speed oscillations can occur. The red arrow in the figure represents are speed range of about 15mph which is quite significant and can contribute to chaotic conditions and rapid deterioration in traffic flow when instability occurs. There is little change in the spread of speed data when comparing July 2022 with September 2021.

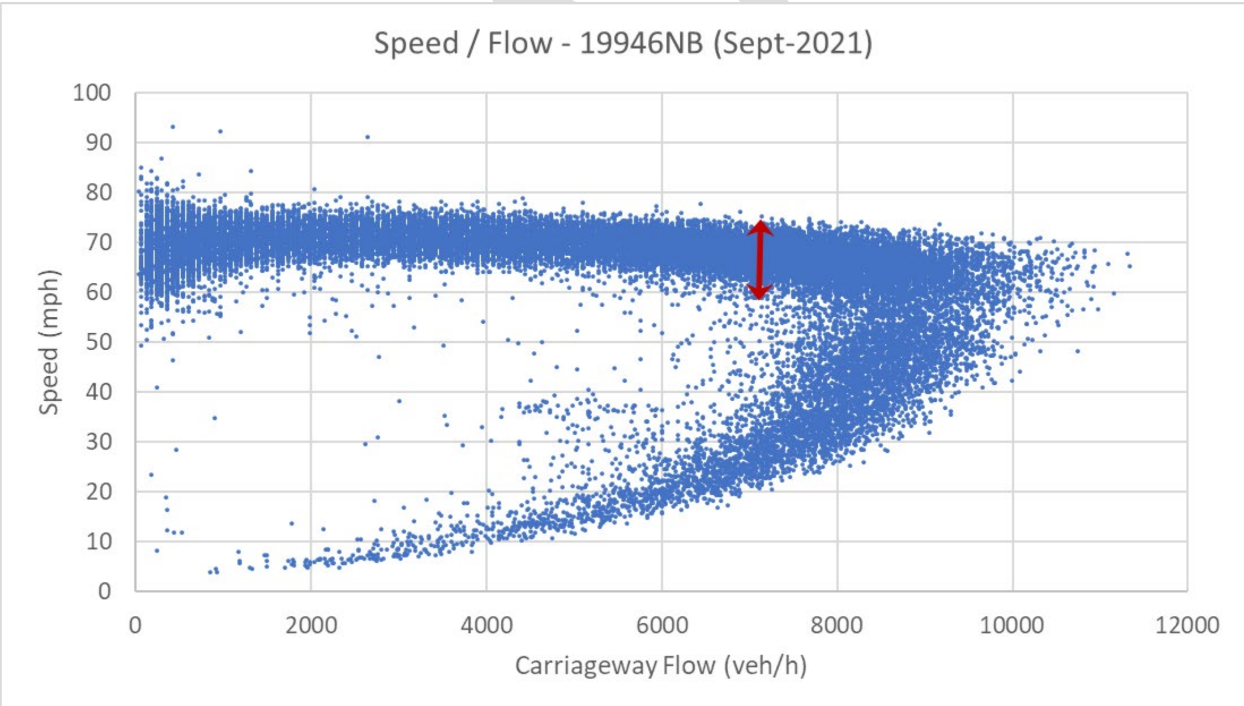


Figure 46: High Speed Variability at a Site Demonstrated in Speed / Flow Data (September 2021)

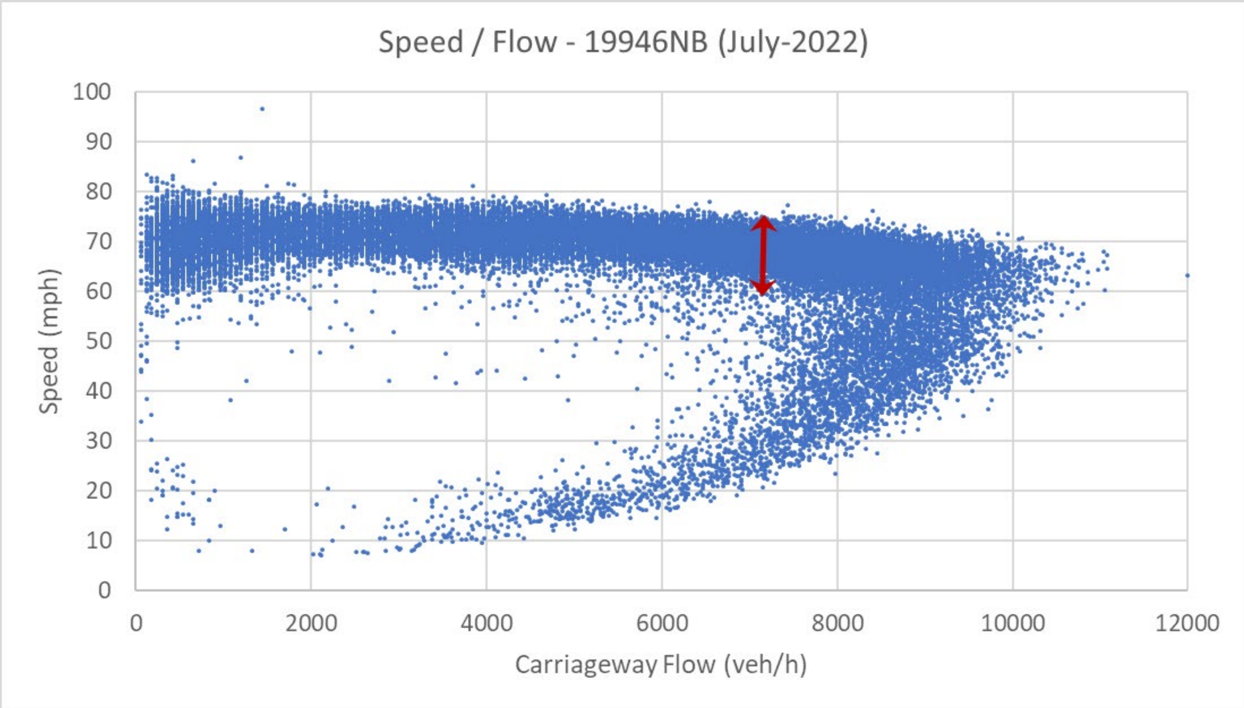


Figure 47: High Speed Variability at a Site Demonstrated in Speed / Flow Data (July 2022)

It high likely that the high speeds and the significant differentials in speeds are contributors to crashes and similar incidents that occur in the corridor on a regular occasion. While excess speed may not always be a primary cause, the prevailing high speeds result in many vehicles rapidly arriving unaware, at a location with congestion or an incident with sudden “locking up” of traffic and the high risk of secondary incidents.

8.6.3 Variation of Speeds Across Lanes

Figure 48 and Figure 49 below show the significant differential in speeds across lanes. Lane 1 represents the median side fast lane while Lane 5 is the outer slow lane. The site selected is just south of the I-225 interchange where there is significant demand that uses the two right lanes to exit the I-25. Due to the interactions between exiting traffic – lane changing to align with the exit – the speeds in the two right lanes are reasonably aligned. However, there is a significant variation in lane speeds compared to the exit lanes and across all other lanes. The difference in average hourly speeds across the carriageway can be up to 16mph and can represent a 20-25% variation compared with the faster lane. At smaller time intervals these differentials are likely even higher.

Significant speed differentials across lanes are known to increase the amount of turbulence and flow breakdown risk in freeway carriageways during periods of high demand. When vehicles change lanes (by need or desire) in higher density traffic, doing so into a lane that is substantially faster or slower than the lane they are coming from requires a speed adjustment (usually through braking) by either the vehicle changing lanes and /or the vehicle(s) behind the gap that received the lane changer. These braking and slowing actions in dense traffic significantly increase the risk of flow breakdown and also crashes. Smoother, more consistent speeds across lanes reduce the degree to which vehicles need to slow or adjust their speeds to lane changing actions.

A comparison of the before and after lane speed profiles shows that the high differentials across lanes still remain. It is notable that the AM peak reduction in speed evident in the baseline stage at the sample locations (which is a known bottleneck sites) experienced less flow breakdown in July 2022 which is likely linked to the pilot project operations.

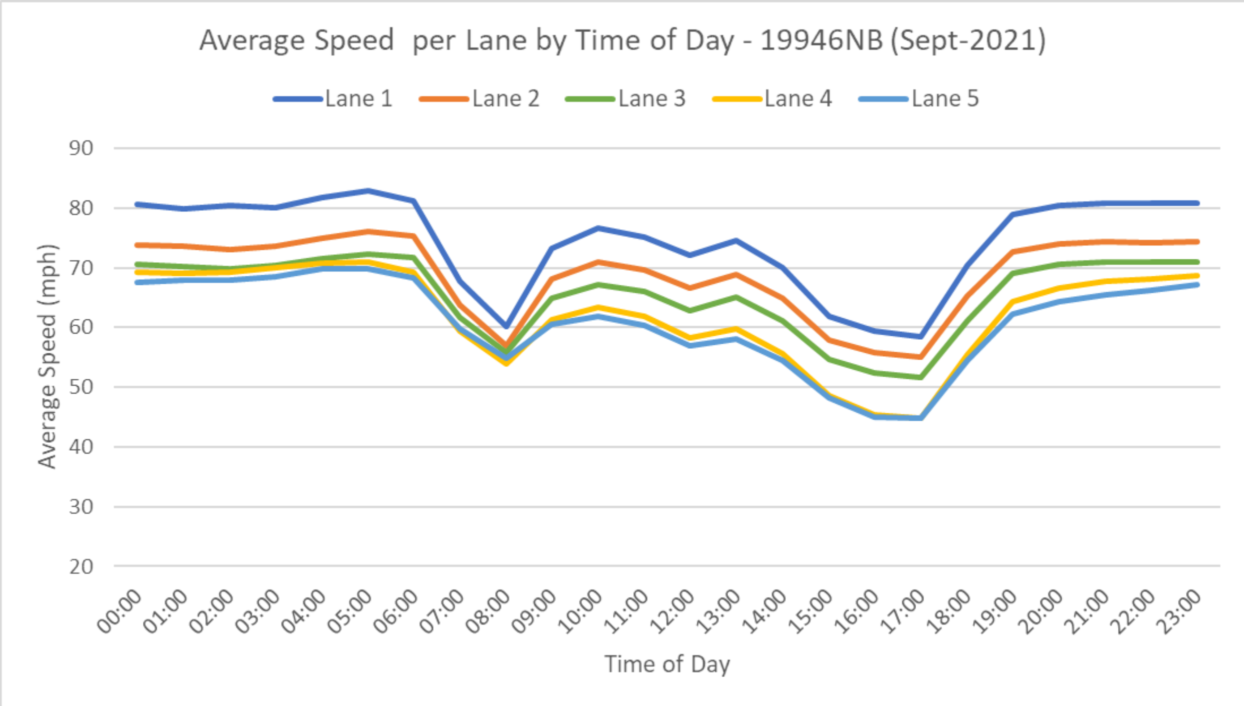


Figure 48: Differential Speeds Across Lanes at a Site (September 2021)

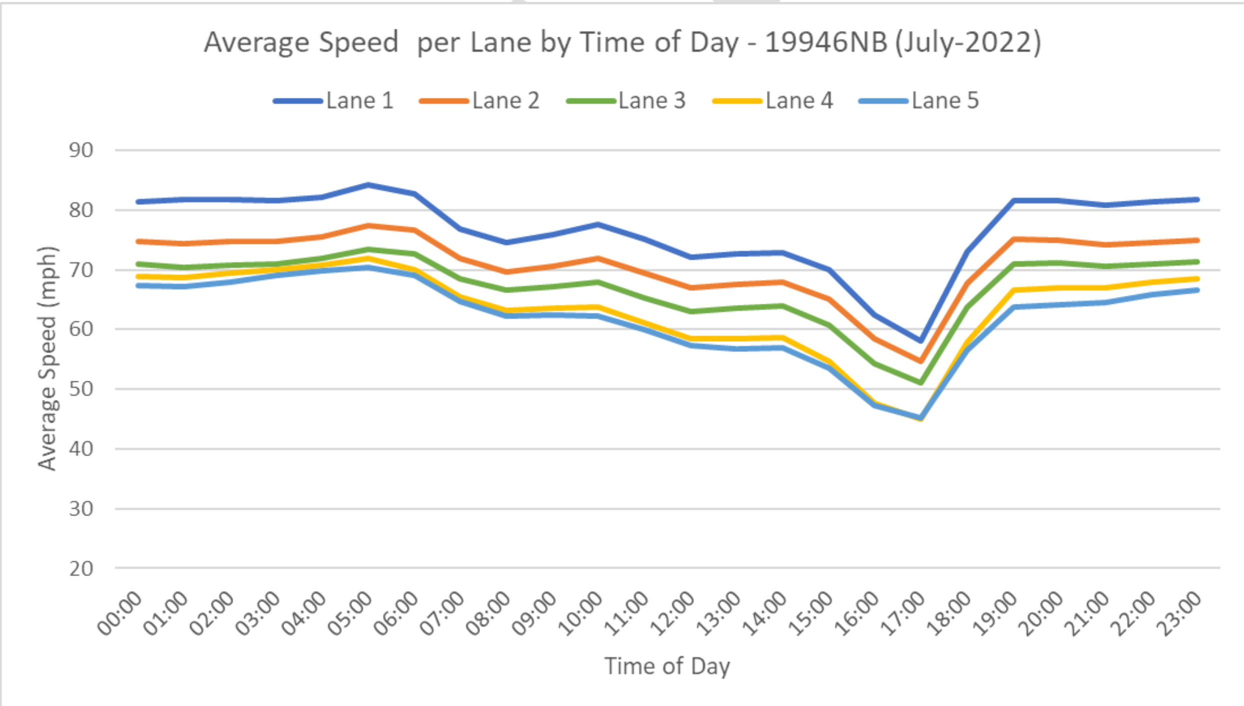


Figure 49: Differential Speeds Across Lanes at a Site (July 2022)

8.7 Driver Response to Ramp Metering Operations

As part of the pilot demonstration, changes were made to a number of ramps, including the number of lanes at the metering stopline and also along the ramps to cater for queue storage. These changes were part of the necessary works required to support the modified operational approach used in conjunction with the STREAMS-AHS control. The operation of the STREAMS-AHS system is also more dynamic to the previous ramp control that was in place along the I-25. Some of these physical and operational changes were unfamiliar to drivers when operations transitioned between various stages.

8.7.1 Three-Lane Ramp Meter Driver Behaviour

Three or more lanes were provided at some ramp metering locations. Generally, only two metered lanes had been used in Colorado prior to the pilot project.

In the initial period of the Arterial Ramps Only stage, drivers did not immediately start using the additional right side shoulder conversions for queueing on approach to the metering stopline, despite the provision of signs permitting them to do so. Driver responses were also observed vary from ramp to ramp. Additional dynamic message signs provided by CDOT were provided which influenced greater use of the additional queue storage over a reasonable period.

During this period of underutilization, the ramp metering operations were tuned to run higher cycle times (lower flow rates were not enabled to run to avoid the generation of longer queues). The queue management settings were also more reactive to queues being detected and pushed ramp flow rates up to mitigate queueing onto the adjacent arterials. A challenge for operators during this period was the incomplete access to all CCTV cameras, and therefore no regular viewing of all queue lengths at impacted ramps, which also resulted in slightly more conservative settings being deployed in operations

Once drivers were directly encouraged to use the additional storage lanes, behaviour changed at a relatively good pace.

The impact of underutilisation of queue storage resulted in longer queues forming in the lanes that are used. In the early periods of operations, this resulted in queue management algorithms engaging more frequently and allowing more traffic onto the mainline (impacting mainline conditions). This limited the ability to go to fully responsive and flexible operations until the lane utilization improved.

8.7.2 System Ramp Meter Driver Behaviour and Demand Impacts

With the pilot project introducing the metering of system ramps for the first time in Colorado, a conservative and circumspect approach was taken to activating and gradually increasing the level of restrictiveness applied in three meters system ramps. A media campaign also preceded the activation of these ramps to assist motorists' awareness of the coming changes.

While this metering approach was new, it was observed that drivers adapted to the need to slow and be metered on these connections – once a queue formed, compliance was generally seen to be quite good. As some of these ramps also had additional queue storage lanes provided, a similar transition period to using these lanes (as noted above) was also observed.

Similar to the discussion about the utilization of additional storage lanes on the widened arterial ramps, the impact of underutilisation of queue storage on two of the three system ramps also resulted in longer queues in the lanes that are used. In the early periods of operations, this resulted in queue management algorithms engaging more frequently and allowing more traffic onto the mainline (impacting mainline conditions), which limited the ability to go to fully responsive and flexible operations until the lane utilization improved.

Each of the system ramps is relatively unique due to differences in demand and available storage and are discussed briefly below.

8.7.2.1 C-470 System Ramp

The C-470 to I-25 System entry ramp was configured with a four lane stopline which involved localised widening of the ramp at the stopline to enable high discharge flows. However, the length of the overall storage (mostly two lanes wide) was significantly below design requirements for the expected design flows and the flows eventually experienced during operations.

Challenges were encountered when this ramp was first activated, especially during the AM peak period. The nature of the ramp demand at this location is such that very high demands were experienced, such as flow rates of up to 2700 veh/h over 15mins. While the theoretical discharge flow rate of a four-lane ramp meter with a low cycle time can technically cater for such high flows, inefficiencies in lane utilisation significantly reduced the initial flow rates that were achieved.

On the first day of the metering at this site, few drivers utilised the outer lanes at the ramp metering stopline, resulting in discharge flows well below the required discharge flows to maintain queues within the available ramp storage. As a result, queues quickly extended back onto the C-470 and ramp metering was manually overridden to ensure safety for the traffic approaching the interchange on the C-470 mainline.

In discussions with CDOT operations, a strategy was developed to gradually introduce the metering operation in stages to allow drivers to become familiar with the metering operation at this site, which included the following sequence.

1. Ramp metering was initially inhibited from switching on early and only allowed to activate after the main demand peak in AM had passed. When activated late in the AM peak, flow rates were maintained at a high flow to avoid creating queues.
2. Ramp metering was then enabled to come on prior to the main AM peak high demand, but at a high rate. The ramp was continuously monitored and manually deactivated if the queue extended back to a pre-agreed location
3. As drivers became more familiar with the ramp metering on the ramp, and utilised the outer lanes, the metering was able to activate prior to the heavy AM peak and remain metering throughout without queues causing any overflow issues. Reasonably high minimum flow rates needed to be maintained in the configuration to limit the build-up of queues.

This sequence of gradually increasing control to enable the C-470 ramp to operate throughout the AM peak period took about 3-4 weeks. Ramp metering operations were able to run flexibly during the PM peak as lower demands could generally be effectively managed without queuing challenges.

As a result of the requirement to run high flow rates during the AM peak to avoid excessive queues, the following limitation existed on this ramp:

- The ramp metering was not able to run with full flexibility (restrictive flows to prevent flow-breakdown) during the full operations stage, thereby allowing too much traffic to enter the corridor at critical times.
- The excess flows from this ramp, particularly during the height of the AM peak period could regularly contribute to the occurrence of flow breakdown at downstream bottlenecks.

It is noted that the warning beacons on the approach to the ramp meter failed in early May. From 9 May during the PM peak onwards, the ramp operation was inhibited for the remaining full operations period as the beacon operations was unable to be restored.

8.7.2.2 E-470 System Ramp

The E-470 ramp had a two lane meter. The demand on this ramp was generally well within the available discharge capacity of the ramp and queues were always observed to be well managed and maintained with the available queue storage area, clear of other free-flowing movements in the system interchange.

8.7.2.3 I-225 System Ramp

The I-225 entry ramp had a four-lane ramp meter and also had extended lengths of outer lanes available for storage, including a dedicated lane from an upstream interchange feeding directly into the right most lane. As a result, drivers utilised the outer lanes for queue storage soon after the activation of metering on this ramp.

In general, queues were able to be managed within the queue storage area of the ramp and there were few occasions of queuing extended back and impacting the upstream section of the I-225 approaching the immediate upstream bifurcation location.

It was found that the queue management algorithms were able to manage the queues fairly effectively on this ramp, although some fine tuning of the parameters for this ramp were needed to ensure that ramp discharges flows were not pushed too high to the detriment of the I-25 mainline. Although queues were able to be managed effectively, ramp discharge flows were not always able to be sufficiently restricted to prevent flow-breakdown downstream of the entry ramp.

8.8 Impacts from Downstream Facilities / Sections

Sections of a freeway never operate in isolation, especially in urban areas. Conditions that occur upstream or downstream, both on the continuing mainline or connected facilities, can have impacts on how a particular section operates. There are two particular conditions that have a significant impact on the operations within the pilot section, noting that these issues have been identified in earlier stages of the pilot project's development. The locations are shown in Figure 50.

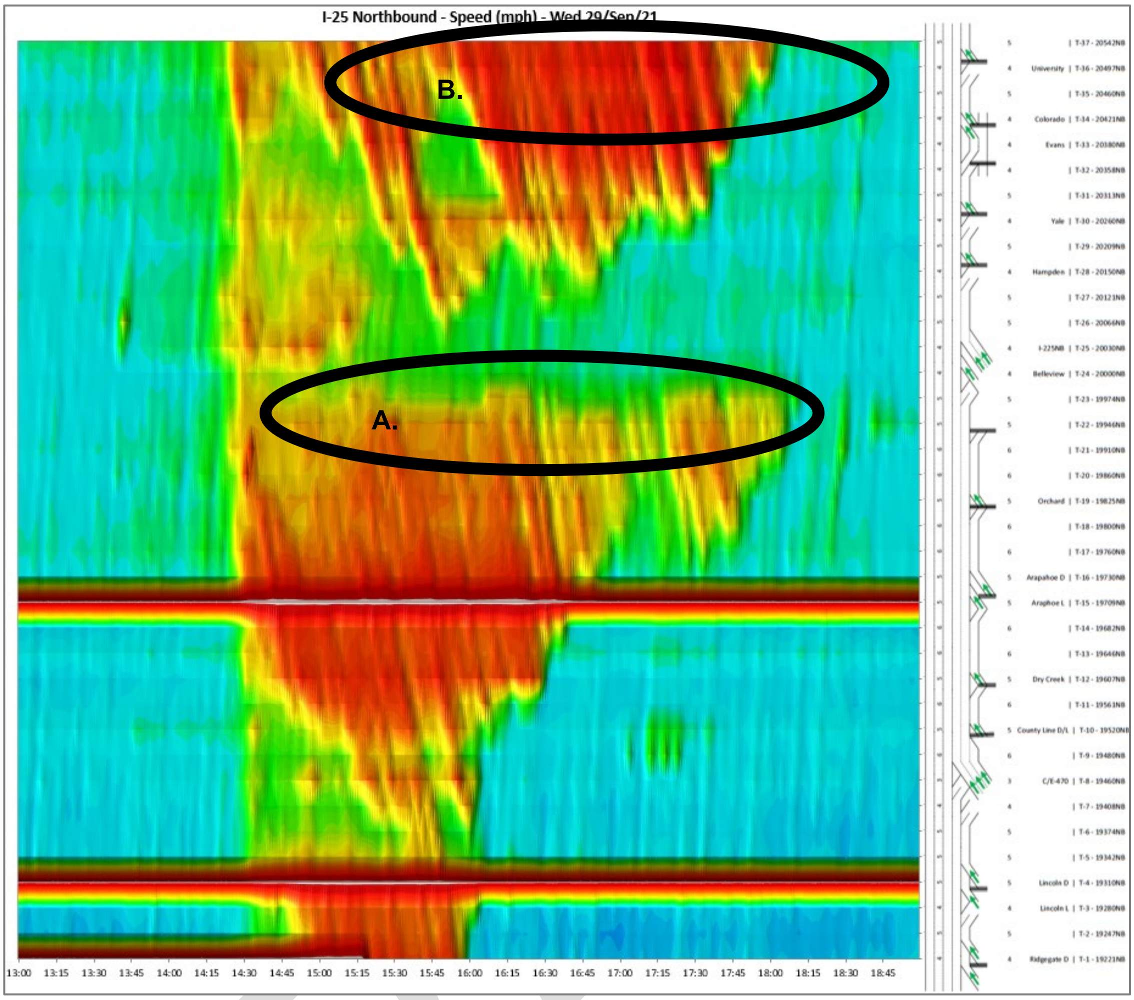


Figure 50: Heat Plot (PM Peak) Highlighting Locations Impacted by Conditions Outside the Pilot Section

8.8.1 Exit to I-225

The conditions related to the I-225 exit are indicated at Location (A.) in Figure 50. In addition to the exit flows to the I-225 being very high, downstream merging and weaving conditions on the I-225 regularly results in queues extending back into the I-25 northbound (and southbound) carriageway. There are two main movements, system ramps from the I-25 north and south, that join to the east of the I-25. During high demand periods, especially during the PM peak, the merging and weaving movements that occur often cause flow breakdown with congestion queuing extending back along the ramps and onto the I-25 mainline carriageways. Figure 51 shows the convergence of the ramps and an occasion from the COTrip website where slowed traffic extends back to the I-25.

Observations of traffic conditions in the corridor and inspection of heat plots across the data collection period indicate that this is a regular occurrence (multiple times a week) impacting northbound traffic flow on the I-25. It is acknowledged that heavy weaving conditions and high exit flows to the I-225 from the I-25 also occur in this area and so there can be multiple causes of flow breakdown through southern approach to the I-225.

It is important to recognise that the ramp metering of upstream entry ramps can assist the density conditions to assist weaving and reduce the risk of flow breakdown. However, ramp metering on the I-25 cannot respond to or prevent flow breakdown the occurs on the I-225 or make any substantial different to the extent of queue back on the I-25.

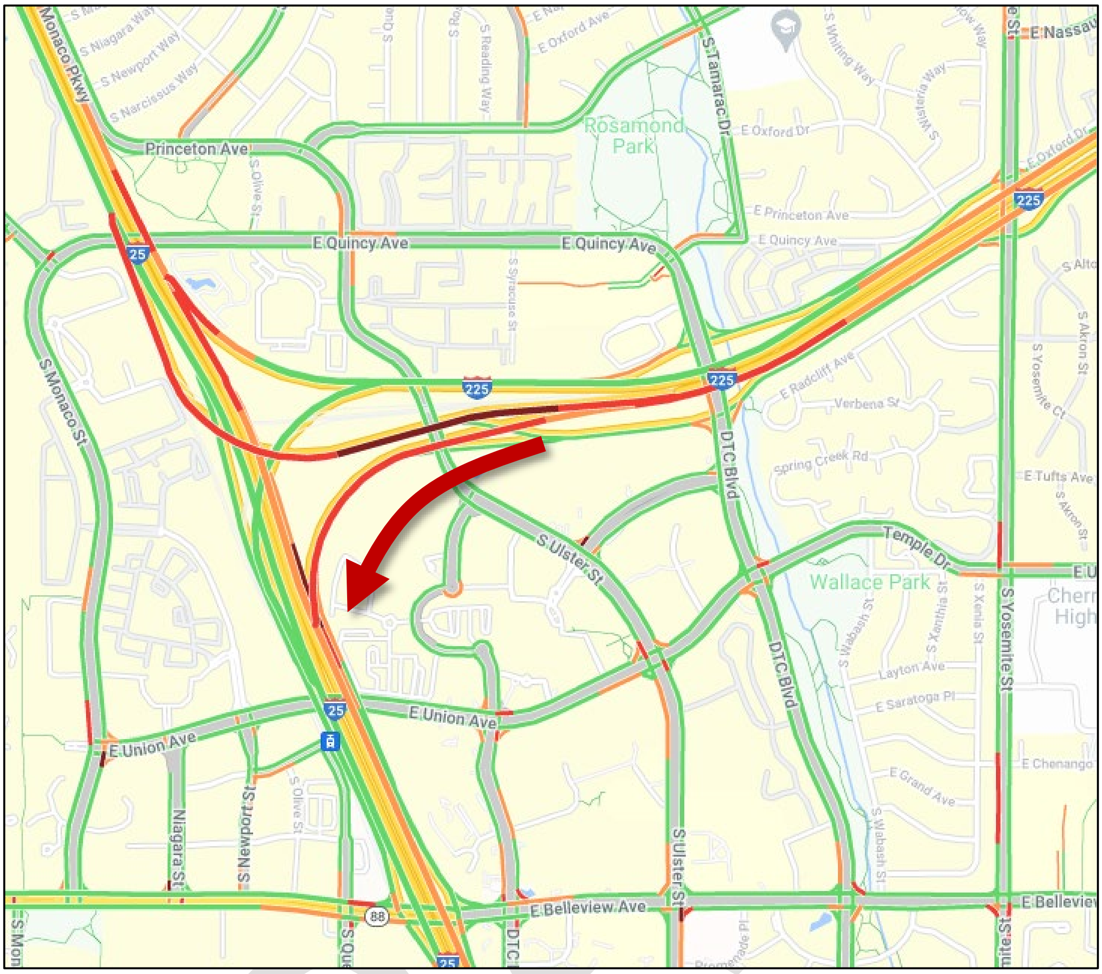


Figure 51: COTrip Screen Capture Showing Queuing (Low Speed) Extending from the I-225 onto the I-25

8.8.2 I-25 Downstream Queue Back

The conditions related to the I-225 exit are indicated at Location (B.) in Figure 50. Congestion due to recurrent flow breakdown or incidents in the corridor can cause queuing that extends back into the northern end of the pilot section. The impacts can vary depending on the time and scale of the conditions that cause the queue back. Figure 52 shows queuing as a result of an incident with lane closures just downstream of the pilot section.

Observations of traffic conditions in the corridor and inspection of heat plots across the data collection period indicate that this is a regular occurrence (multiple times a week) impacting conditions particularly in the north of the pilot section during both AM and PM peak periods.

Similar to the earlier discussion, ramp metering on the pilot section of the I-25 cannot respond to or prevent flow breakdown the occurs further downstream (beyond the area monitored by associated detection) or make any substantial difference to the extent of queue back into the pilot section.

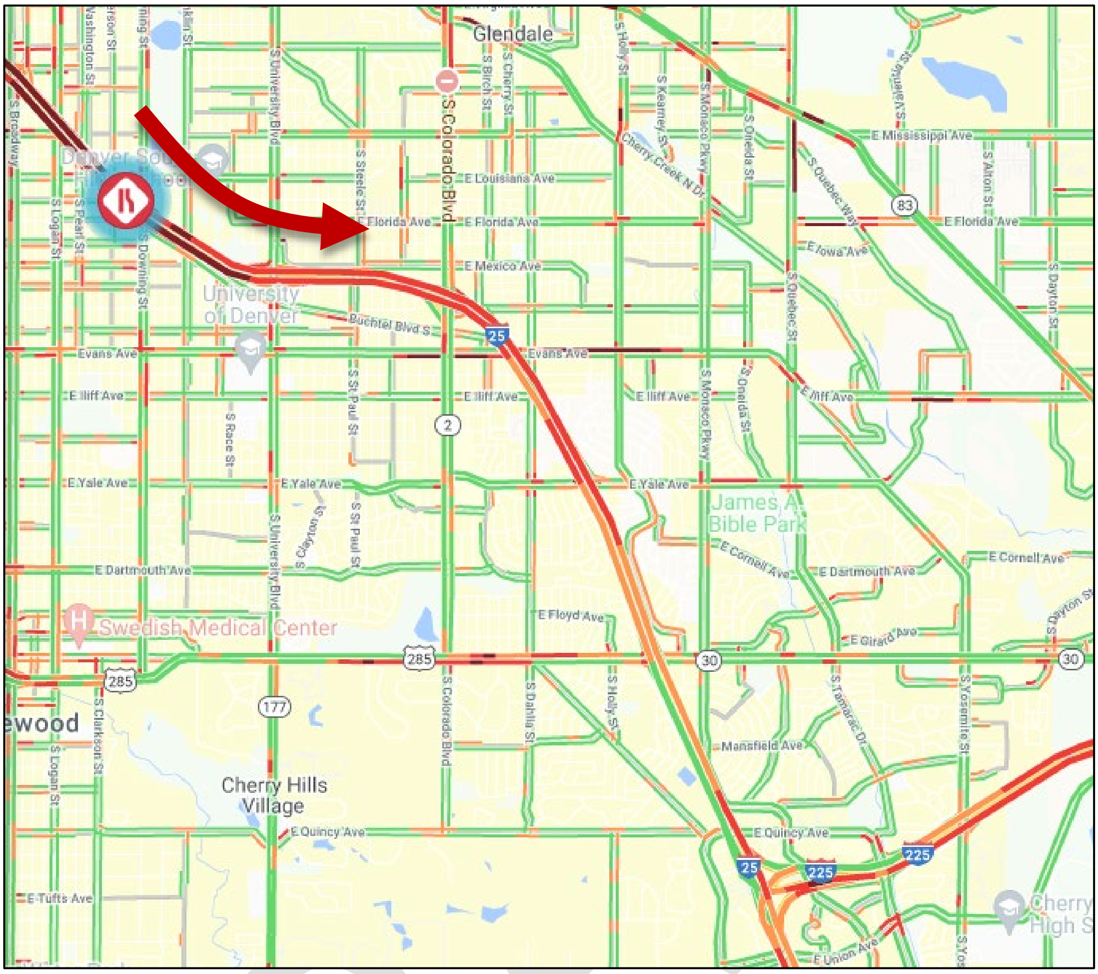


Figure 52: COTrip Screen Capture Showing Queuing (Low Speed) Extending from the Downstream Sections the I-25

8.9 Limited Ramp Storage on Metered Ramps

Part of the SMART 25 project involved minor civil work and pavement repurposing to increase the available queue storage on entry ramps within the pilot section. Despite these works, a small number of key locations were unable to be suitably upgraded to cater for the high traffic demands that were expected and/or experienced during operations. This can be a real-world challenge when provisioning of additional storage can potentially impact high costs assets, such as the widening of bridge structures or ramps with little physical space for expansion.

Ramp designs were initially based on traffic data from 2016/17. Significant changes occurred between the design and the operations phase of the project resulting in much higher flows on some ramps than anticipated.

Examples of locations where operational flexibility was limited due to physical limitations:

- **Ridgegate Parkway Entry Ramp:** No modifications were undertaken at this ramp. During the pilot project, the traffic demands experienced on this ramp greatly exceeded the stopline discharge and storage provisions which caused queues to extend onto the adjacent arterial for significant lengths during the early stages of operations.
    - In order to limit the impact of queues on the ramp impacting the upstream facility, the ramp metering was not able to run with full flexibility during the full operations stage, thereby allowing too much traffic to enter the corridor at critical times, making the nearby downstream bottleneck more difficult to manage effectively.
    - An additional detector was added during pilot operations to account for some drivers that drifted into shoulder space at the back of the ramp. This improved the queue algorithm

responsiveness and assisted in better managing queues; however, it did not significantly improve the capacity of the ramp to assist mainline operations.

- **C-470 to I-25 System Entry Ramp:** Widening of the ramp at the stopline enabled very high discharge flows, however the length of the overall storage was significantly below design requirements for the expected design flows and the flows eventually experienced during operations. Long queues were able to quickly develop when metering was too restrictive, and drivers did not use the additional lanes at the stopline.
  - Following activation, the ramp was initially inhibited during the heaviest part of the AM peak but gradually switched on for longer periods during the busy period while being closely monitored whenever it was operating and manually overridden is queues did reach agreed threshold lengths.
  - To limit the impact of queues extending to the upstream facility, the ramp metering was not able to run with full flexibility during the full operations stage, thereby allowing too much traffic to enter the corridor at critical times.
  - The excess flows from this ramp, particularly during the height of the AM peak period regularly contributed to the occurrence of flow breakdown at downstream bottlenecks.
- **Evans Road Entry Ramp:** No modifications were undertaken on this ramp. In addition to having only half the desired design storage, two additional aspects limited the effectiveness of this ramp to manage the nearest downstream bottleneck.
  - The ramp feeds into a short collector-distributor arrangement and also provides a non-conventional access to a local road exit ramp.
  - These arrangements result in a greater distance between the ramp meter and the mainline merge which decreases the effect of breaking up traffic platoons – traffic can "re-bunch" before reaching the mainline merge.
  - Not all traffic using the ramp meter is bound for the freeway mainline as they can also directly access two exits from the ramp and collector arrangement. This has the effect of using queue storage for traffic that will not access the freeway mainline and due to the unknown balance of traffic accessing the mainline, the metering algorithms cannot appropriately gauge the amount of traffic to resolve instability at the merge bottleneck.

8.10 Device and System Challenges

Throughout the various stages of the pilot demonstration, various devices or system faults introduced challenges for operating the coordinated ramp metering system at optimum levels. Device and system faults can have varying degree if impact on operations depending on the location and the time over which they may occur. In some cases, very minor impact may be experienced where the control system can compensate for the problems that arise. In other cases, impacts can be more noticeable and can potentially result in sub-optimal conditions in the pilot section. The following list summarises some of the challenges that were experienced through the pilot project and highlight the need for prompt responses to enable the return to optimal operations as soon as possible.

- Intermittent communication or power faults with detection, limited available data for operations and data collection.
- Prolonged ramp detector faults (on a small number of ramps) limited ramp operations to either fixed time operations or switched off – operations is not effective for mainline control. E.g. the Belleview entry ramp did not have effective queue management throughout the entire project, although queue impacts could be mitigated due to the excess available storage at this site.
- Delayed availability of flashing warning beacons on system ramps – initially delayed transition to full operations and resulted in the C-470 ramp meter being deactivated (and therefore ineffective) for 2+ months during the full operations.
- Failed flashing warning beacons on the C-470 Ramp resulted in metering operations being suspended for safety reasons. The beacons remained in a failed state from 9 May 2022 until the end of the full operations stage, resulting in uncontrolled high flows especially during the AM peak for the last 12 weeks of the pilot operations.

- Lantern pedestals being struck by vehicles, removing the ability to meter at some sites for varying periods. This situation also caused a delay in the transition to full operations.
- Roadside detector installations being struck by vehicles and remining inactive for a time.
- General debris blocking TIRTL detector beams, although this was generally remedied promptly onsite.
- Significant and regular (above average) snowfalls throughout the December to February period resulted in blocked TIRTL detector beams often for days until melted. This often resulted in ramp operations being disabled or detuned (fixed-time) in agreement with CDOT.

8.11 Incidents and Events – Observations from Data

It is possible to identify significant and some minor incidents in from the data collected throughout the baseline and operational stages. Incidents can be observed in the heat plots produced from the processed speed, flow and occupancy data. Analysis of the processed travel time data can also be used to identify unusual events that cause rapid and excessive increases in travel time, both at a section level and overall corridor level.

During the operational stages, close monitoring of conditions was undertaken during peak periods which also allowed more accurate identification of incidents as they were logged by operators. Monitoring logs are available as part of other project deliverables and can be reviewed in conjunction with this report.

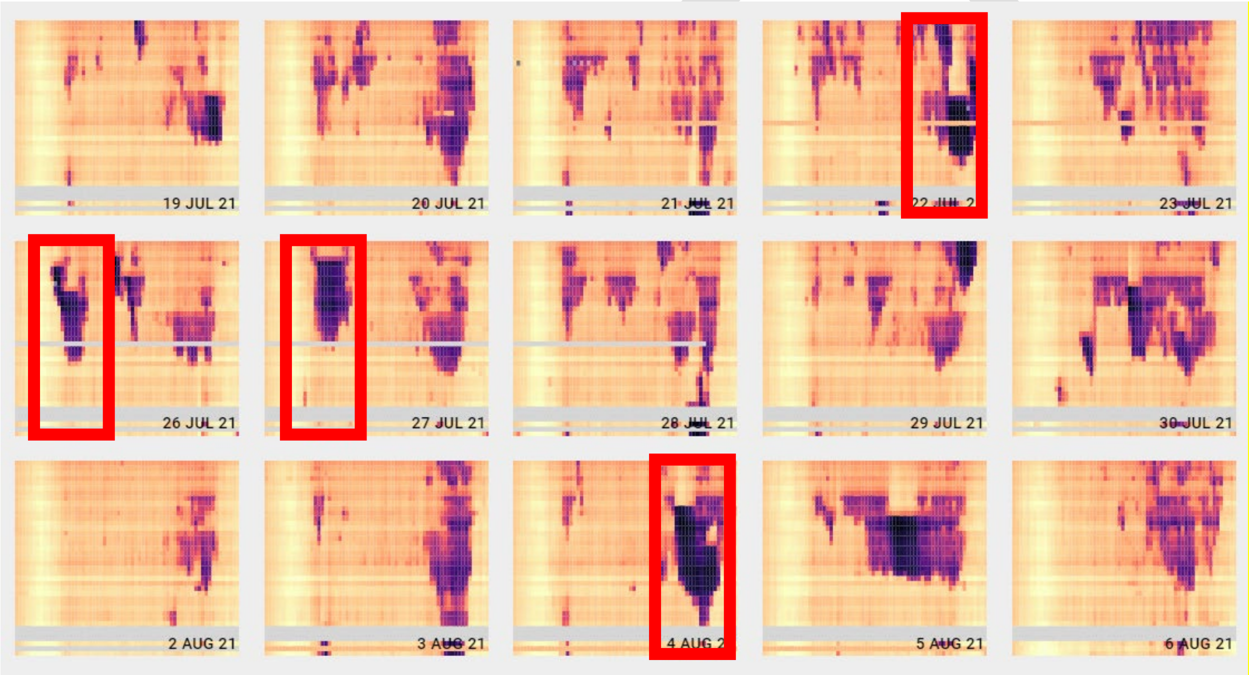


Figure 53: Example of Excluded Periods during the Baseline Data Collection Phase

All excluded periods within the data collection period are listed in Appendix B and are also highlighted on daily heat plots in Appendix H.

9 COVID-19 Pandemic Impacts

During 2020, from March onwards, much of the world, including Denver CO, entered into lockdowns with varying levels of restrictions due to the COVID-19 Pandemic. “Stay at Home” orders were issued for Denver which significantly impacted the levels of traffic flow in the I-25 corridor due to the reduction of commuting trips to the Denver downtown area and other large employment areas, such as the Denver Tech Center. Significant reduction in on campus learning at educational facilities also reduced the amount of personal vehicle trips taken the corridor. Throughout the remainder of 2020 and 2021, most workers that could work from home did so resulting in a significant reduction in demand throughout the day.

At the time of the commencement of the Smart 25 pilot project in July 2021, a significant number of workers in the greater Denver area were still working from home, although with the easing of some restrictions, some activities involving on-road travel was returning to the road network, impacting different parts of the network at different times of the day. It is also understood that the utilization of public transit services (such as the light rail services in the I-25 corridor) was lower than prior to the pandemic.

Throughout the operational stages of the pilot project, there were continued changes to traffic patterns as travel and economic activity returned to the transport network after periods of stay at home orders and other restrictions. Although the term “returned’ is used, it is reasonable to assume and also likely that the post-pandemic conditions will differ from those prior and this is evident from some of the analysis presented in the following sections. Differences are expected both in the level of demand in the corridor as well as the way in which the corridor is utilized (i.e. trip types, trips by time of day, trip lengths, changed origin destination patterns, mode shift from transit to private vehicles etc.).

To understand some of the changes, historic traffic volume and travel time data was sourced from available CDOT sources.

9.1 Long Term Traffic Volume Data

Section 5.5 outlines the locations of permanent count stations on the I-25 in the vicinity of the pilot section. Data from Site No. 000012 was used for the following discussion, which is considered representative of the traffic demand entering the pilot section from the south. It is acknowledged that the demands entering and leaving the I-25 corridor within the pilot section will also likely have changed over time, however, there is insufficient data from the intersecting routes or ramps to further analyse long term changes in demands.

The information presented in the following plots compares traffic volume data from the years up to and including 2021 and provides some context for the changing traffic patterns entering and utilizing the I-25 corridor pilot section. It is noted that 2022 AADT data is not available until after 2022 so the plot below cannot be updated to cover most of the operational stages of the pilot project.

9.1.1 Long Term Changes in AADT

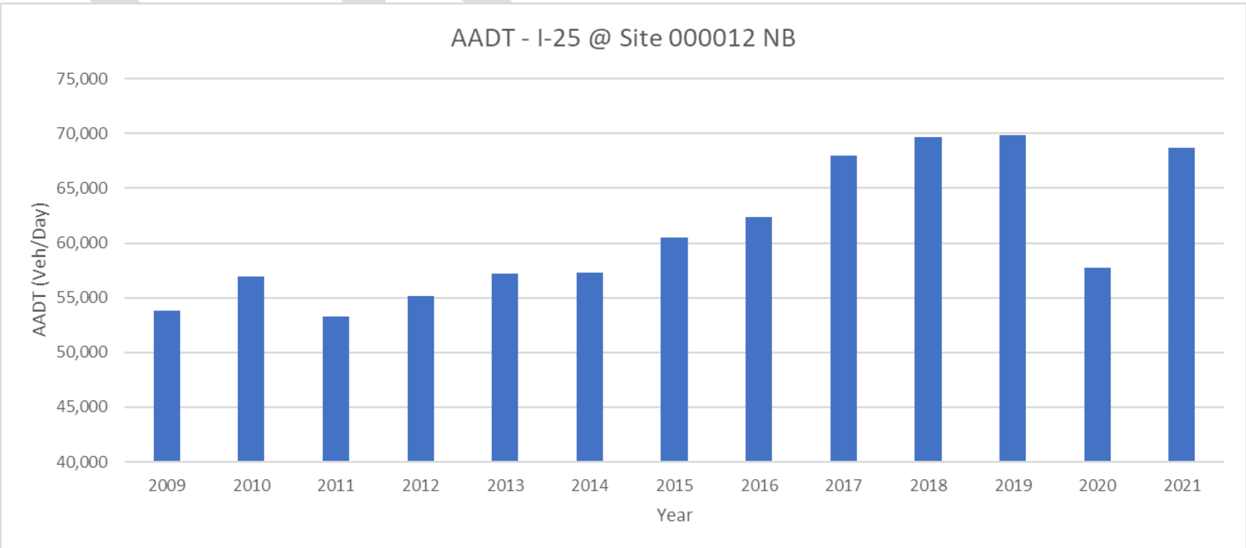


Figure 54: PCS No. 000012 – AADT from 2009 to 2021

Figure 54 shows that Average Annual Daily Traffic (AADT) demand entering the I-25 northbound grew steadily from 2011 to 2019, with some indication that daily demands may have been starting to plateau around 2018-2019. During 2020, the AADT was reduced by about 17% compared with the preceding year. The 2021 AADT was marginally lower than in 2019 (by about 2%), although it is important to understand the different demand patterns across the day, which is discussed in more detail below.

It is also noted that the original planning for the Smart 25 Pilot was undertaken in 2015-2016 using traffic data available at the time. By the time delivery activities for the pilot were underway in 2019, daily traffic volumes had increased on average by about 15% and in 2021 were still 13% higher than the planning demands used for design.

9.1.2 Changes in Daily Volumes by Month

Figure 55 compares average weekday daily volumes across the years 2019-2022 by month, in part to understand the potential seasonality patterns as well as the impacts of the COVID-19 pandemic. Peak months are generally through June-August, discounting the 2020 volumes.

The 2020 volumes were expectedly well below nearby years due to restrictions, with the most notable reduction in April 2020.

Volumes though the second half of 2021 were similar to 2019 across the whole day, although as discussed further below, patterns across the day are different.

Volumes in the first quarter of 2022 were above 2021 volumes, but below 2019. From the start of the second quarter of 2022 (April onwards), volumes exceeded those from 2019. The sections below indicate the period of the day in which these increases were experienced.

To understand whether there was a significant change in demands due to relaxing COVID-19 Pandemic conditions, it is important to compare the similarity for baseline stage and the following operational stages. It can be seen that the yellow Arterial Ramps Only stage is below the levels of the Baseline and Full Operations stages. The Full Operations and Baseline stages are fairly similar although the Full Operations starts a bit lower and ends a bit higher.

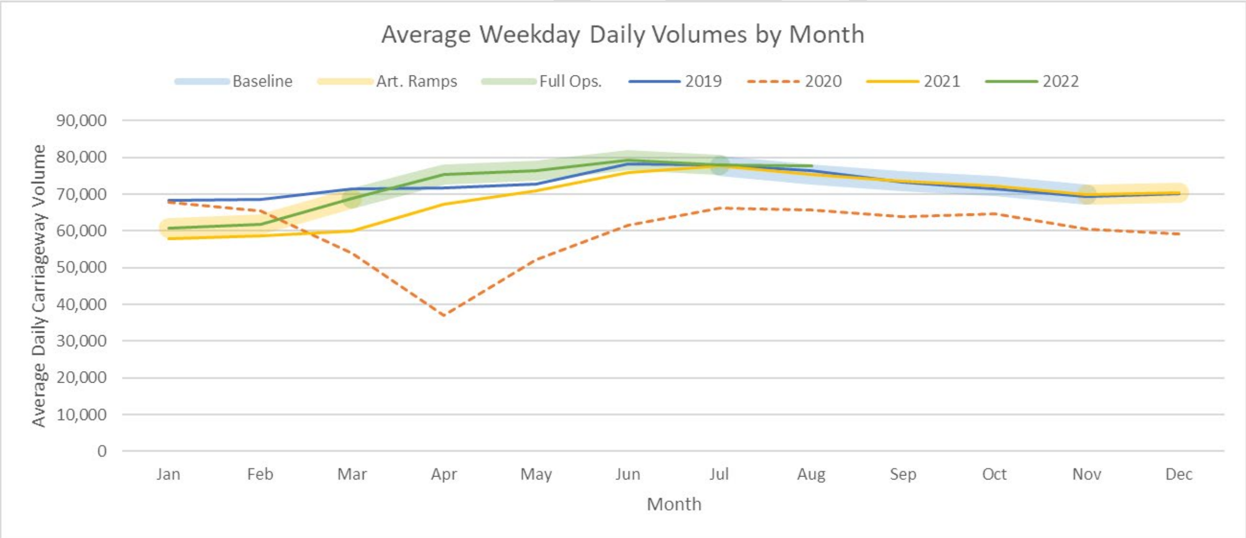


Figure 55: PCS No. 000012 – Peak Period Average Volumes from 2019 to 2022

9.1.3 Changes in Daily Traffic Profile – Yearly

Figure 56 has been updated from the equivalent figure in the *Baseline Performance Report* with 2022 data. To account for only part of 2022 being included, the data from 2019-2021 has been limited to the same months to avoid the impacts of seasonality in the latter part of the year. The figure demonstrates that the distribution of trips across the day had significant year on year changes during the COVID-19 pandemic. It is observed that the changes in patterns are not uniform across the day nor necessarily aligned with the AADT (daily) changes discussed above.

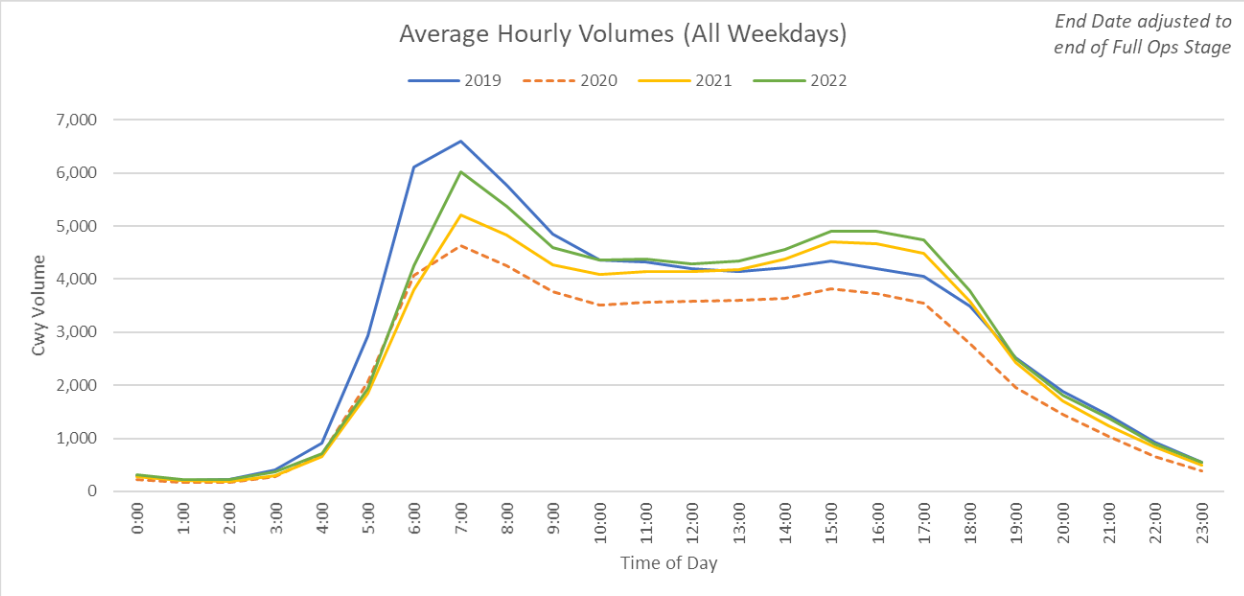


Figure 56: PCS No. 000012 – Daily Average Weekday Volume Profile from 2019 to 2022

The AM peak period exhibits an expected drop in the 2020 Pandemic impacted year traffic and a recovery rise in 2021, although still not back to 2019 levels.

The PM peak period on the other hand sees a shift towards increased on-road activity during 2020. The PM Post-Pandemic demands were notably higher than the two prior years.

The 2022 data shows a continued growth in the High Off-Peak and PM Peak with the added significant rise in the AM Peak over 2021 volumes. The AM peak period in 2022 is still not back to the levels in 2019, with the 2022 starting later and not reaching the same AM maximum.

Figure 57 below summarises the total average volumes in the peak periods which reinforces the summary above.

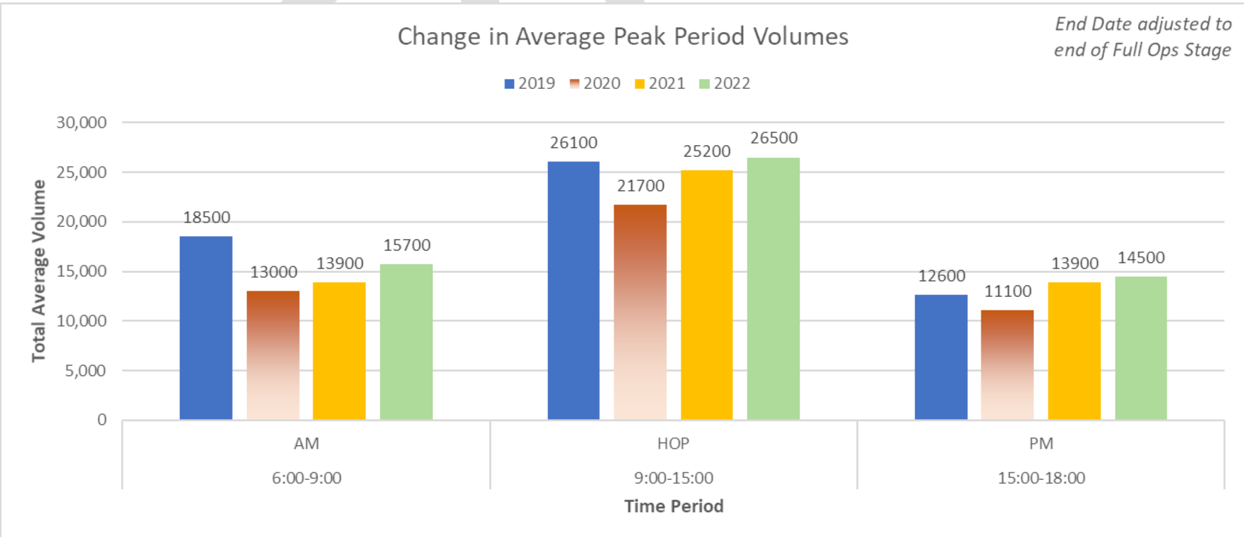


Figure 57: PCS No. 000012 – Peak Period Average Volumes from 2019 to 2022

9.1.4 Changes in Daily Traffic Profile – Pilot Project Stages

The following comparison of the pilot project stages is provided here in the context that the data is sourced from the same location as the extended historic review of impacts due to the COVID-19 Pandemic.

The profiles shown in Figure 58 below show that northbound volumes entering the pilot section reduced below the baseline period during the arterial ramps only stage. This is somewhat expected with the holiday period and lower seasonal demand from November to February. Inclement weather is also likely to have influenced the arterial ramps only stage with significant snowfalls throughout January and February 2022. The full operations period shows a slightly higher volume across the day than the baseline period – in the order of 2-4% during peak periods. A further comparison of traffic flows within the pilot section of the corridor is provided in Section 8.3.1.

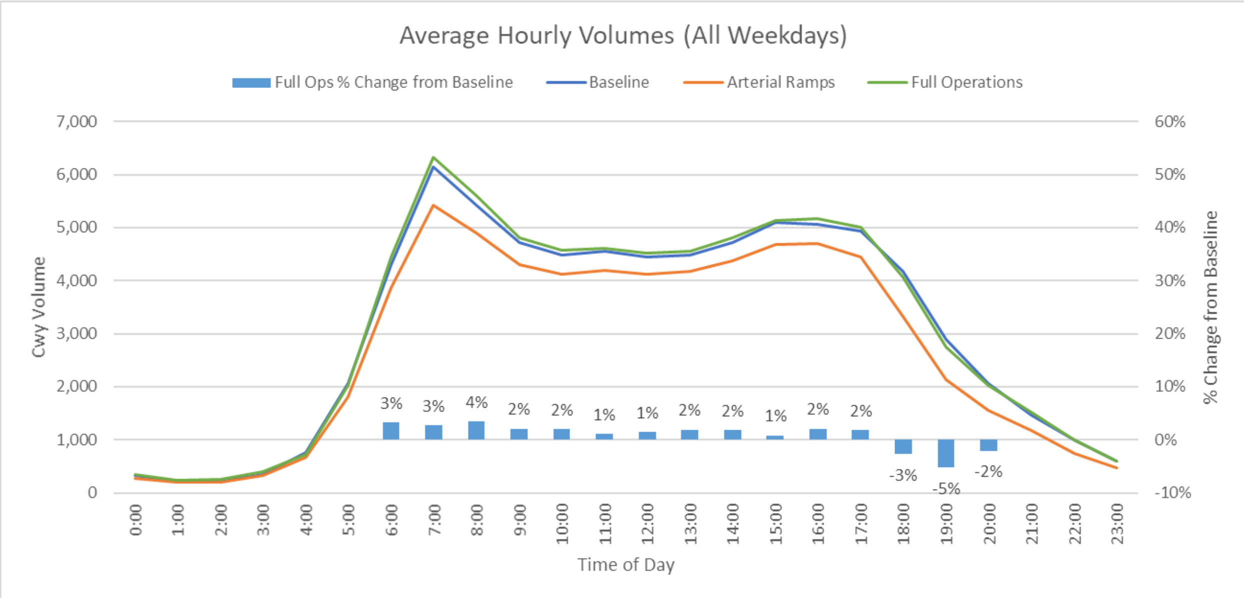


Figure 58: PCS No. 000012 – Peak Period Average Volumes – Pilot Project Stages

9.1.5 Changes in AADT

Figure 59 shows the Daily AADT across the ~3½ year period from 2019-2022. The highlighted areas show the various stages of the pilot project. This assists in understanding the operating conditions during the baseline and operating stages and demonstrates consistency with the changes in the average daily weekday profiles, shown in Figure 56.

Across the AM Peak Period, in the 2021 baseline period, the volumes remained below those experienced in 2019, but higher that 2020 volumes for the same period.

Across the PM Peak Period, in the 2021 baseline period, volumes exceed the 2019 (and 2020) volumes.

Across the entire day, baseline traffic volumes in 2021 are quite similar to 2019, although based in the inspection of the peak period volumes, this suggests a shift in times of travel and / or a change in the trip types and origin / destination patterns along the I-25.

During 2022, which mostly covered the operational stages, it can be seen that the AM Peak volumes exceed 2021 but remain below 2019 volumes. However, the in PM peak and all day flows, the 2022 generally trend higher than previous years, especially from March onwards.

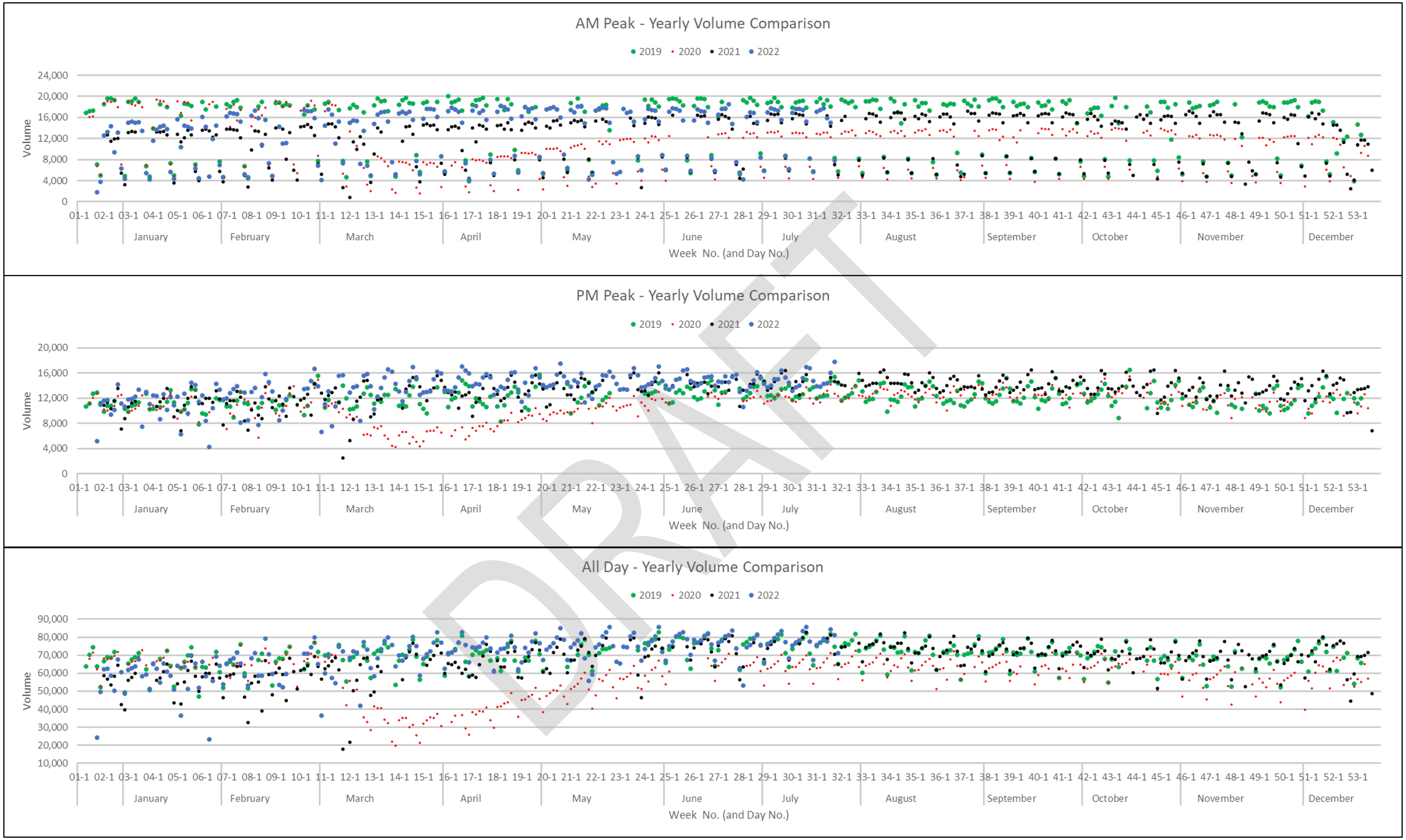


Figure 59: PCS No. 000012 – Daily AADT Date Series from 2019 to 2022

9.2 Long Term Travel Time Data

(Note: The figures and summary of the historic travel times in this section are unchanged from the Baseline Performance Report.)

Travel time measures from the three full years from 2019 to 2021 inclusive have been produced from the INRIX data made available for the corridor. The comparison across the three years was undertaken to help understand the changes in travel times in the pilot section of the I-25 before and during the COVID-19 pandemic. At the time of the data collection period, some restrictions were still in place meaning that conditions had not returned to pre-pandemic settings.

Figure 60 shows the average travel time daily profiles for each year and Figure 61 shows the overall AM and PM peak period average travel times and planning times (95th percentiles).

During 2019, it is noted that both AM and PM peak periods experience similar average travel times and planning times.

As expected, with significant reductions in traffic demand in the corridor, travel times throughout 2020 were very low with small travel time increases above free-flow during the PM peak period (TTI<1.15). When reviewing the travel time data in parallel with the traffic volume data entering from the southern end of the corridor, it is interesting to note that the 2019 and 2020 volumes are quite similar during the PM Peak period. It is possible that this demand pattern did not carry all the way through the corridor. There is also potential that the origin-destination patterns through the corroder were different changing the way that ramp traffic interaction and congestion patterns formed.

During 2021, with restriction easing but setting not returning to pre-pandemic settings, peak period delays began to increase, although they did not return to the 2019 levels. It is also observed that the peak period impacts differed with the AM Peak period experiencing lower travel times that the PM peak. This may be due to differences in types of trips or the occupations of the road users using the corridor compared with pre-pandemic times, changing the dominant times at which people were using the corridor, in addition to lower overall demands in the AM peak.

Comparing the corresponding 2021 vs 2019 traffic volume data from the south also indicates likely changes in traffic patterns (trip purposes by time of day and trip ends) throughout the corridor. During the AM peak, entering volumes had almost returned to 2019 levels, be it with about a 30-minute to 1-hour delay in the start of the peak period. During the PM peak period, entering volumes were almost 500 vehicles / hour higher.

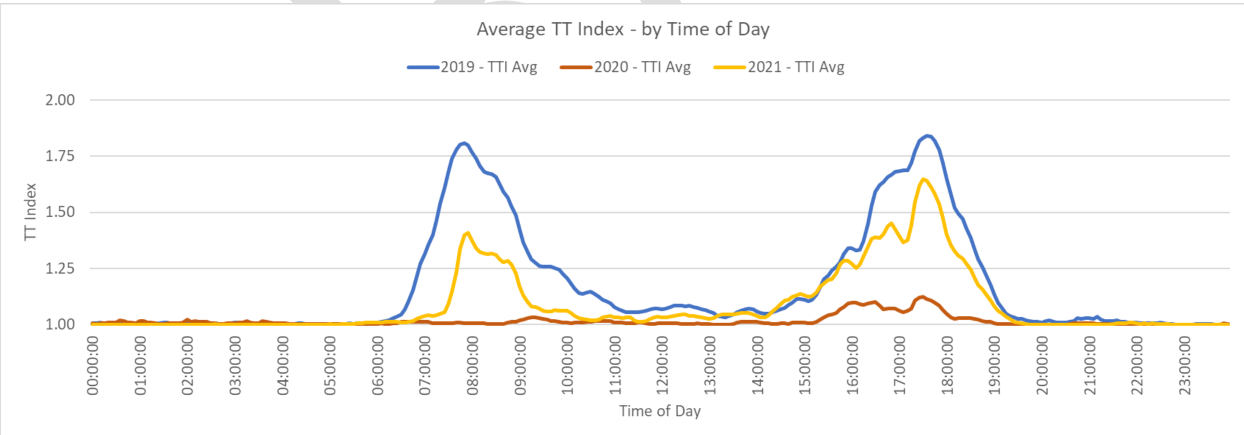


Figure 60: Daily Average Travel Time Profiles from 2019 to 2021

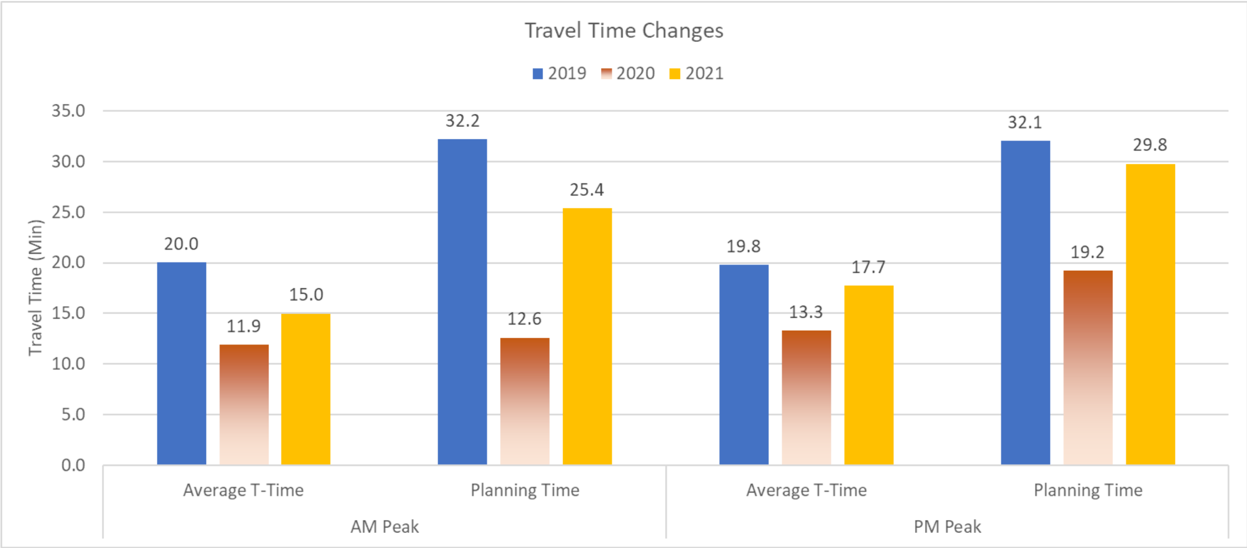


Figure 61: Peak Period Travel Time and Travel Time Indices from 2019 to 2021

10 Conclusion

The main performance indicators that have been used to assess the full operation stage of the SMART 25 pilot project shows that significant travel time and delay reductions have been achieved. Greater improvements were experienced during the PM peak. Although significant reduction in delays were still measured during the AM peak, the changes in travel times were small.

Challenges in managing the AM peak period demands are likely due to the very short but very high traffic demand peak the generally occurs in the corridor between 7:30 and 8:00AM. This was particularly evident on the C-470 system ramp. While challenges at this ramp are not the only contributor, the lack of physical queue storage to enable effective restrictive control when needed, and the device faults inhibiting operations during the project, limited the system's ability to prevent more flow-breakdown than occurred.

While areas of flow breakdown still occurred during the PM peak period, the reductions in travel time and delay as a result of the pilot ramp metering operations, in spite of the rise in demand in the PM peak (compared with prior periods – baseline and pre-pandemic).

The coordinated ramp metering operations have demonstrated that increased operational capacity (higher sustainable flows) have been achieved and that even when flow-breakdown has occurred, average speeds are still higher in the congested conditions than during the baseline stage.

Although the SMART 25 pilot project was impacted by the COVID-19 Pandemic and the associated impacts on traffic demands, analysis of the traffic demands and flows entering and throughout the corridor have shown that the demands in the corridor remained comparable during the full operational stage of the project. It was observed the that average demands across the whole arterial ramps only operational stage of the pilot were notably lower than the baseline and full operations stages.

The benefits that have been reported were achieved despite a number of the challenges discussed in this report. These include, but are not limited to:

- Higher volumes in the corridor and on various ramps due to a combination of delayed commencement of the project and interim growth in the southern greater Denver area.
- Insufficient ramp capacity on some key ramps due to project and physical constraints
- Adverse weather impacting the pilot corridor
- Congestion queuing back into the pilot project section from downstream locations, both on the I-25 and an intersecting route
- Device and system faults and losses restricting the ability operate the coordinated ramp metering at full capability at all times.

11 References

CDOT. (2005). *Best Practices Guidebook: Collecting Short Duration Manual Vehicle Classification Counts on High Volume Urban Facilities.* Denver, CO: CDOT.

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Appendix A

Alignment of INRIX TT Sections and TIRTL Based Mainline Segments

The alignment of the travel time sections for each of the data sets (TIRTL and INRIX based) is mostly influenced by the predefined locations and source system attributes. The primary principal for alignment was ensuring that the overall length of the pilot section matched. In the event that measures from the different sources are compared throughout the entire project area, the distance travelled overall would be the same.

The two parts of Figure 62 shown below are equally scaled and aligned by starting chainage to demonstrate the proximity and alignment of the various defined segments and sections.

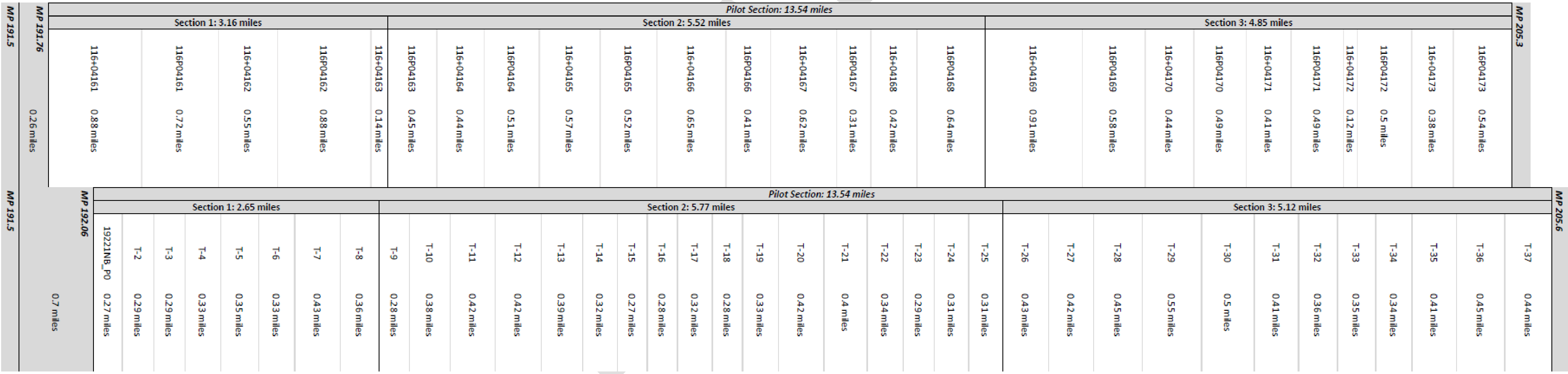
The predefined INRIX waypoint locations were the controlling data set for setting the overall pilot section measurement length of 13.54 miles. The INRIX travel time sections are only used for reporting travel times by the overall and section lengths.

- The start was aligned with the first waypoint before the Ridgegate Parkway entry ramp – Segment Starting ID 116+04161 at Approx. MP 191.76
- The end was aligned with the last waypoint in the vicinity of the University Boulevard entry ramp – Segment Ending ID 116P04173 at Approx. MP 205.30
    - It is noted that the end of the INRIX based travel time segments ends just prior to the final TIRTL detector (T-37 @ MP205.42), however, this was considered reasonable to avoid capturing travel time information from beyond the study area by too great a distance.

The segments defined from the TIRTL detector locations were generally positioned so that the related TIRTL detector was centered in each segment. The exception to this is the two end segments which were marginally adjusted in length on the side without a neighboring TIRTL detector. These end adjustments were applied to match the overall pilot section length for consistent comparison of metrics. The mainline detection based segments were used to determine VMT, VHT, average section speeds and mainline delays.

- The start of the first mainline TIRTL based measurement segment is approx. MP 192.06
- The end of the last mainline TIRTL based measurement segment is approx. MP 205.60

INRIX Travel Time Sections



TIRTL Detector Based Segments (Detector generally centered within each segment)

Figure 62: Segment and section definitions utilised for data aggregation and reporting – Alignment between INRIX and TIRTL based segments

It can be seen from the aligned segment and section references that the three sub-sections (1, 2 and 3) have slightly different reference locations and lengths. Again, this is due to the pre-existing INRIX waypoints and the real-world mis-alignment that arises in order to ensure reasonable segment definitions using the mainline TIRTL detectors' locations and ensure consistent aggregation of volume dependent metrics.

Figure 63 and Figure 64 below demonstrate the proximity of the start and end of the travel time sections based on the two data sources.

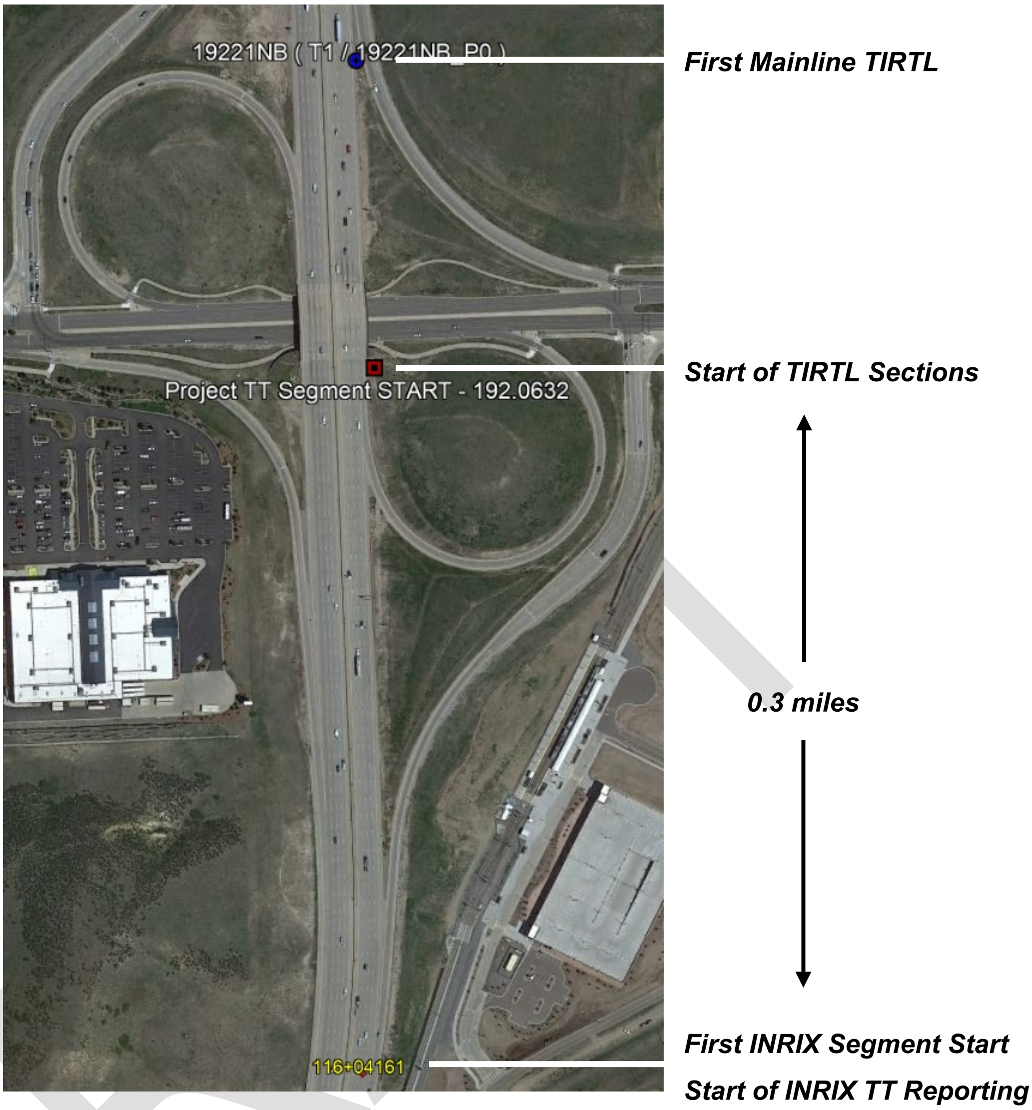


Figure 63: Segment start references – southern end (near Ridgegate Parkway)

Figure 64: Segment end references – northern end (near University Boulevard)

Appendix B

Exclusion Dates

Table 28: List of Excluded Dates

Date Exclusions	Reason	Peak Affected	Holiday / Period
Thu, 22/Jul/2021	Major Incidents	PM Peak	Data Collection
Mon, 26/Jul/2021	Major Incidents	AM Peak	Data Collection
Tue, 27/Jul/2021	Major Incidents	AM Peak	Data Collection
Wed, 04/Aug/2021	Major Incidents	PM Peak	Data Collection
Mon, 16/Aug/2021	Major Incidents	PM Peak	Data Collection
Thu, 19/Aug/2021	Major Weather	PM Peak	Data Collection
Tue, 24/Aug/2021	Major Incidents	All	Data Collection
Wed, 25/Aug/2021	Major Incidents	AM Peak	Data Collection
Thu, 02/Sep/2021	Major Incidents	AM Peak	Data Collection
Mon, 06/Sep/2021	Holiday	All	Labor Day
Thu, 09/Sep/2021	Major Incidents	AM Peak	Data Collection
Mon, 13/Sep/2021	Major Incidents	PM Peak	Data Collection
Wed, 15/Sep/2021	Major Queue back	PM Peak	Data Collection
Thu, 16/Sep/2021	Major Incidents	PM Peak	Data Collection
Tue, 28/Sep/2021	Major Incidents	AM Peak	Data Collection
Mon, 04/Oct/2021	Holiday	All	Francis Xavier Cabrini Day
Tue, 12/Oct/2021	Major Incidents	AM Peak	Data Collection
Wed, 13/Oct/2021	Major Queue back	AM Peak	Data Collection
Tue, 26/Oct/2021	Major Incidents	PM Peak	Data Collection
Wed, 27/Oct/2021	Major Incidents	AM Peak	Data Collection
Mon, 08/Nov/2021	Major Incidents	PM Peak	Arterial Ramps Only
Thu, 11/Nov/2021	Holiday	All	Veterans Day
Mon, 15/Nov/2021	Major Incidents	AM Peak	Arterial Ramps Only
Fri, 19/Nov/2021	Major Incidents	PM Peak	Arterial Ramps Only
Wed, 24/Nov/2021	Holiday Related	All	Thanksgiving
Thu, 25/Nov/2021	Holiday	All	Thanksgiving
Fri, 26/Nov/2021	Holiday Related	All	Thanksgiving
Mon, 29/Nov/2021	Major Incidents	All	Arterial Ramps Only
Fri, 10/Dec/2021	Major Weather	AM Peak	Arterial Ramps Only
Fri, 24/Dec/2021	Holiday Related	All	Christmas
Sat, 25/Dec/2021	Holiday	All	Christmas
Sun, 26/Dec/2021	Holiday	All	Christmas
Mon, 27/Dec/2021	Christmas Assoc.	All	Arterial Ramps Only
Tue, 28/Dec/2021	Low Demand + Incidents	All	Arterial Ramps Only
Wed, 29/Dec/2021	Low Demand + Incidents	All	Arterial Ramps Only
Thu, 30/Dec/2021	Low Demand + Incidents	All	Arterial Ramps Only
Fri, 31/Dec/2021	Holiday	All	New Year
Sat, 01/Jan/2022	Holiday	All	New Year

Date Exclusions	Reason	Peak Affected	Holiday / Period
Sun, 02/Jan/2022	Snow	All	Arterial Ramps Only
Mon, 03/Jan/2022	Snow	All	Arterial Ramps Only
Tue, 04/Jan/2022	Snow	All	Arterial Ramps Only
Wed, 05/Jan/2022	Snow	All	Arterial Ramps Only
Thu, 06/Jan/2022	Snow	All	Arterial Ramps Only
Fri, 07/Jan/2022	Snow	All	Arterial Ramps Only
Fri, 14/Jan/2022	Snow	All	Arterial Ramps Only
Mon, 17/Jan/2022	Holiday	All	Martin Luther King Jr. Day
Wed, 19/Jan/2022	Snow	All	Arterial Ramps Only
Fri, 21/Jan/2022	Snow	All	Arterial Ramps Only
Tue, 25/Jan/2022	Snow	All	Arterial Ramps Only
Wed, 26/Jan/2022	Snow	All	Arterial Ramps Only
Thu, 27/Jan/2022	Snow	All	Arterial Ramps Only
Fri, 28/Jan/2022	Snow	All	Arterial Ramps Only
Sat, 29/Jan/2022	Snow	All	Arterial Ramps Only
Tue, 01/Feb/2022	Snow	All	Arterial Ramps Only
Wed, 02/Feb/2022	Snow	All	Arterial Ramps Only
Thu, 03/Feb/2022	Snow	All	Arterial Ramps Only
Fri, 04/Feb/2022	Snow	All	Arterial Ramps Only
Sat, 05/Feb/2022	Snow	All	Arterial Ramps Only
Sun, 06/Feb/2022	Snow	All	Arterial Ramps Only
Fri, 11/Feb/2022	Snow	PM Peak	Arterial Ramps Only
Sat, 12/Feb/2022	Snow	All	Arterial Ramps Only
Sun, 13/Feb/2022	Snow	All	Arterial Ramps Only
Wed, 16/Feb/2022	Snow	PM Peak	Arterial Ramps Only
Thu, 17/Feb/2022	Snow	All	Arterial Ramps Only
Fri, 18/Feb/2022	Snow	All	Arterial Ramps Only
Sat, 19/Feb/2022	Snow	All	Arterial Ramps Only
Mon, 21/Feb/2022	Holiday	All	Washington-Lincoln Day
Tue, 22/Feb/2022	Snow	All	Arterial Ramps Only
Wed, 23/Feb/2022	Snow	All	Arterial Ramps Only
Thu, 24/Feb/2022	Snow	All	Arterial Ramps Only
Fri, 25/Feb/2022	Snow	All	Arterial Ramps Only
Sat, 26/Feb/2022	Snow	All	Arterial Ramps Only
Sun, 27/Feb/2022	Snow	All	Arterial Ramps Only
Mon, 28/Feb/2022	Snow	All	Arterial Ramps Only
Sun, 06/Mar/2022	Snow	AM Peak	Arterial Ramps Only
Mon, 07/Mar/2022	Snow	AM Peak	Full Operations
Tue, 08/Mar/2022	Major Incidents	PM Peak	Full Operations
Wed, 09/Mar/2022	Snow	All	Full Operations
Thu, 10/Mar/2022	Snow	All	Full Operations
Fri, 11/Mar/2022	Snow	All	Full Operations
Sat, 12/Mar/2022	Snow	AM Peak	Full Operations

Date Exclusions	Reason	Peak Affected	Holiday / Period
Thu, 17/Mar/2022	Snow	All	Full Operations
Fri, 18/Mar/2022	Snow	AM Peak	Full Operations
Wed, 23/Mar/2022	Major Incidents	PM Peak	Full Operations
Tue, 29/Mar/2022	Major Weather	PM Peak	Full Operations
Thu, 31/Mar/2022	Holiday	All	Cesar Chavez Day
Thu, 07/Apr/2022	Major Incidents	All	Full Operations
Thu, 14/Apr/2022	Major Incidents	AM Peak	Full Operations
Fri, 15/Apr/2022	Major Incidents	PM Peak	Full Operations
Tue, 19/Apr/2022	Major Incidents	AM Peak	Full Operations
Wed, 20/Apr/2022	Major Incidents	All	Full Operations
Thu, 21/Apr/2022	Major Incidents	PM Peak	Full Operations
Thu, 28/Apr/2022	Major Incidents	PM Peak	Full Operations
Mon, 02/May/2022	Major Weather	AM Peak	Full Operations
Tue, 03/May/2022	Major Queue back	PM Peak	Full Operations
Fri, 06/May/2022	Major Incidents	PM Peak	Full Operations
Wed, 11/May/2022	Major Incidents	PM Peak	Full Operations
Thu, 12/May/2022	Major Queue back	PM Peak	Full Operations
Tue, 17/May/2022	Major Incidents	All	Full Operations
Fri, 20/May/2022	Snow	PM Peak	Full Operations
Wed, 25/May/2022	Major Incidents	PM Peak	Full Operations
Thu, 26/May/2022	Major Incidents	AM Peak	Full Operations
Mon, 30/May/2022	Holiday	All	Memorial Day
Tue, 31/May/2022	Police Incident	PM Peak	Full Operations
Thu, 02/Jun/2022	Major Queue back	PM Peak	Full Operations
Tue, 07/Jun/2022	Major Incidents	AM Peak	Full Operations
Fri, 10/Jun/2022	Major Incidents	PM Peak	Full Operations
Tue, 14/Jun/2022	Major Incidents	All	Full Operations
Wed, 15/Jun/2022	Major Incidents	All	Full Operations
Thu, 16/Jun/2022	Major Incidents	PM Peak	Full Operations
Fri, 17/Jun/2022	Major Incidents	PM Peak	Full Operations
Wed, 22/Jun/2022	Incident and Weather	All	Full Operations
Thu, 23/Jun/2022	Major Incidents	PM Peak	Full Operations
Tue, 28/Jun/2022	Major Queue back	PM Peak	Full Operations
Sat, 01/Jul/2022	Major Incidents	PM Peak	Full Operations
Tue, 05/Jul/2022	Major Queue back	PM Peak	Full Operations
Mon, 11/Jul/2022	Major Incidents	PM Peak	Full Operations
Tue, 12/Jul/2022	Major Queue back	PM Peak	Full Operations
Thu, 14/Jul/2022	Major Incidents	PM Peak	Full Operations
Tue, 19/Jul/2022	Major Incidents	PM Peak	Full Operations
Wed, 20/Jul/2022	Major Incidents	PM Peak	Full Operations
Thu, 21/Jul/2022	Major Incidents	PM Peak	Full Operations
Tue, 26/Jul/2022	Major Incidents	All	Full Operations
Thu, 28/Jul/2022	Major Incidents	PM Peak	Full Operations

Appendix C

Derived Metrics Definition, References, Assumptions and Derivation

Extracts from Appendix G of the Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies (National Academies of Sciences, Engineering, and Medicine, 2012).

APPENDIX G

Computation of Travel Time Metrics

Introduction

The key principle for constructing reliability metrics for use in Project L03 was that the metrics had to be based on the measurement of travel times over an appreciable amount of time and meaningful highway distances. Travel times are easily relatable to nontechnical audiences, and once measured they can be transformed into a wide variety of additional metrics. The Travel Time Index (TTI) was used as the primary congestion metric in Project L03 for various reliability estimation and prediction models.

Three reasons exist for this choice. First, because study sections vary in length, using raw travel times is misleading, and the travel times must be normalized for distance. As a unitless index, the TTI is normalized. Second, the TTI is already in widespread use in congestion performance monitoring. Third, the moments and derivative measures derived from the TTI turn out to be identical to those of the travel time distribution for a particular road section and time slice. An alternative metric to the TTI is the travel rate (the inverse of space mean speed, in minutes per mile).

For the statistical modeling, moments from the distribution of TTIs were used as the dependent variables (e.g., the 80th percentile TTI). As shown below, these can be easily converted to travel times, and these travel times can be used to create additional performance metrics (e.g., delay).

Calculation of Travel Time Index

The starting point for the research was to transform field data into travel time–based metrics. The first step in this process was to define highway sections over which travel time statistics would be calculated. The following principles were used in defining sections:

- Sections should be relatively homogenous in terms of traffic and geometric conditions. Multiple interchanges are allowed as long as they do not provide for major drops or additions in traffic volumes along the section;
- Sections should represent portions of trips taken by travelers. Typical distances for urban freeway sections are 3 to 6 miles; and
- Major bottlenecks, defined as major freeway-to-freeway interchanges, can be present at the downstream end of the section, but never in midsection.

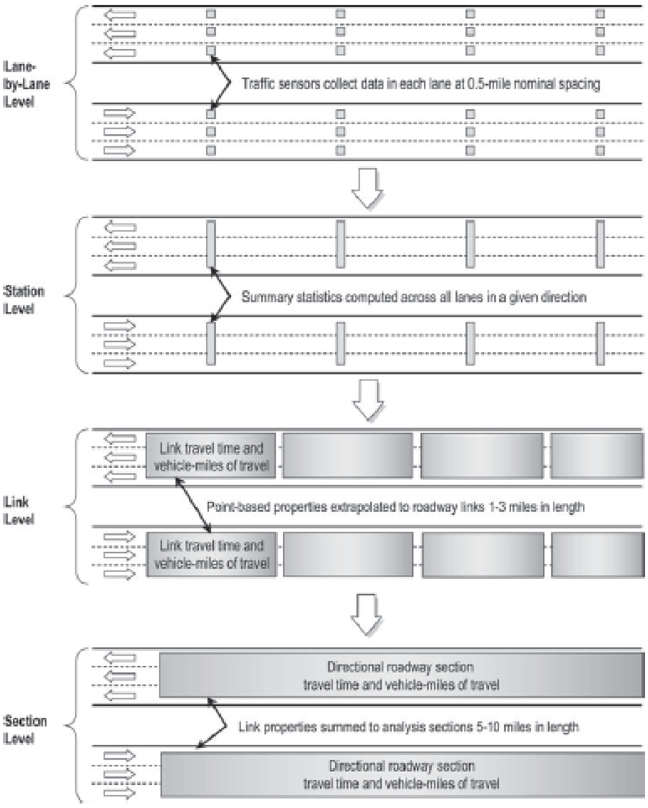
The majority of data that were available came from urban freeway surveillance systems, specifically, point detection of volumes and speeds from closely spaced equipment. These point measurements were converted to travel times over fixed highway distances with a method in widespread use by researchers and practitioners: it is assumed that the point speed measures the travel time over a distance half the distance to the nearest upstream and downstream detectors. This assumption works well if detector spacing is close (i.e., 0.5-mile spacing or less). Figure G.1 shows the process for computing section travel times from individual detectors; this was done at a 5-minute time interval level. For each detector zone, vehicle miles traveled (VMT) and vehicle hours traveled (VHT) were computed:

$$VMT = VOLUME * DetectorZoneLength \quad (G.1)$$

$$VHT = VMT / (Min(FreeFlowSpeed, Speed)) \quad (G.2)$$

When aggregating to the section level, at least half of the detectors had to report valid data for each of the 5-minute periods; otherwise the data were set to *missing*. If less than half of the detector data was missing, VMT and VHT were factored up based on the ratio of total section length to the sum of the lengths of the individual detector zones.

For every 5-minute interval in the year, total VMT and VHT were computed. From these, key performance measures were computed:



Source: Turner, S., R. Margiotta, and T. Lomax, *Monitoring Urban Freeways in 2003: Current Conditions and Trends from Archived Operations Data.* Report No. FHWA-HOP-05-018. December 2004. http://mobility.tamu.edu/mmp/FHWA-HOP-05-018/.

Figure G.1. Converting spot speeds to section travel times.

$$\text{SpaceMeanSpeed} = \text{VMT}/\text{VHT} \quad \text{(G.3)}$$

$$\text{TravelRate} = 1/\text{SpaceMeanSpeed} \quad \text{(G.4)}$$

$$\text{TTI} = \text{MAX}\left(1.0, \left[\text{TravelRate}/(1/\text{FreeFlowSpeed})\right]\right) \quad \text{(G.5)}$$

Because the bases for the measures were total VMT and VHT, the process was self-weighting. For urban freeways, FreeFlow-Speed was fixed at 60 mph. Note that TTI was not allowed to be lower than 1.0; that is, speeds higher than 60 mph were set to 60 mph. This adjustment was made because the purpose of the study was to measure congestion, not high speeds. If speeds were not capped, the resulting statistics would be biased because of the credit given to high speeds. However, the original data have been preserved for future examination by researchers who may wish to remove this restriction.

The congestion metrics were computed for each 5-minute period in a day over the course of a year. For any given analysis time slice (e.g., peak hour, peak period), a TTI distribution and its moments were computed as the VMT-weighted average of all the 5-minute TTIs in that time slice for the entire year. The various moments of the TTI distributions (e.g., 95th percentile TTI) were then used in the statistical modeling.

Table G.1. Travel Time and TTI Distributions for A.M. Peak Hour, Selected Atlanta Study Sections

Section	Travel Time (min)					TTI			
	Free-Flow	10th Percentile	Median	Mean	95th Percentile	10th Percentile	Median	Mean	95th Percentile
1	5.510	5.510	5.523	5.562	5.629	1.000	1.002	1.009	1.022
2	5.840	5.846	7.601	7.805	10.727	1.001	1.302	1.337	1.837
3	4.970	5.091	7.548	7.580	10.996	1.024	1.519	1.525	2.213
4	4.550	4.560	5.081	5.411	7.342	1.002	1.117	1.189	1.614
5	6.860	6.883	10.113	10.013	13.152	1.003	1.474	1.460	1.917

Note: Section 1 is a radial freeway leading away from the I-285 Beltway; its peak is in the afternoon.

Converting Predicted TTI Percentiles to Other Metrics

TTI percentiles can be thought of as a ratio comparing the travel time for a given percentile with the travel time under free-flow conditions. For example, a 95th percentile TTI of 1.8 means that the 95th percentile travel time is 80% higher than the free-flow travel time. Therefore, the travel time associated with any percentile can be computed as

$$\text{TravelTime}_n = \text{TTI}_n * \text{TravelTime}_{ff} \quad \text{(G.6)}$$

where n is the percentile and TravelTime_{ff} is the travel time under free-flow conditions.

Travel times can be combined with other data to compute other congestion-related metrics such as vehicle hours of delay:

$$\text{SpaceMeanSpeed} = \text{SectionLength}/\text{TravelTime} \quad \text{(G.7)}$$

$$\text{Delay} = \left(\left[\frac{\text{SectionLength}}{\text{SpaceMeanSpeed}}\right] - \left[\frac{\text{SectionLength}}{\text{FreeFlowSpeed}}\right]\right) * \text{Volume} \quad \text{(G.8)}$$

Percentiles for the various travel times can also be used to compute the Buffer Index and Skew Index:

$$\text{Buffer Index} = \frac{\left(\begin{array}{c}\text{95th percentile travel time}\\ -\text{ mean travel time}\end{array}\right)}{\text{mean travel time}} \quad \text{(G.9)}$$

$$\text{Skew Index} = \frac{\left(\begin{array}{c}\text{90th percentile travel time}\\ -\text{ median travel time}\end{array}\right)}{\left(\begin{array}{c}\text{median travel time}\\ -\text{ 10th percentile time}\end{array}\right)} \quad \text{(G.10)}$$

As an example, consider the data in Table G.1, which were derived from a few Atlanta study sections for 2007. Both the travel time and TTI distributions were developed by following the procedure discussed above. Applying Equation 6 for the 95th percentile for Section 2,

$$\begin{aligned}\text{95th percentile travel time} &= \text{95th percentile TTI} \\ &\quad * \text{free-flow travel time} \\ &= 1.837 * 5.840 \\ &= 10.728\end{aligned}$$

which matches the actual 95th percentile travel time developed straight from the data (accounting for slight round-off error).

Note also that the Buffer and Skew Indices can be computed either from the travel times or TTIs. Again for Section 2, the Buffer Index using the TTI distribution is

$$(1.837 - 1.337)/1.337 = 0.374$$

And with the pure travel times is

$$(10.727 - 7.805)/7.805 = 0.374.$$

Appendix D

Travel Time Results for Partial Length of the Full Operations Stage (to 9 May 2022)

These results are provided to cover the first part of the Full Operation stage when all 18 metered ramps were generally operating. On the 9 May 2022, the advanced warning beacons on the C-470 entry ramp failed resulting in the ramp being manually disabled for the remainder of the pilot operations period.

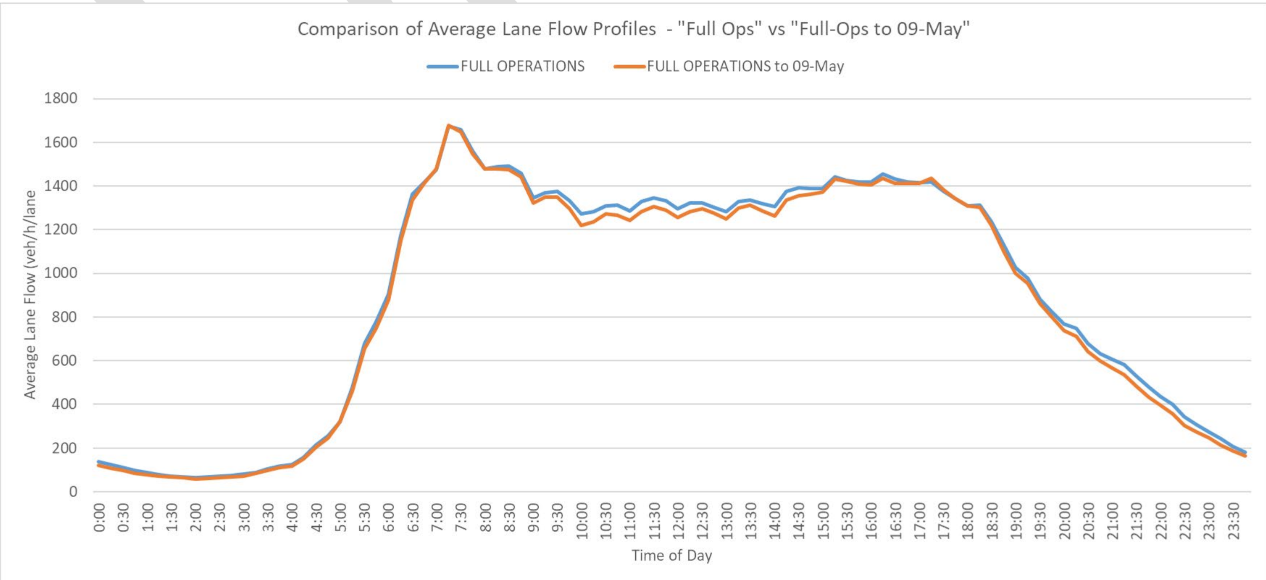
The partial period and complete period dates are as follows:

- 7 March to 9 May 2022 (9 weeks)
- 7 March to 29 July 2022 (21 weeks)

The following table provides the partial full operations stage alongside the complete full operations. It can be seen that the travel time reductions for the partial period are better than the complete period in the high off-peak and PM peak but worse in the AM peak.

Peak Period	Section	*Arterial Ramps Only (vs Baseline)*	*Full Operations (vs Baseline)*	*Full Operations to 09 May 202 (vs Baseline)*
AM Peak	**All**	**-0.9%**	**-2.0%**	**1.8%**
	Section 1	0.3%	-0.3%	**1.7%**
	Section 2	-0.1%	-3.7%	**1.0%**
	Section 3	-2.4%	-1.0%	**2.7%**
High Off-Peak	**All**	**-5.0%**	**-0.7%**	**-2.9%**
	Section 1	-1.5%	0.7%	**0.7%**
	Section 2	-5.5%	-1.3%	**-3.7%**
	Section 3	-6.4%	-0.7%	**-4.1%**
PM Peak	**All**	**-6.0%**	**-14.3%**	**-17.1%**
	Section 1	-3.7%	-6.3%	**-11.8%**
	Section 2	-4.8%	-18.0%	**-22.8%**
	Section 3	-8.7%	-14.0%	**-12.9%**

Since demand can influence the congestion and travel time outcomes, the following figure and table compare some flow and VMT comparisons for the same periods.



The figure above compares the average per lane flows in the corridor. This generally indicates that the AM and PM peak periods had similar overall lane flows while the high off-peak had lower lane flows. This could indicate a reason for the difference in the off-peak period, but it doesn't assist in understanding the AM and Peak Period

The table below shows average daily VMT and indicates that the average daily VMT for the complete period was higher than for the partial period, indicating higher demands across the day and can partly explain why travel times improvements across the complete full operations period were not as pronounced as the partial period.

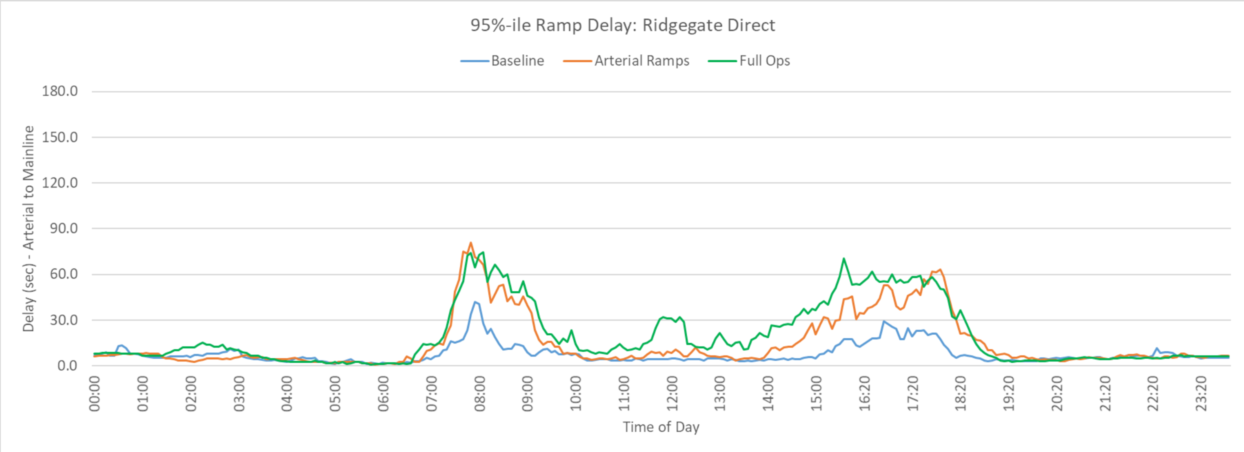
Pilot Section	Full Ops to July	Full Ops to May	Delta (May - July)
All	1,424,389	1,397,207	-27,182
Sec 1	214,728	210,060	-4,668
Sec 2	653,525	638,269	-15,257
Sec 3	556,136	548,879	-7,257

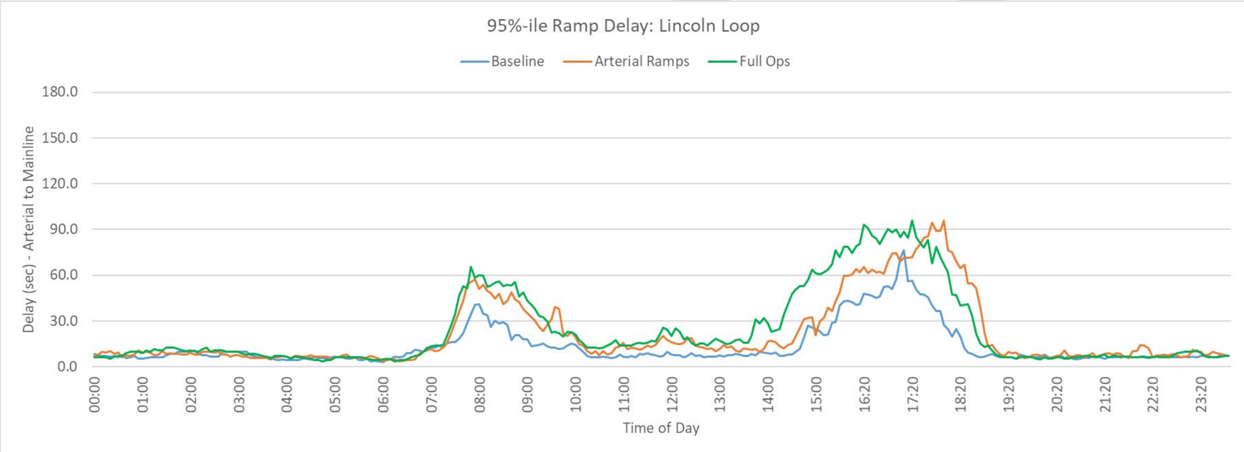
Whether the results (worse in the AM peak and better in the PM peak) can be attributed primarily to the operation of the C-470 ramp is difficult to ascertain. It could be expected that AM performance would be better given the high demands managed on the ramp during the AM peak, however this is not the measured outcomes which suggests other aspects are influencing the outcomes. It is likely that operation of the C-470 ramp can assist the PM peak, although reduced flows in the high off-peak leading into the PM peak could also contribute here.

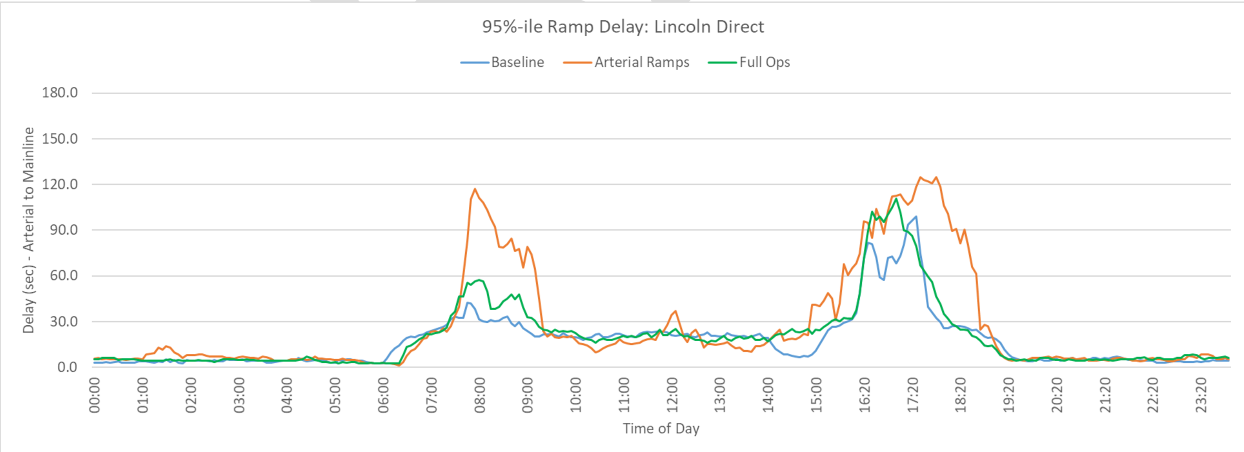
It is also noted that while all ramps may have been operating, there was a short period (first two weeks of 9 weeks) during the full operations stage that the Lincoln Direct was unable to run adaptively, limiting its effectiveness.

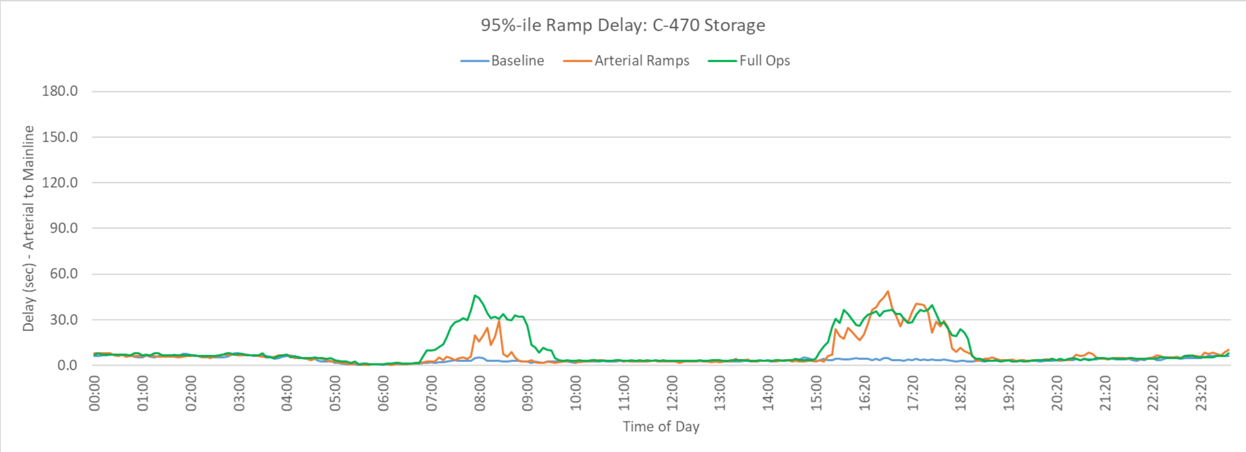
Appendix E

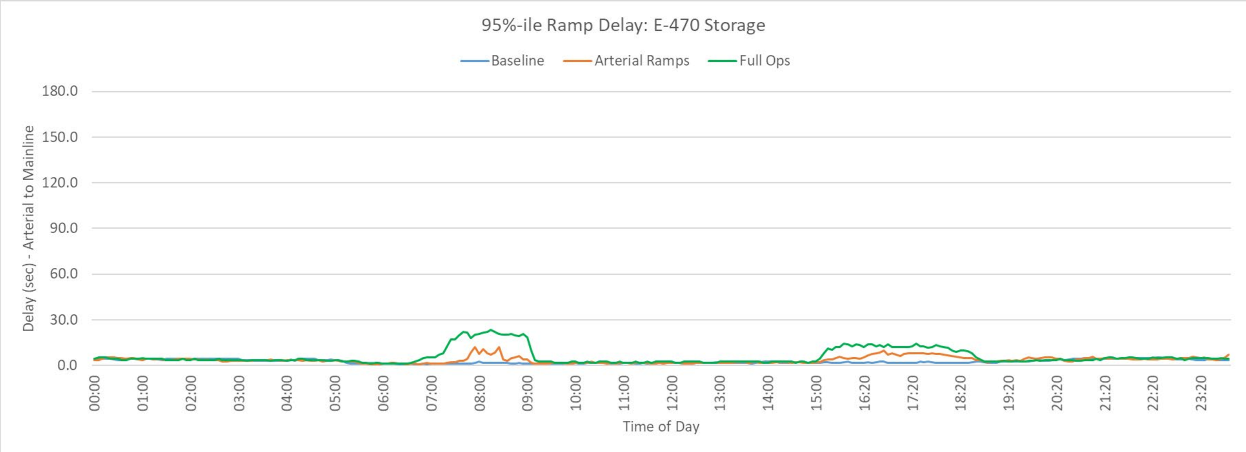
Individual Ramp Delays Plots – Comparing Project Phases








95%-ile Ramp Delay: C-470 Storage
Baseline
Arterial Ramps
Full Ops
180.0
150.0
120.0
90.0
60.0
30.0
0.0
Delay (sec) - Arterial to Mainline
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:20
17:20
18:20
19:20
20:20
21:20
22:20
23:20
Time of Day


95%-ile Ramp Delay: E-470 Storage
Baseline
Arterial Ramps
Full Ops
180.0
150.0
120.0
90.0
60.0
30.0
0.0
Delay (sec) - Arterial to Mainline
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
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14:00
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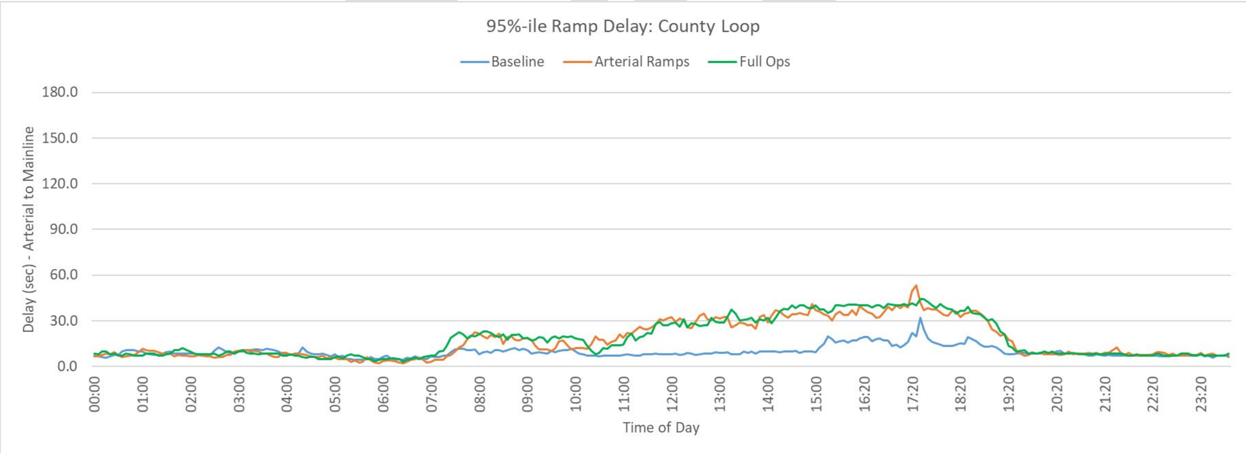
16:20
17:20
18:20
19:20
20:20
21:20
22:20
23:20
Time of Day


95%-ile Ramp Delay: County Loop
Baseline
Arterial Ramps
Full Ops
180.0
150.0
120.0
90.0
60.0
30.0
0.0
Delay (sec) - Arterial to Mainline
00:00
01:00
02:00
03:00
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17:20
18:20
19:20
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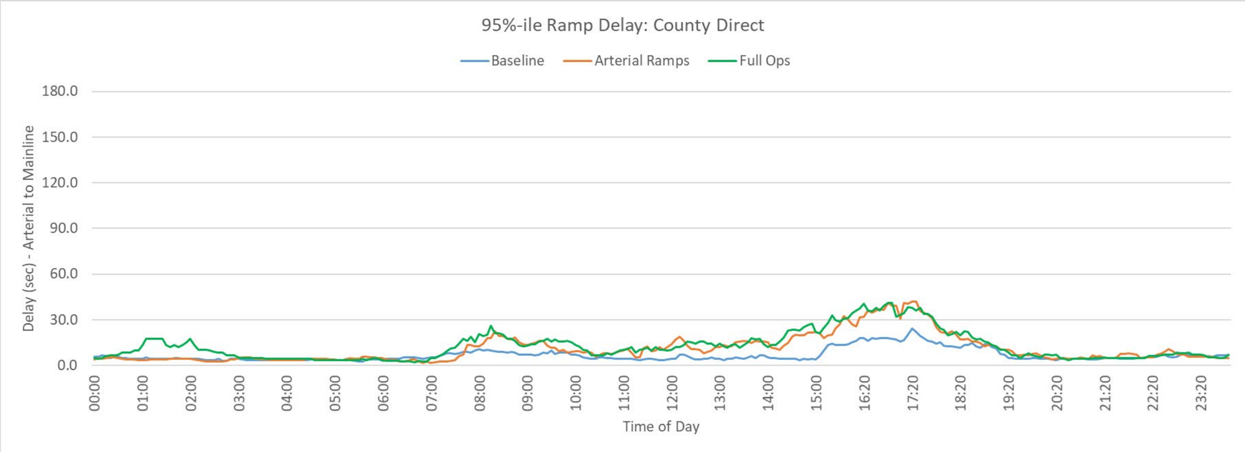
21:20
22:20
23:20
Time of Day


95%-ile Ramp Delay: County Direct
Baseline
Arterial Ramps
Full Ops
Delay (sec) - Arterial to Mainline
180.0
150.0
120.0
90.0
60.0
30.0
0.0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
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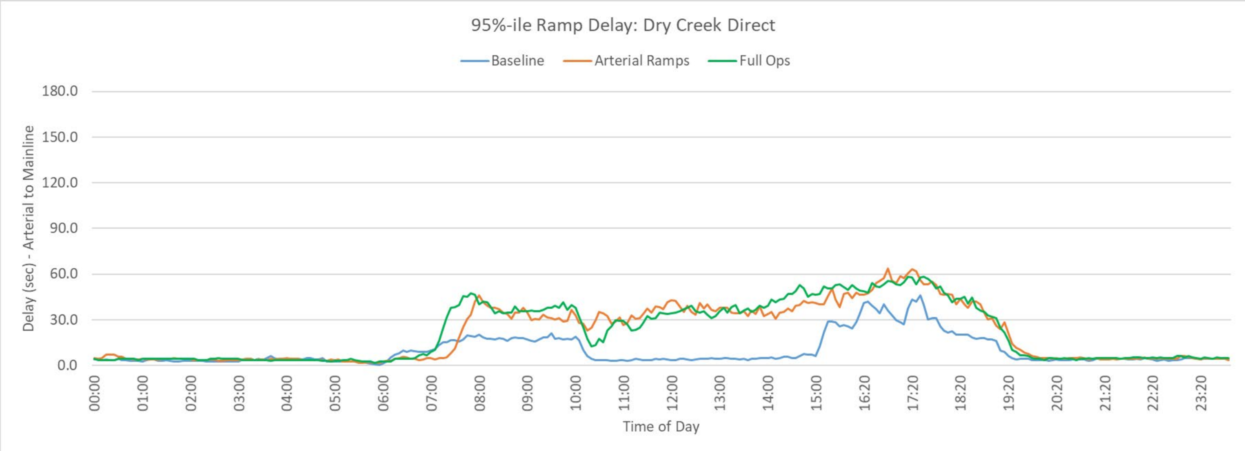
22:20
23:20
Time of Day


95%-ile Ramp Delay: Dry Creek Direct
Baseline
Arterial Ramps
Full Ops
Delay (sec) - Arterial to Mainline
180.0
150.0
120.0
90.0
60.0
30.0
0.0
00:00
01:00
02:00
03:00
04:00
05:00
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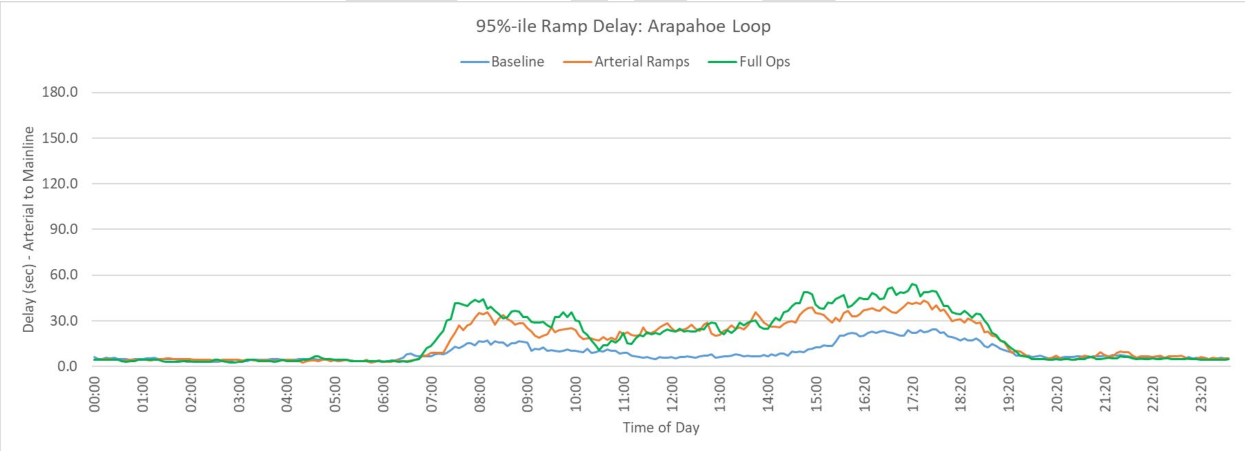
22:20
23:20
Time of Day


95%-ile Ramp Delay: Arapahoe Loop
Baseline
Arterial Ramps
Full Ops
Delay (sec) - Arterial to Mainline
180.0
150.0
120.0
90.0
60.0
30.0
0.0
00:00
01:00
02:00
03:00
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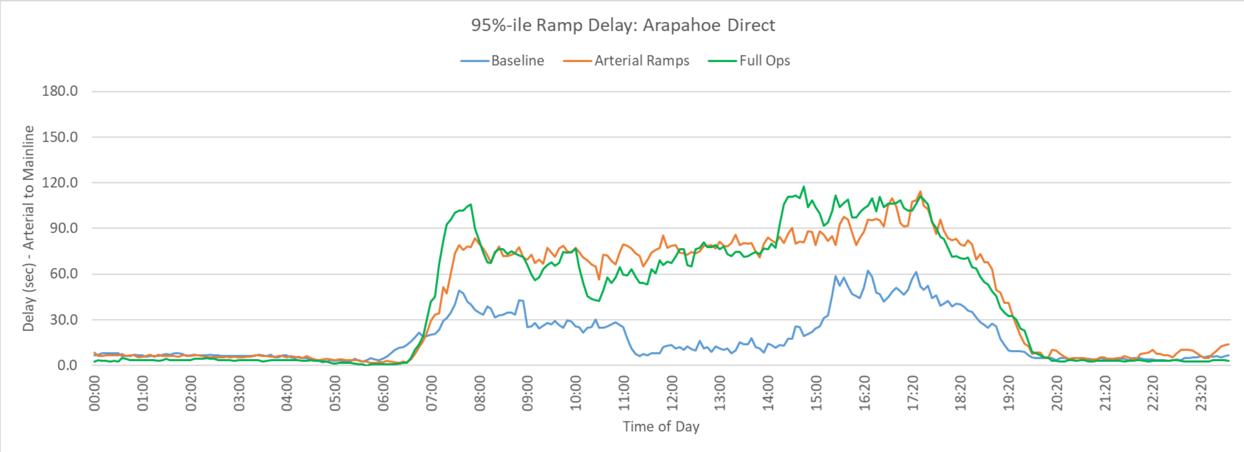
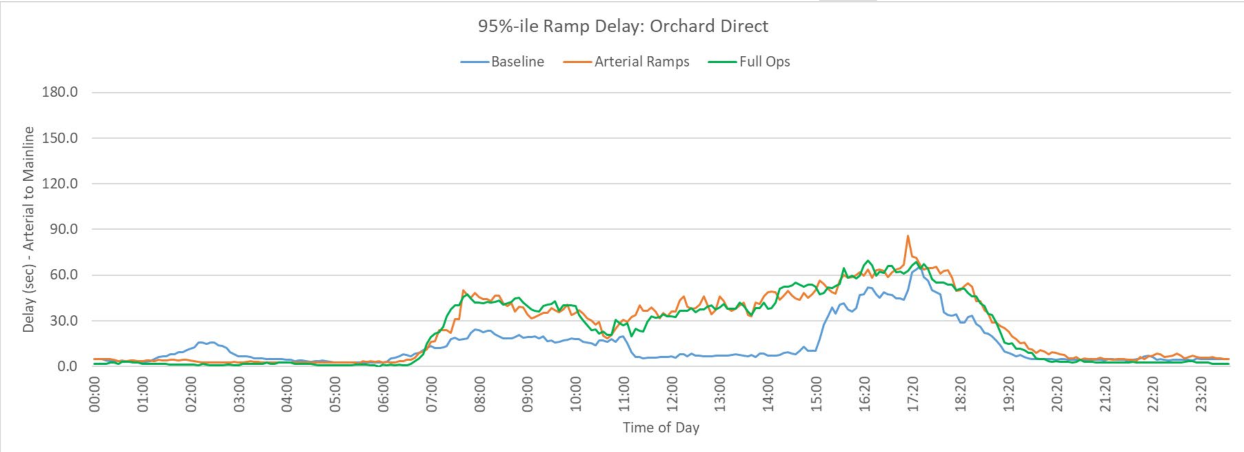
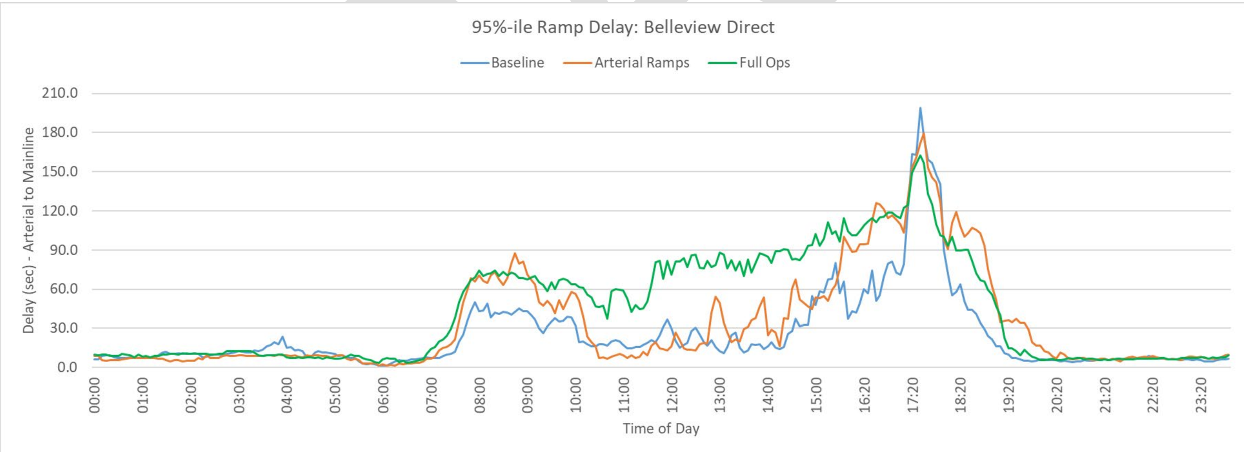
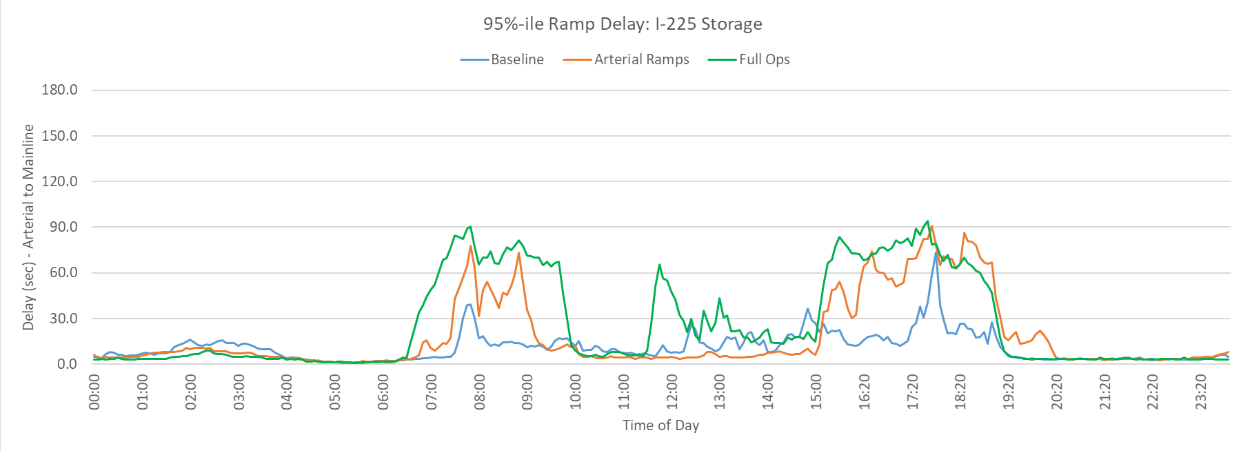
21:20
22:20
23:20
Time of Day







<u>Note:</u> *Belleview vertical axis different to cover high PM peak period delays*


95%-ile Ramp Delay: I-225 Storage
Baseline
Arterial Ramps
Full Ops
Delay (sec) - Arterial to Mainline
180.0
150.0
120.0
90.0
60.0
30.0
0.0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
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11:00
12:00
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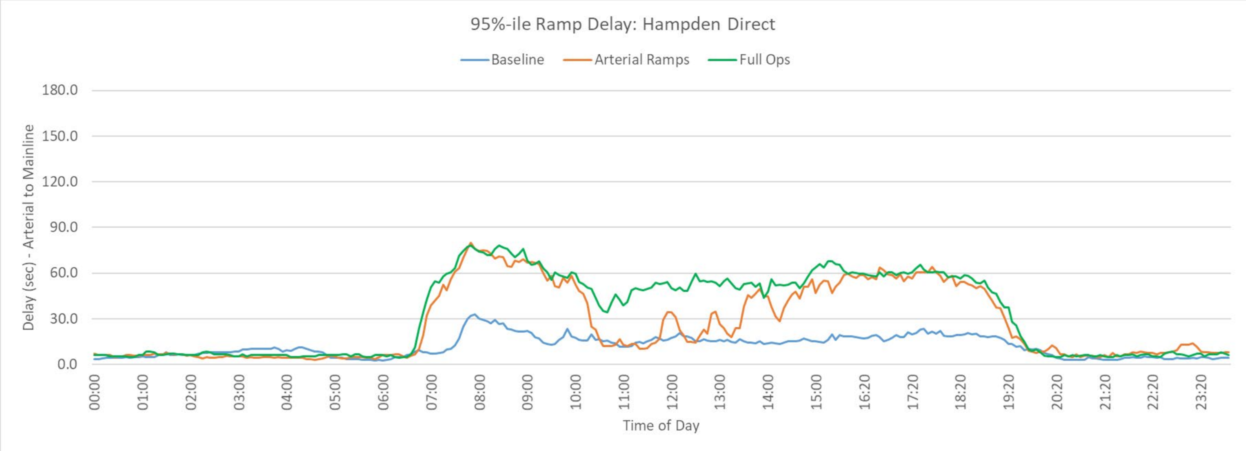
16:20
17:20
18:20
19:20
20:20
21:20
22:20
23:20
Time of Day


95%-ile Ramp Delay: Hampden Direct
Baseline
Arterial Ramps
Full Ops
Delay (sec) - Arterial to Mainline
180.0
150.0
120.0
90.0
60.0
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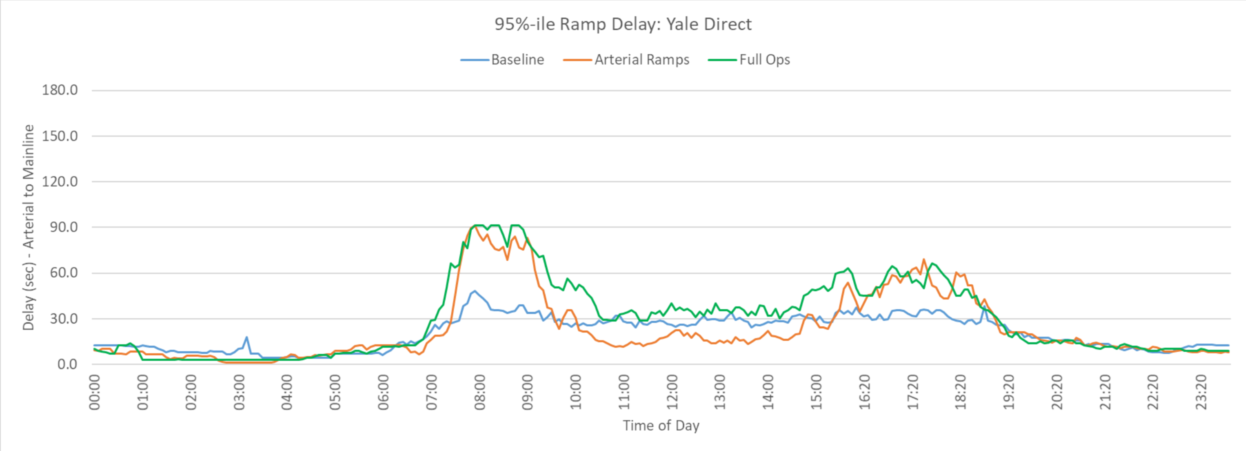
23:20
Time of Day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Baseline
Arterial Ramps
Full Ops
Delay (sec) - Arterial to Mainline
180.0
150.0
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21:20
22:20
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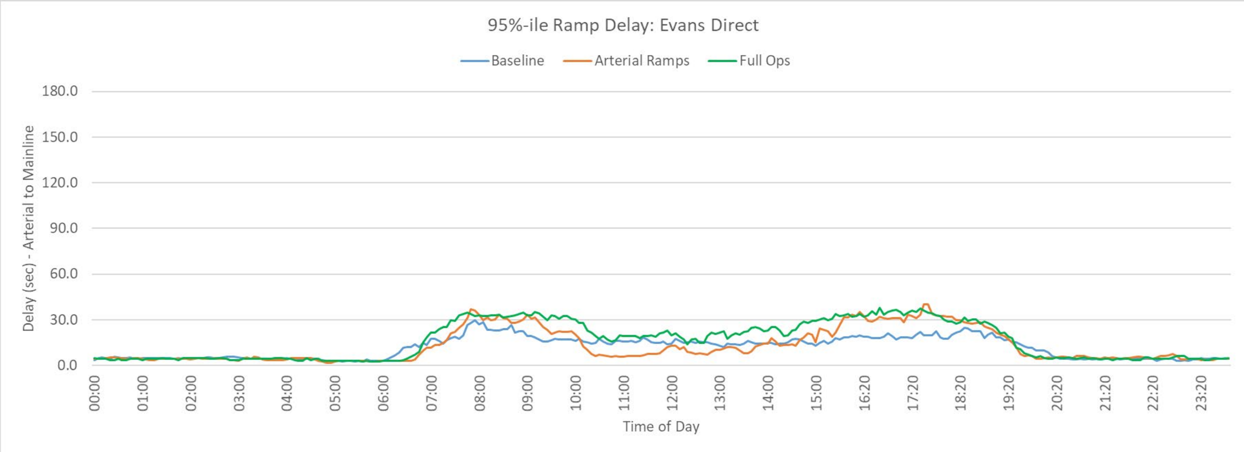
Time of Day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Baseline
Arterial Ramps
Full Ops
Delay (sec) - Arterial to Mainline
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150.0
120.0
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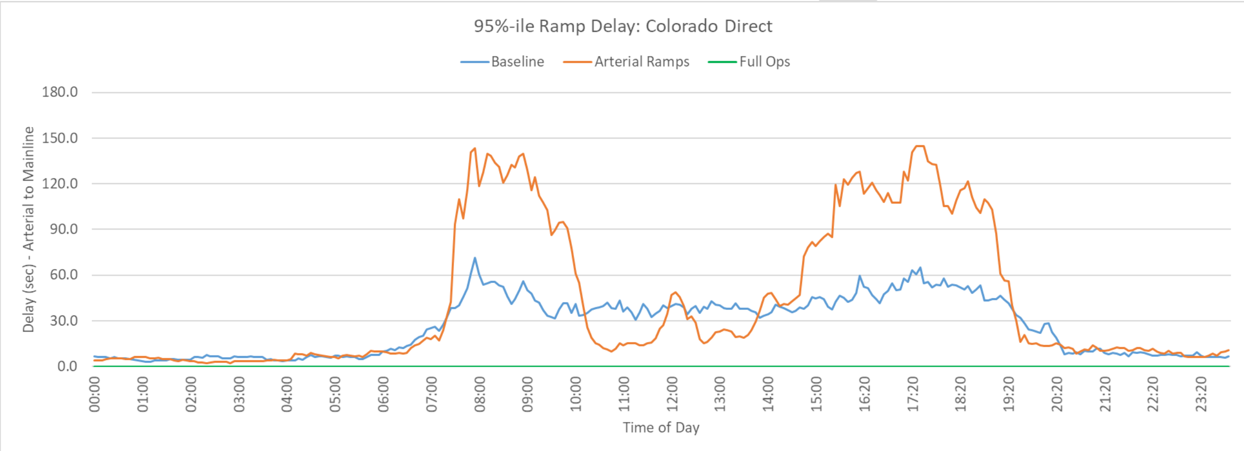
00:00 01:00 02:00 03:00 04:00 05:00 06:00 07:00 08:00 09:00 10:00 11:00 12:00 13:00 14:00 15:00 16:20 17:20 18:20 19:20 20:20 21:20 22:20 23:20
Time of Day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Baseline
Arterial Ramps
Full Ops
Delay (sec) - Arterial to Mainline
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120.0
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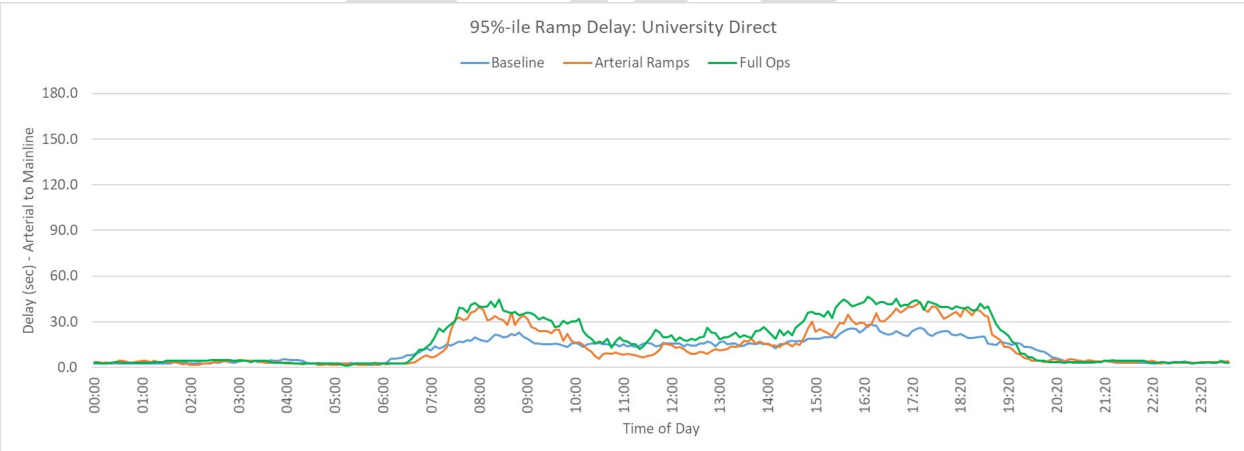
Time of Day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Baseline
Arterial Ramps
Full Ops
Delay (sec) - Arterial to Mainline
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120.0
90.0
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Time of Day

Appendix F

Probability of Flow Breakdown Curves – Recurrent Bottleneck Sites

Refer to Accompanying Attachments

- Appendix F - P_FBD_Plots - Measured and Weibull Curves.pdf

Appendix G

Productivity, Speed and Flow Distributions

Refer to Accompanying Attachments

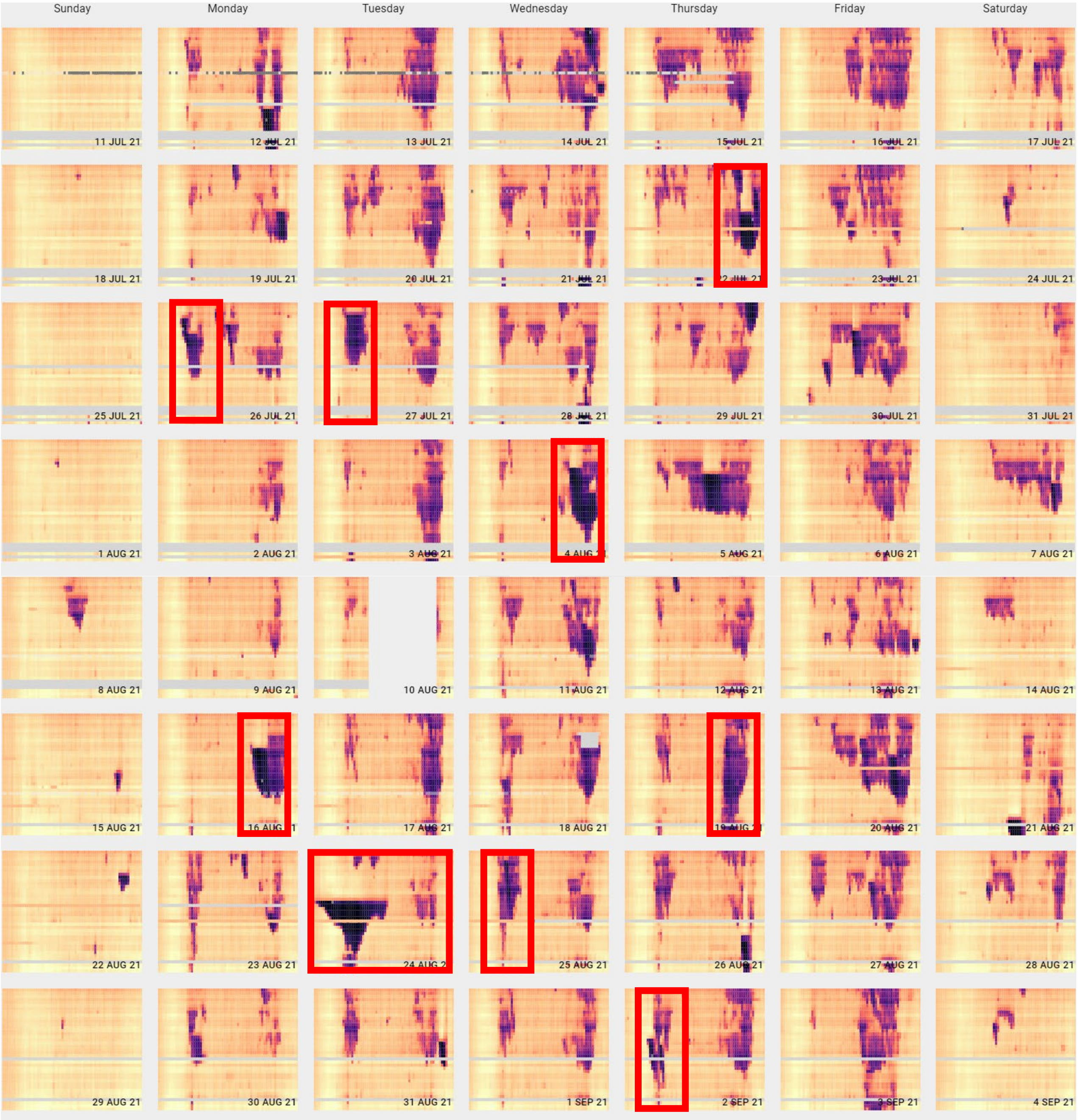
- Appendix G - Profiles and Distributions - Prod-Speed-Flow.pdf

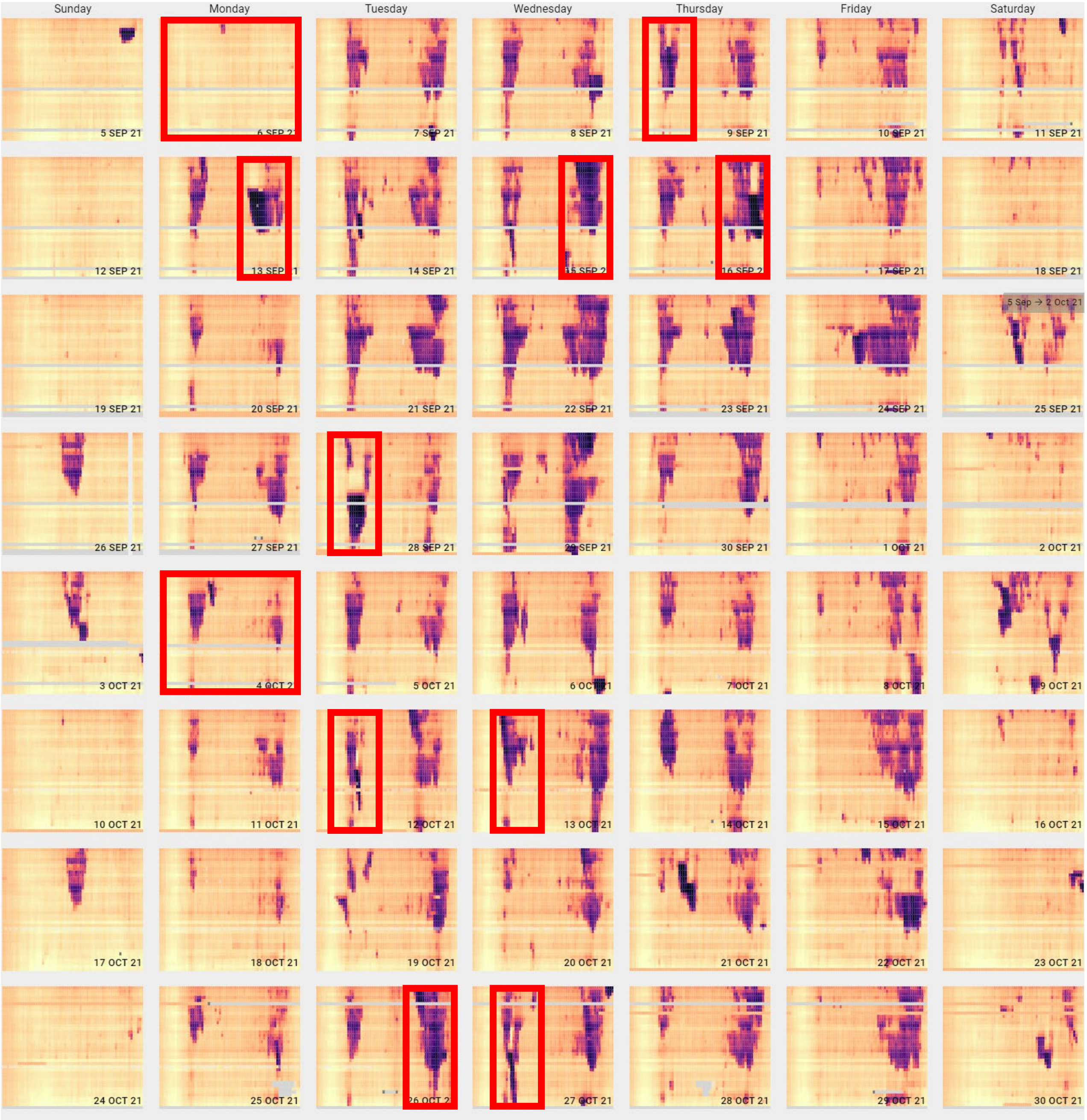
Appendix H

Heat Plots – 04:00 to 20:00 - 15-minute Data

Note: Red highlights indicate excluded days – Refer to Section 6.1.3.

Baseline Stage – July 2021 to October 2021

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5 SEP 21
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22 SEP 21
23 SEP 21
24 SEP 21
5 Sep → 2 Oct 21
25 SEP 21
26 SEP 21
27 SEP 21
28 SEP 21
29 SEP 21
30 SEP 21
1 OCT 21
2 OCT 21
3 OCT 21
5 OCT 21
7 OCT 21
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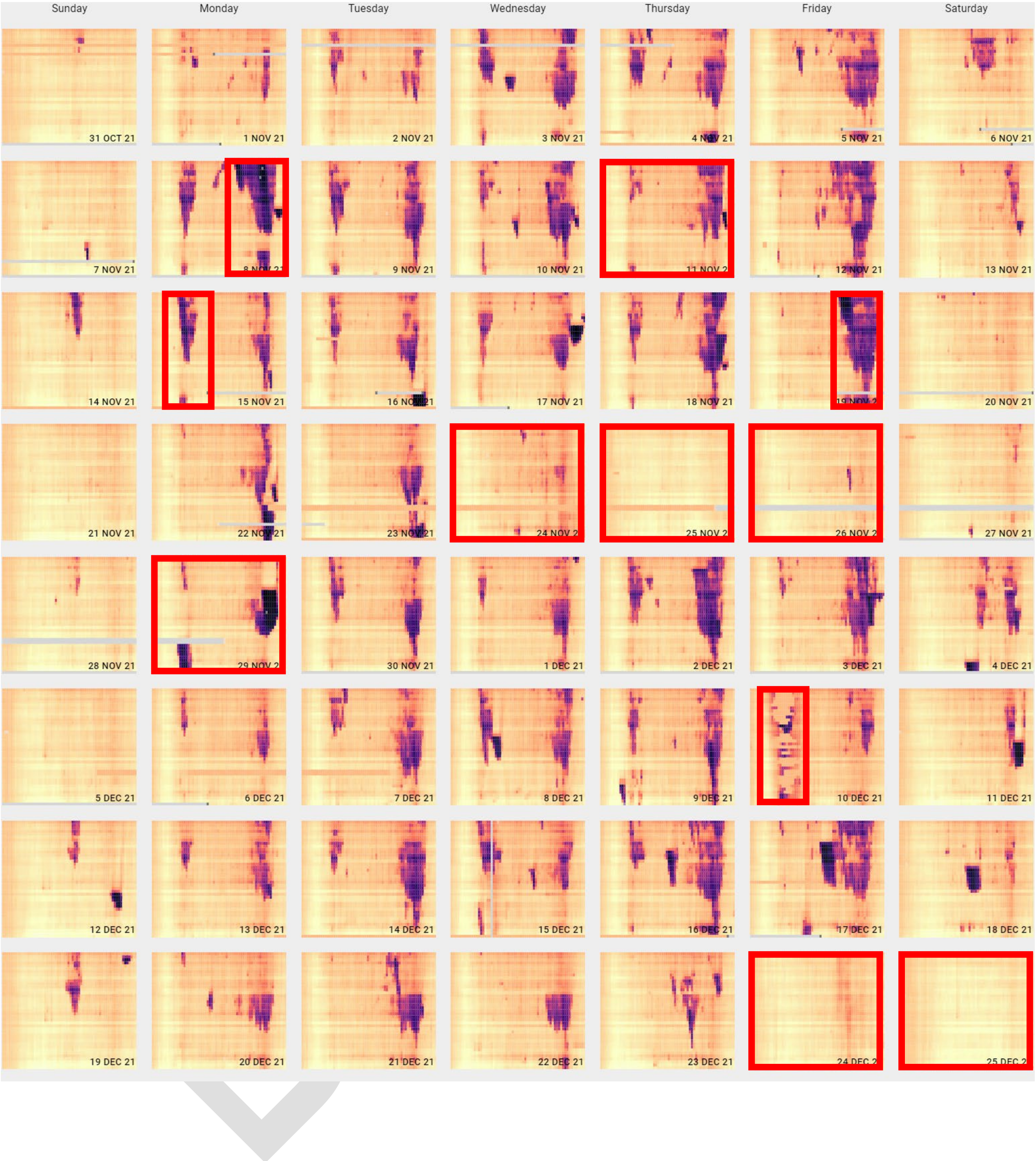
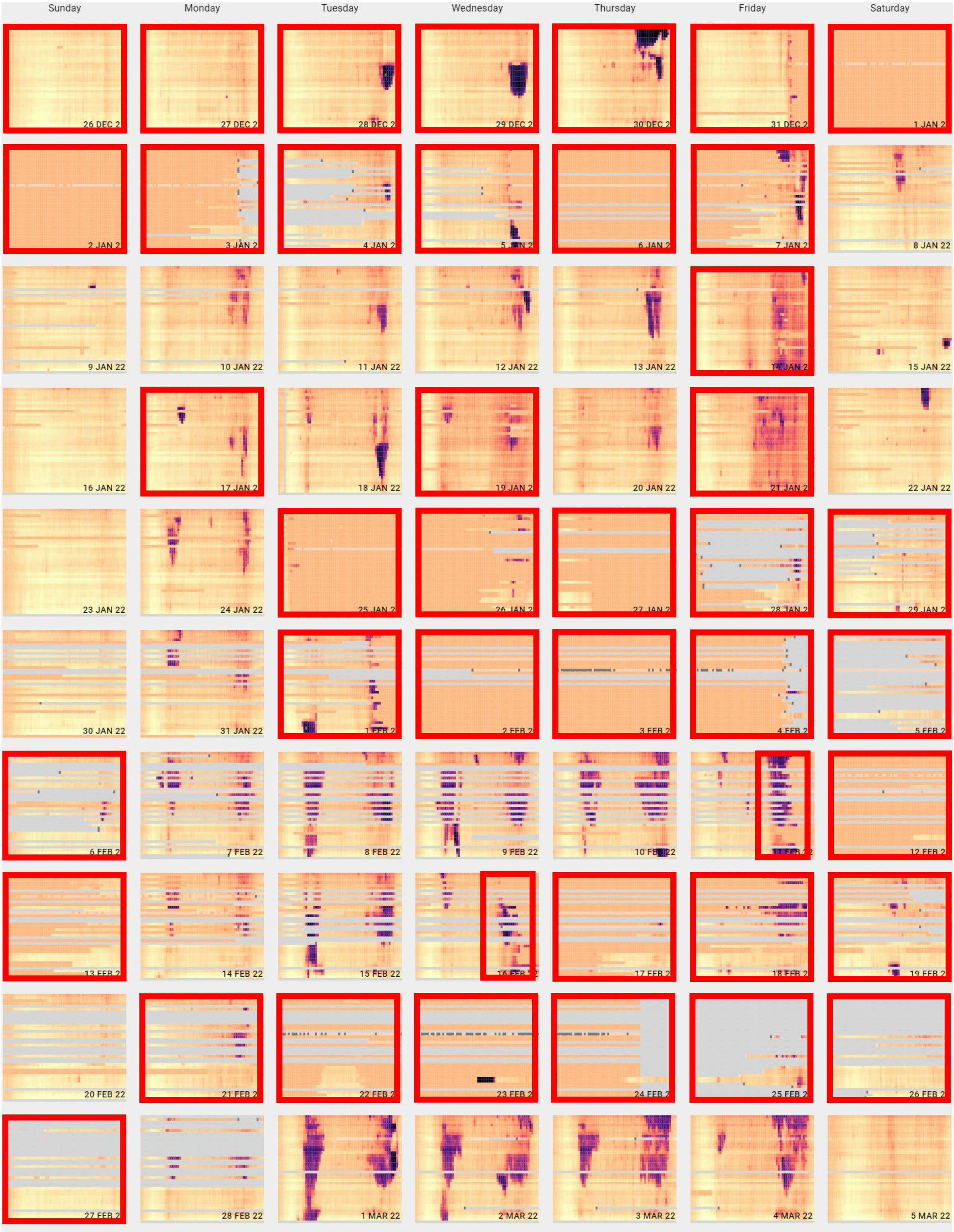
27 OCT 21
28 OCT 21
29 OCT 21
30 OCT 21

Arterial Ramps Only Stage – November 2021 to March 2022

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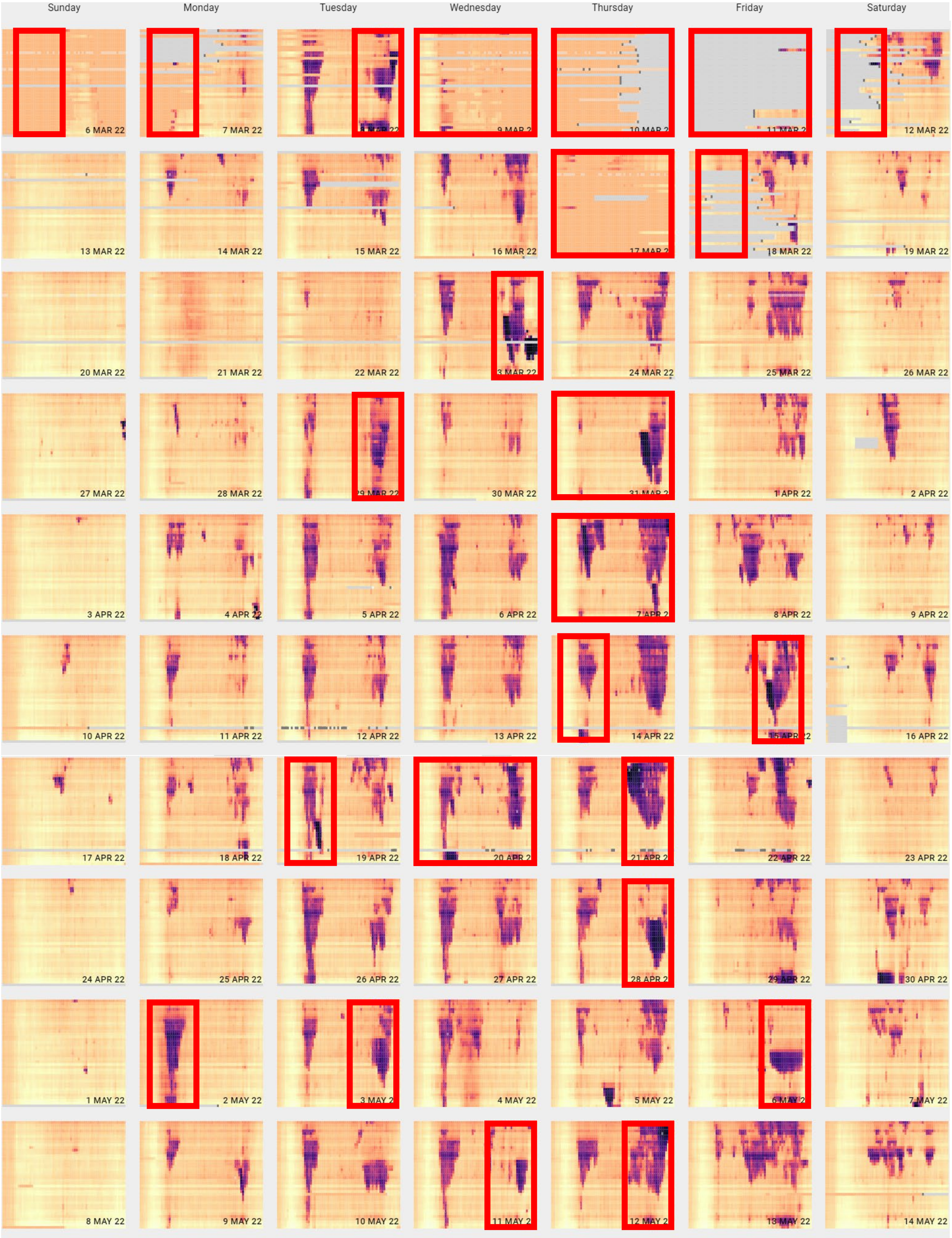
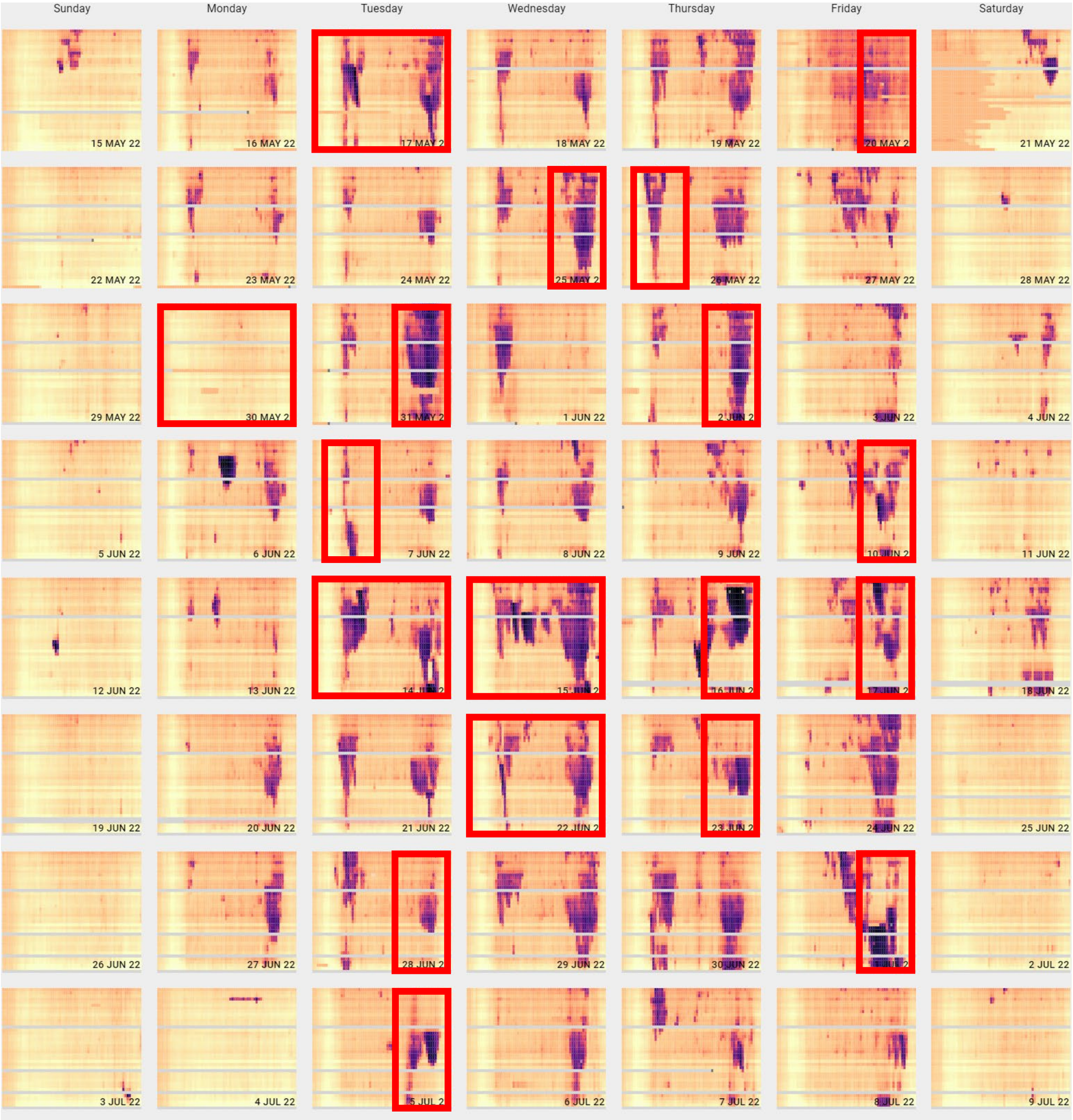
24 JAN 22
30 JAN 22
31 JAN 22
7 FEB 22
8 FEB 22
9 FEB 22
14 FEB 22
15 FEB 22
20 FEB 22
28 FEB 22
1 MAR 22
2 MAR 22
3 MAR 22
4 MAR 22
5 MAR 22

Full Operations Stage – March 2022 to March 2022




Sunday
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24 MAY 22
27 MAY 22
28 MAY 22
29 MAY 22
1 JUN 22
4 JUN 22
5 JUN 22
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26 JUN 22
27 JUN 22
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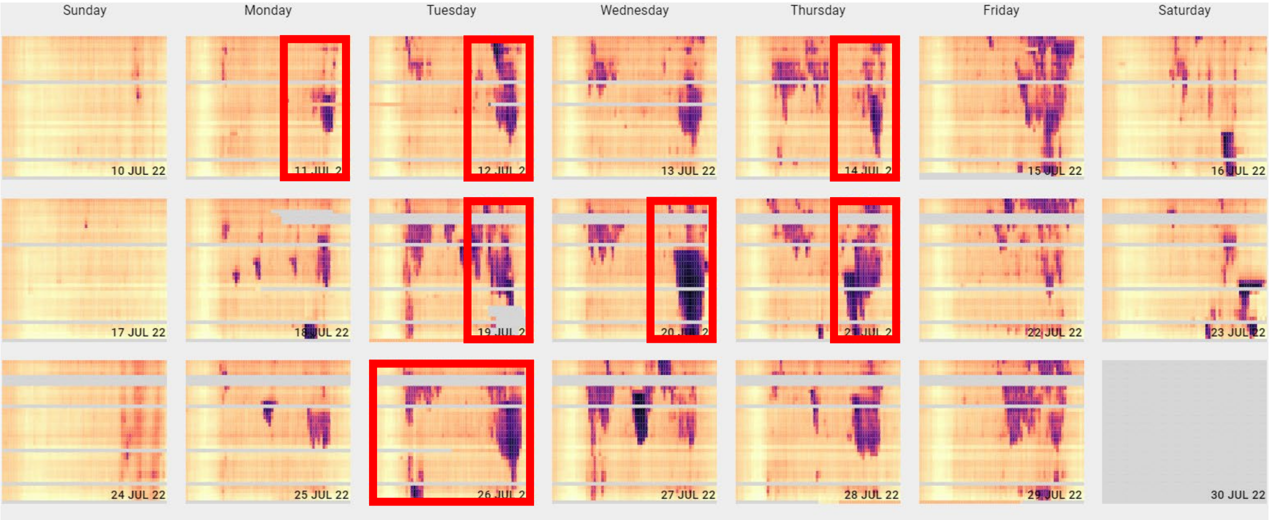
30 JUN 22
2 JUL 22
3 JUL 22
4 JUL 22
6 JUL 22
7 JUL 22
8 JUL 22
9 JUL 22



Heat Plots (Weekly Grouping) – 5-minute Data

Refer to Accompanying Attachments

- Combined S1 Baseline Wk Heat Plots - Jul-21 to Oct-21.pdf
- Combined S2 Arterial Ramps Only Wk Heat Plots - Nov-21 to Mar-22.pdf
- Combined S3 Full Ops Wk Heat Plots - Mar-22 to Jul-22.pdf

Appendix I

Mainline Flows – Daily, Max AM and Max PM Histograms

Refer to Accompanying Attachments

- Appendix I-1 - Daily and Peak Flow Plots Mainline_All Sites.pdf

Ramp Flows – Daily, Max AM and Max PM Histograms

Refer to Accompanying Attachments

- Appendix I-2 - Daily and Peak Flow Plots Ramps_All Sites.pdf