I-24 MOTION Traffic Patterns

CEE598 Traffic Flow Theory

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1 Introduction

1.1 Overview

The Interstate-24 MObility Technology Interstate Observation Network (I-24 MOTION) project provides an unprecedented dataset for traffic flow analysis. Covering a 4.2-mile stretch of Interstate 24 near Nashville, Tennessee, the network utilizes 294 high-resolution roadside cameras to capture detailed vehicle movements. Data processing involves advanced computer vision and data fusion techniques to generate high-fidelity vehicle trajectories. This project aims to analyze a sample of this data (specifically from November 21, 2022, and potentially other days) to understand traffic dynamics, identify patterns, assess data quality, and explore specific traffic phenomena like congestion and stop-and-go waves. The analysis leverages the publicly available data and resources provided by the I-24 MOTION team [5].

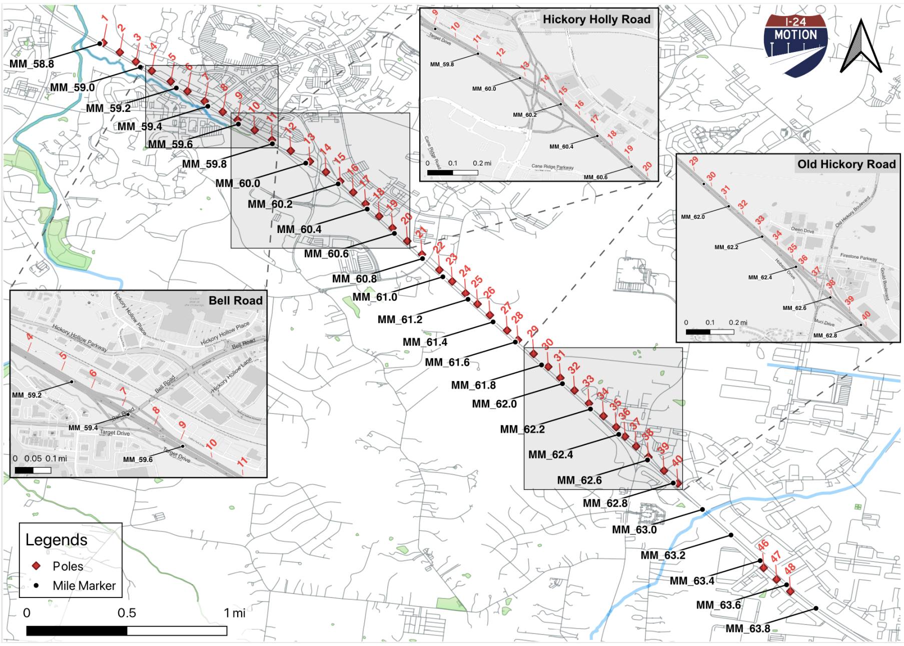


Figure 1: An overview of I-24 MOTION map with pole locations, key landmarks and approximate mile-markers.

1.2 Dataset Details

The I-24 MOTION is a dedicated instrument for traffic science located on a 4.2-mile (6.75 km) stretch of I-24 near Nashville, Tennessee. This section of the 4-5 lane (each direction) freeway experiences frequent congestion. The primary output of the instrument is high-fidelity vehicle trajectory data, generated from video captured by the sensor network.

Internally, the trajectory data originates from a MongoDB (NoSQL) database. Public data releases, like the sample data for November 21, 2022 used in this project, are provided in formats such as JSON. As highlighted in the data tutorial [6], the JSON files typically cover 10-minute intervals and can be extremely large (hundreds of MB to potentially 100s of GB), necessitating iterative parsing techniques (e.g., using the 'ijson' library in Python) for efficient processing. The instrument captures data covering approximately 230 million vehicle miles of travel annually.

1.3 Data Attributes, Ranges, and Coordinate System

Each record in the dataset represents an individual vehicle trajectory, containing vehicle attributes and detailed motion information. Table 1 presents the data schema, adapted from Table III in [1].

Table 1: Vehicle Trajectory Document Schema

Attribute	Description	Unit	Example Value
_id	Unique ID generated by database	-	63732b74e1fa5a45ae0c2fdd
timestamp	Unix timestamps after correction	sec	[1668600002.0133328, ...]
first_timestamp	Min timestamp from trajectory	sec	1668600002.0133328
last_timestamp	Max timestamp from trajectory	sec	1668600007.2098653
x_position	Array of back-center longitudinal position	feet	[316800, 316801, ...]
y_position	Array of back-center lateral position	feet	[-12, -12, ...]
length	Vehicle length	feet	18.3
width	Vehicle width	feet	6.4
height	Vehicle height	feet	5.4
merged_ids	Fragments with time overlaps	-	[id1, id2]
fragment_ids	Fragments without time overlaps	-	[id1, id2]
starting_x	The first value in x_position	feet	123.2
ending_x	The last value in x_position	feet	5763.3
coarse_vehicle_class	Vehicle class from object detector	-	0
direction	1 if eastbound, -1 westbound	-	1
compute_node_id	Name of compute server	-	"videonode1"
local_fragment_id	Integer unique to each tracked vehicle	-	[1, 2, 3]

Key aspects of the data include:

- **Coordinate System:** Data is natively provided in a curvilinear 2D roadway coordinate system. The primary (x) axis aligns with the roadway median (positive eastbound), and the secondary (y) axis is locally perpendicular (positive towards the eastbound side, following a left-hand rule). Coordinates are in feet. The x-coordinate is offset such that postmile 60 corresponds to x=316800 ft [1]. Conversions to state plane coordinates (EPSG 2274) are possible using provided spline information.
- **Reference Point:** Trajectory positions (‘x_position‘, ‘y_position‘) record the 2D footprint of the back center of the vehicle.
- **Sampling Rate:** Trajectories are re-sampled to a uniform frequency of 25 Hz for exact timestamp-based indexing.
- **Time Range:** Data covers full days, with specific releases often focusing on peak periods (e.g., 6:00 AM - 10:00 AM for the initial release).
- **Derived Quantities:** Velocity, acceleration, and steering angle can be computed from the position information using finite differences.

1.4 Collection Methods and Sensors

The I-24 MOTION instrument utilizes a dense network of roadside cameras connected via fiber optics to a central compute facility.

- **Sensors:** 276 pole-mounted, 4K resolution Pan-Tilt-Zoom (PTZ) network IP cameras are used. They are mounted on 40 dedicated steel poles, 110-135 feet tall, spaced approximately 500-600 feet apart to ensure continuous, overlapping fields of view and minimize occlusion [1]. Figure 2 shows a diagram of the instrument layout.

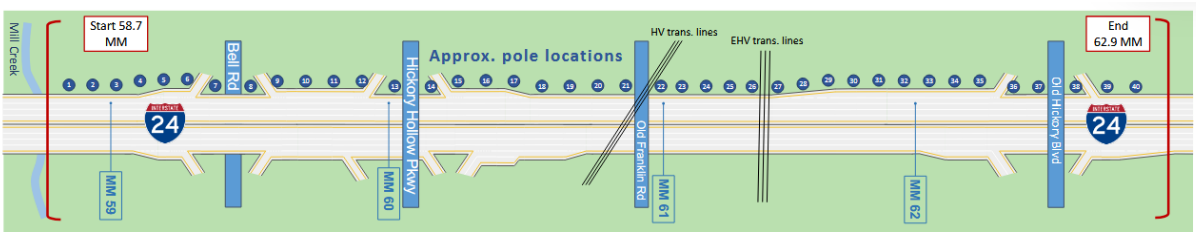


Figure 2: Diagram of the I-24 MOTION instrument

- **Camera System:** Each pole typically hosts a cluster of 6 cameras managed by a camera lowering device (CLD) for maintenance. Cameras are synchronized using Network Time Protocol (NTP) to GPS-based time servers, providing frame timestamps with 10 microsecond accuracy relative to the camera clock. Video is captured at up to 30 fps (H.264 encoded, stored in MKV containers) [1].
- **Processing Pipeline:**
  a) *Video Ingest:* Streams are recorded in 10-minute chunks.
  b) *Detection and Tracking:* A crop-based tracking method using Retinanet (ResNet-50 backbone) and a Kalman filter motion model detects vehicles as 3D rectangular prisms and tracks them within camera views.
  c) *Coordinate Transformation:* Homography transforms detected object positions into the shared roadway coordinate system.
  d) *Trajectory Post-processing:* An automated pipeline performs data association (matching fragments across nodes) and trajectory reconciliation (smoothing, outlier correction) to produce the final trajectories [1].
- **Data Availability:** Processed datasets are made publicly available via the project website [5] with associated metadata and documentation [1].

The resulting data provides high spatial and temporal resolution but can contain artifacts (e.g., fragmentation, gaps due to occlusion or packet loss) inherent to the complex collection and processing system.

2 Time-Space Diagram Analysis

2.1 Generating the Time-Space Diagram

A time-space diagram visualizes vehicle trajectories by plotting their longitudinal position (x-coordinate) against time. The generation process involves loading the trajectory data, filtering it for the desired direction and time window, calculating speed, and plotting the results.

2.1.1 Code Implementation Details

- **Data Handling:** Given the potentially large size of the JSON trajectory files, the Python script uses the 'requests' library to download the data and the 'json' library for iterative parsing. This allows the processing of each trajectory record one by one without loading the entire file into memory.
- **Timezone:** An important step is handling timezone which is in UTC Unix format. It identifies the specific date of the data by reading the first record's timestamp and converting it to a date using the specified local timezone ('America/Chicago').
- **Data Filtering:** Trajectories are filtered based on 'direction == -1' (Westbound) and whether their start time falls within the calculated UTC timestamp window.
- **Calculations:** For each valid trajectory:
  - Longitudinal positions ('x_position'), originally in feet, are converted to miles by dividing by 5280 for plotting on the Y-axis (Mile marker).
  - Instantaneous speed is calculated using finite differences between consecutive positions (in feet) and timestamps (in seconds).
  - Speed is converted from feet per second to miles per hour (mph). Absolute speed is used.

The plot was generated using a Sol supercomputer. Figure 3 shows the space-time diagram for the specified time window on November 21, 2022.

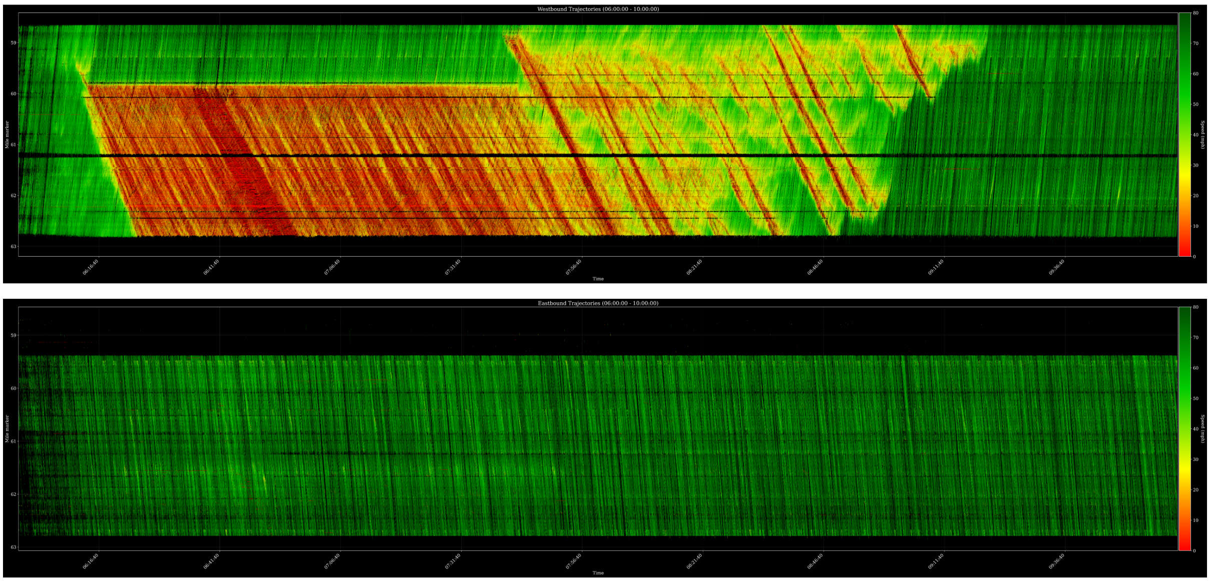


Figure 3: Time-Space Diagram for I-24 Westbound (top) and Eastbound (bottom), Nov 21, 2022 (06:00 - 10:00 America/Chicago Time)

2.2 Observed Data Quality Issues

Examining the time-space diagram (Figure 3) reveals potential data quality issues in trajectory data:

1. **Fragmented Trajectories:** Many trajectories appear shorter than the full 4.2-mile segment length. This indicates the vehicle tracking might be lost and then potentially re-acquired later, or the vehicle exited/entered mid-segment. Fragmentations manifest as discontinuous pieces of trajectory corresponding to a single

vehicle.

2. **Missing Pole:** Overpass occlusion results in lost tracked vehicles, which also manifests as a contiguous spatial range of data missing across all recording time. This artifact will be addressed with an intelligent data processing step that matches objects disappearing under bridges with objects reappearing on the other side.
3. **Trajectory Gaps:** Some trajectories have temporal gaps, potentially due to camera occlusions (e.g., by large trucks), camera handoff issues, or processing artifacts.
4. **Positional Noise:** Trajectories are not perfectly smooth, exhibiting slight noise in the x or y position. This is often related to the inherent accuracy limitations of computer vision algorithms and calibration. While likely minor for macroscopic analysis, it can affect microscopic measures like acceleration.
5. **Inconsistent Start/End Points:** Vehicles entering or exiting via ramps within the segment will naturally have trajectories that don't span the entire length. This is expected behavior, not necessarily a quality issue, but needs consideration during analysis (e.g., when calculating segment travel times).
6. **Outliers:** Occasional erroneous trajectories (e.g., non-physical speeds or movements) might exist due to tracking errors.

These issues are common in real-world sensor data and need to be acknowledged or addressed depending on the specific analysis task.

3 Analysis of Nov 21, 2022 Westbound Traffic

This section analyzes the traffic dynamics on the I-24 Westbound segment for November 21, 2022, between 06:00 and 10:00, primarily using the time-space diagram (Figure 3) and incorporating known incident information.

3.1 Time-Space Diagram and Macroscopic Patterns

The time-space diagram (Figure 3) provides a comprehensive visualization of traffic flow. Key macroscopic patterns observed on this Monday morning include:

- **Congestion Evolution:** The segment begins in a relatively free-flow state (green/yellow colors) before 6:15 AM. A sharp transition to congestion occurs around **6:15 AM**, spreading rapidly upstream. Deep congestion, characterized by widespread low speeds (red/orange colors) and stop-and-go behavior, dominates the period from approximately **6:30 AM to 8:45 AM**.
- **Recovery Phase:** Traffic conditions begin to improve starting around 8:45 AM, with the recovery front initiating downstream (near MM 62.5) and propagating upstream. By 10:00 AM, the downstream portion has largely recovered, while the upstream end likely still experiences residual effects.
- **Stop-and-Go Waves:** Within the heavily congested period, prominent diagonal stripes of red/orange are visible, representing classic stop-and-go waves propagating upstream against the direction of traffic flow.

3.2 Incident Impact Analysis

The observed congestion patterns were significantly shaped by specific non-recurrent events reported for this day [1]:

- **Primary Incident (Event A):** A severe rear-end crash occurred near **MM 59.5-59.7** around **6:14 AM**. This event, blocking lanes 1, 2, and the left shoulder, directly triggered the major congestion onset seen shortly after in the time-space diagram. The resulting queue propagated significantly upstream, and the incident's impact persisted until approximately **7:43 AM**, a duration of about 1.5 hours. Figure 4 provides a zoomed view of the congestion formation near the incident site.
- **Secondary Incident (Event B):** Debris was reported on lanes 1 and 2 near **MM 58.8** between **7:40 AM and 7:44 AM**. This brief event, located upstream of the primary crash site, likely caused a localized perturbation or slight delay in the recovery process within the already existing congestion.
- **Underlying Demand:** While incidents were the primary triggers, the event occurred during a peak Monday morning commute period. High background traffic demand likely exacerbated the severity and spatial extent of the resulting queues.

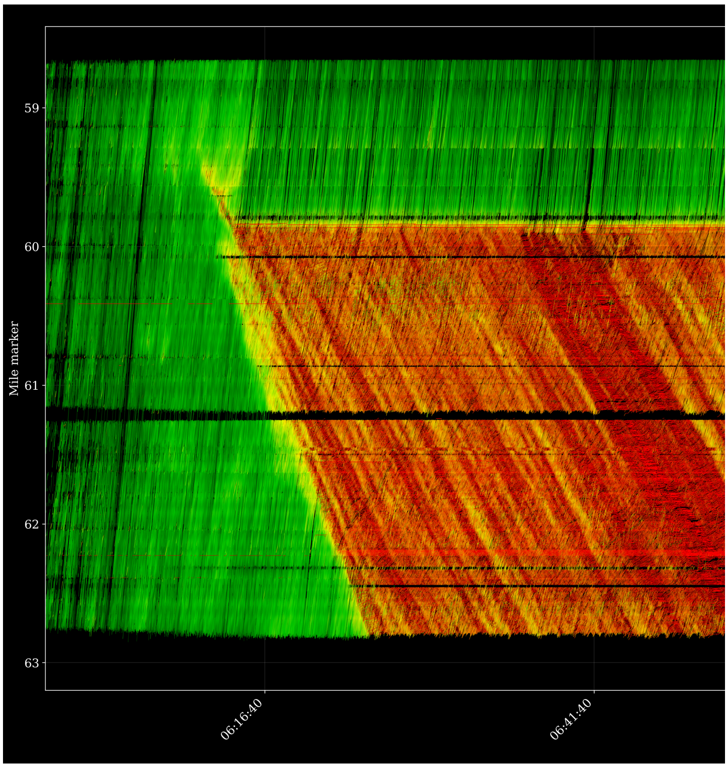


Figure 4: Zoomed-in Time-Space Diagram near MM 59.7 showing Congestion Onset after 6:14 AM Crash.

3.3 Data Quality and Artifacts

While the time-space diagram effectively visualizes macroscopic patterns, it is important to notice the characteristics and artifacts inherent in the underlying trajectory data [1]:

- **Fragmentation:** Individual vehicle paths are often represented by multiple shorter segments ("fragments") due to tracking limitations (e.g., occlusion) or vehicles entering/exiting the segment. This is not easily visible at the macroscopic scale but affects microscopic analyses.
- **Data Gaps (Pole Outage):** A distinct horizontal band lacking data is evident around MM 61.0-61.2 in Figure 3. This corresponds to a known outage of cameras

on Pole 25, rendering traffic behavior unobservable in that specific zone during this period.
- **Other Potential Issues:** While less prominent, other artifacts like positional noise, minor gaps from packet drops, or potential outliers might exist in the dataset, requiring consideration for specific analysis tasks.

3.4 Congestion Wave Characteristics

The distinct stop-and-go waves observed during the congested period (roughly 6:30 AM to 8:45 AM) are a key feature of the traffic dynamics on this day.
- **Propagation Speed:** As analyzed using visual estimation, these waves propagate upstream with an average speed of approximately **-11.6 mph**. This aligns reasonably well with the -12.6 mph calculated using more detailed methods for the crash event (Event A) in [1].
- **Periodicity:** The waves appear quasi-periodic, with visual inspection suggesting varying periods throughout the congestion. Table VII in [1] reports a prominent period of 2.1 minutes associated with Event A.
- **Amplitude:** The waves represent significant speed oscillations, with speeds dropping close to zero within the wave troughs and recovering partially in the crests (e.g., 0-14.8 mph fluctuation range reported for Event A [1]).

The clear visualization of these waves and the ability to estimate their properties highlight the value of the high-resolution I-24 MOTION data for studying traffic flow instabilities.

4 Lane Speed Analysis

Traffic speed often varies across different lanes due to factors like driver behavior (faster vehicles preferring left lanes), truck lane restrictions (if any), and proximity to ramps. We analyze the instantaneous speed variations by lane for the Westbound direction on Nov 21, 2022.

Instantaneous speeds were calculated for each trajectory data point within the 06:00 - 10:00. Each data point was assigned to a specific lane (Lane 1 = leftmost/median, increasing to the right) and speed data was aggregated by lane and direction.

Findings: The analysis reveals distinctly different speed patterns between the two directions during this morning period.

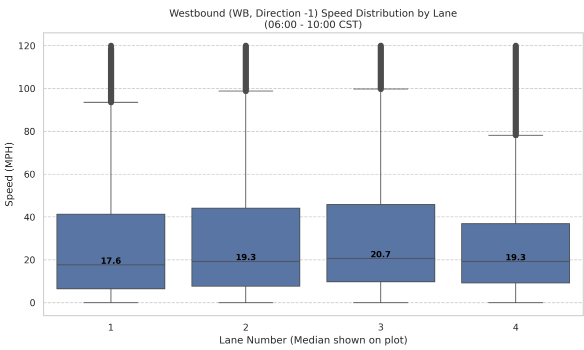
Eastbound (EB, Direction 1):
- **Conditions:** Generally higher speeds, indicating less severe congestion compared to the Westbound direction during this time.
- **Lane Trend:** A clear trend of decreasing speed from left to right is observed (Figures 5b and 6b).
  - Lane 1: Highest median (76.2 mph) and mean (75.35 mph).
  - Lane 2: Median 71.1 mph, mean 70.16 mph.
  - Lane 3: Median 66.5 mph, mean 65.73 mph.
  - Lane 4: Lowest median (63.1 mph) and mean (62.55 mph).

  This hierarchy is typical for moderate to free-flowing conditions.

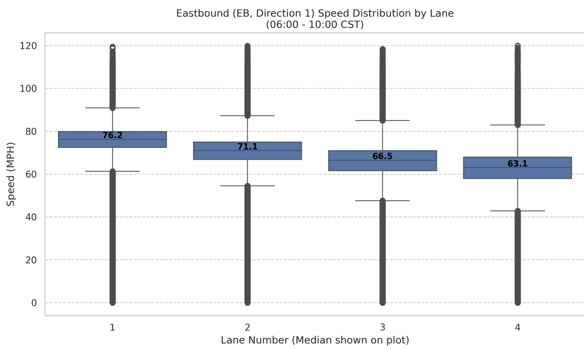
- **Variability:** Speed distributions are relatively compact around their medians, with standard deviations around 8.6-9.0 mph across all lanes, suggesting reasonably consistent speeds within each lane. The violin plots show unimodal distributions centered near the respective medians.

Westbound (WB, Direction -1):

- **Conditions:** Significantly lower speeds, indicative of heavy congestion during the morning peak, consistent with the time-space analysis.
- **Low Speeds:** Median speeds are very low: 17.6 mph (Lane 1), 19.3 mph (Lane 2), 20.7 mph (Lane 3), and 19.3 mph (Lane 4). Mean speeds (25.0-28.2 mph) are higher than medians, pulled up by speeds during brief periods of movement between stop-and-go waves.
- **High Variability:** Extremely high standard deviations (19.8-25.0 mph) confirm wide speed variations. The box plots (Figure 5a) show tall boxes and long whiskers, while the violin plots (Figure 6a) show a bimodal or multimodal structure with a large density of vehicles near 0 mph and another spread of higher speeds, characteristic of stop-and-go traffic.
- **Homogenization Trend:** The clear speed hierarchy seen eastbound breaks down. While Lane 1 has the lowest median, Lanes 2, 3, and 4 have very similar median and mean speeds, suggesting speed homogenization across the general-purpose lanes under heavy congestion.

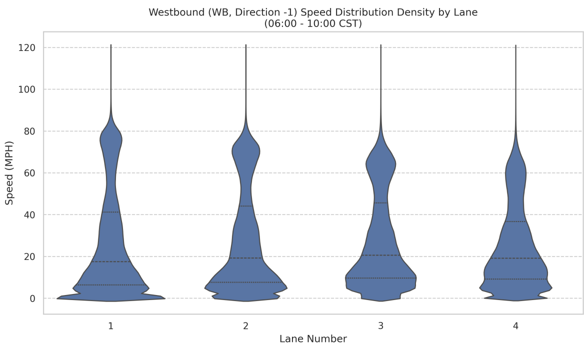


(a) Westbound (WB, Direction -1)

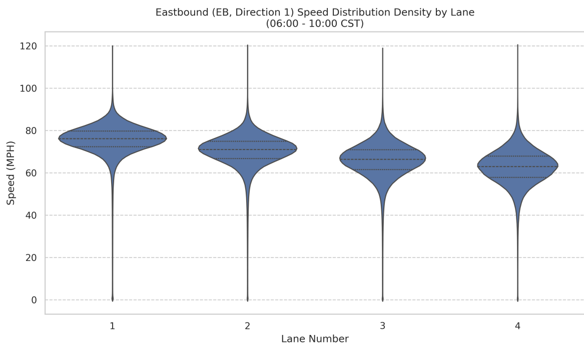


(b) Eastbound (EB, Direction 1)

Figure 5: Box plots showing speed distributions (MPH) by lane number between 06:00 and 10:00 CST on Nov 21, 2022. Median speeds are annotated.



(a) Westbound (WB, Direction -1)



(b) Eastbound (EB, Direction 1)

Figure 6: Violin plots showing speed distribution density by lane number between 06:00 and 10:00 CST on Nov 21, 2022.

The eastbound direction shows relatively uncongested flow with a clear speed hierarchy across lanes, while the heavily congested westbound direction exhibits significantly lower speeds, high variability characteristic of stop-and-go waves, and a breakdown of the typical lane speed hierarchy.

5 Stop-and-Go Wave Analysis

Stop-and-go waves are characteristic features of congested traffic flow, visible as backward-propagating waves of deceleration and acceleration (diagonal red/orange stripes) in the time-space diagram (Figure 3). The propagation speed of these waves is a key parameter in traffic flow theory and can be estimated visually from the slope of these waves, as demonstrated in Figure 7.

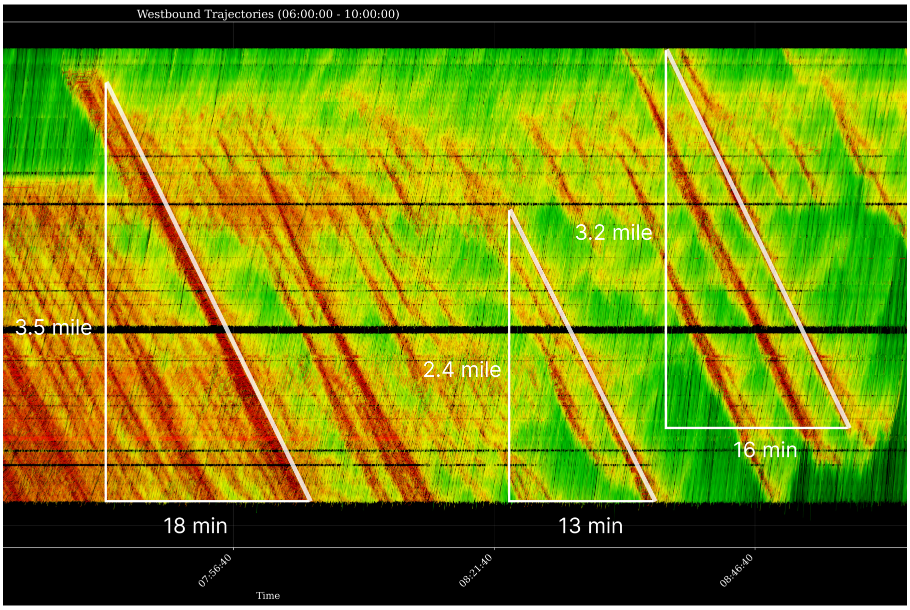


Figure 7: Shockwave estimation

Methodology (Visual Estimation): The propagation speed (w) of the stop-and-go waves is estimated directly from the slope of the wave fronts or rears in the time-space diagram:

1. Visually identify distinct, relatively parallel waves during the congested period on the Nov 21, 2022 (WB) time-space diagram. Figure 7 highlights three such waves.
2. For each highlighted wave, determine the distance covered (Δx in miles) and the time taken (Δt in minutes) from the annotations provided on the figure.
3. Calculate the wave speed magnitude in mph:

$$|w_{\text{mph}}| = \frac{\Delta x \text{ (miles)}}{\Delta t \text{ (minutes)}/60 \text{ (min/hr)}}$$

4. Since the waves propagate upstream (opposite to the direction of traffic flow), assign a negative sign to the calculated speed to represent the velocity relative to the roadway (w_{mph}).
5. Average the speeds calculated from the different waves shown.

Alternatively, the propagation speed of these waves can be calculated using cross-correlation methods, as detailed in [1, Appendix F]

Findings: Applying the visual estimation method to the three annotated waves in Figure 7:

- **Wave 1 (Left):** $\Delta x = 3.5$ miles, $\Delta t = 18$ minutes. Speed $= -\frac{3.5}{18/60} = -\frac{3.5}{0.3} = -11.67$ mph.
- **Wave 2 (Middle):** $\Delta x = 2.4$ miles, $\Delta t = 13$ minutes. Speed $= -\frac{2.4}{13/60} = -\frac{2.4\times 60}{13} \approx -11.08$ mph.
- **Wave 3 (Right):** $\Delta x = 3.2$ miles, $\Delta t = 16$ minutes. Speed $= -\frac{3.2}{16/60} = -\frac{3.2}{16}\times 60 = -0.2 \times 60 = -12.0$ mph.

The estimated propagation speeds for these individual waves are approximately -11.67 mph, -11.08 mph, and -12.0 mph.
The average propagation speed based on these three visual estimations is:

$$w_{\text{avg}} = \frac{-11.67 - 11.08 - 12.0}{3} \approx \textbf{-11.6 mph}$$

6 Addressing Data Quality Issues

The I-24 MOTION dataset, while providing unprecedented detail, inherently contains artifacts resulting from the complex data collection and processing pipeline, as discussed detailed in [1, 4]. Key issues include trajectory fragmentation, data gaps (due to occlusions, camera outages, or network issues), positional noise, timestamp inaccuracies, and potential outliers or ID swaps. Given the sheer volume of the data (e.g., 70GB uncompressed for a single 4-hour period [2]), methods to address these quality issues must be computationally efficient and scalable.

Based on the challenges identified and methods discussed in the provided literature, here are proposed approaches:

1. **Advanced Trajectory Data Association:**
   Primarily addresses fragmentation, where a single vehicle is represented by multiple trajectory segments, and potential ID swaps. This is noted as a key limitation inhibiting long-term analysis [2].
   Method: The I-24 MOTION project already employs post-processing pipelines involving data association [1]. Techniques like formulating the problem as a Minimum Cost Circulation (MCC), and using Negative Cycle Canceling (NCC), are effective [3]. The Online NCC algorithm presented in [3] processes fragments as they arrive and maintains memory bounds, making it suitable for the dataset's volume. Further enhancements could involve incorporating more complex motion models into the cost function used by these association algorithms.

2. **Handling Large Data Gaps (e.g., Pole Outages):** Addresses missing data over significant spatial extents, like the gap near MM 61 due to the Pole 25 outage.
   Method:
   - *Exclusion/Flagging:* For analyses sensitive to gaps, exclude data points or trajectories passing through the affected area/time.
   - *Macroscopic Interpolation:* Use methods like the Adaptive Smoothing Method (ASM) [2] to interpolate the macroscopic speed field across the gap based

on surrounding data. Virtual trajectories generated through this field would smoothly traverse the gap.

- *Model-Based Imputation:* Use calibrated traffic flow models (e.g., CTM) to simulate behavior within the gap, conditioned on observed boundary conditions.

3. **Quality Flagging:** Retaining information about data reliability for downstream use. *Method:* Instead of simply discarding data deemed low quality, augment trajectory records with flags indicating potential issues. This allows users to filter data based on their specific analysis requirements and tolerance for different error types.

Addressing these issues effectively at the scale of I-24 MOTION necessitates leveraging parallel and distributed computing frameworks (e.g., Dask, Spark) and prioritizing online or efficient batch algorithms where possible. The ongoing development of the I-24 MOTION processing pipeline aims to continually improve data quality by incorporating such methods [1].

7 Analysis of Additional Data

Trajectory data for five additional days were selected from the I-24 MOTION data calendar for analysis. The selected days are:

- Thursday, Jun 06, 2024
- Tuesday, Sept 10, 2024
- Thursday, Oct 03, 2024
- Thursday, Oct 17, 2024
- Friday, Jul 26, 2024

- **Jun 06 (Thur):** This Thursday morning exhibits a example of severe, recurrent rush-hour congestion on I-24 westbound. The traffic state is dominated by stop-and-go conditions from before 6:00 AM until well past 8:30 AM. The congestion likely originates from a bottleneck downstream of the observed segment. A known data gap exists around MM 61.0-61.2 due to issues with Pole 25. The overall pattern is indicative of a typical heavy weekday commute with significant delays.

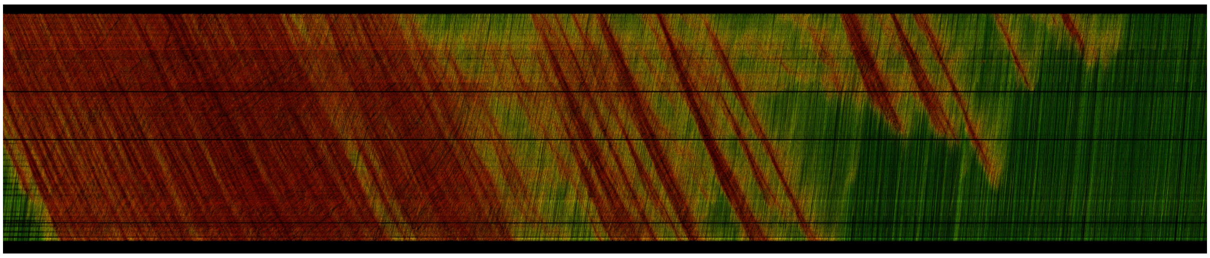


Figure 8: Time-Space Diagram of Westbound, Jun 06 (Thur), 2024

- **Sept 10 (Tue):** This time-space diagram shows a typical, heavy weekday morning commute pattern with significant congestion. The pattern is very similar to the Thursday, June 06 example, featuring a prolonged period of stop-and-go traffic dominated by backward-propagating waves. The congestion appears driven by a downstream bottleneck. The data quality is impacted by the known issue at Pole 25 (MM 61.0-61.2) and a noticeable vertical discontinuity around 8:35 AM.

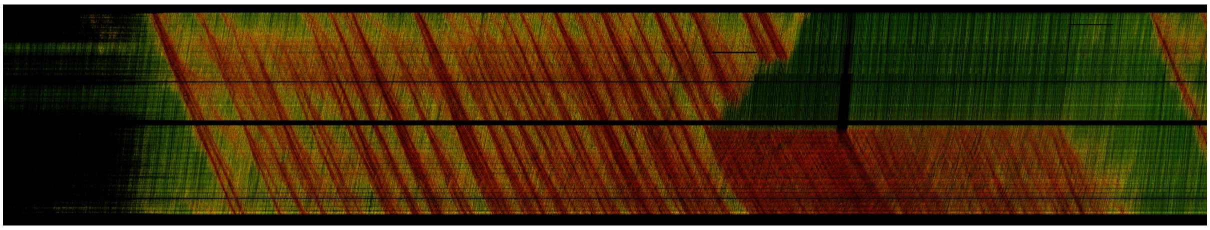


Figure 9: Time-Space Diagram of Westbound, Sept 10 (Tue), 2024

- **Oct 03 (Thur):** Traffic volumes were significantly lower throughout the day compared to weekdays. No major congestion or distinct peak periods were observed. Flow remained largely free-flow, except potentially for short durations related to minor incidents or unusual maneuvers. The horizontal band of missing data around MM 61.0-61.2 is still visible. There appear to be numerous thin, somewhat irregular horizontal black lines or bands scattered across the plot. These might represent noise in the data processing.

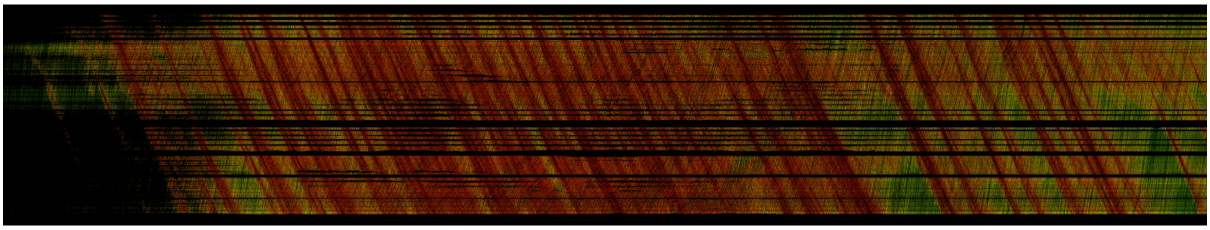


Figure 10: Time-Space Diagram of Westbound, Oct 03 (Thur), 2024

- **Oct 17 (Thur):** The segment starts relatively free-flowing (green/yellow) before 6:30 AM. Congestion begins to build noticeably between 6:30 AM and 7:00 AM, initiating downstream (top of plot) and propagating upstream (downwards). Significant congestion (widespread orange/red) is present from roughly 7:00 AM until about 9:00 AM.There is a significant block of missing data (black area) at the very beginning of the time window (left edge) for the upstream portion of the segment.

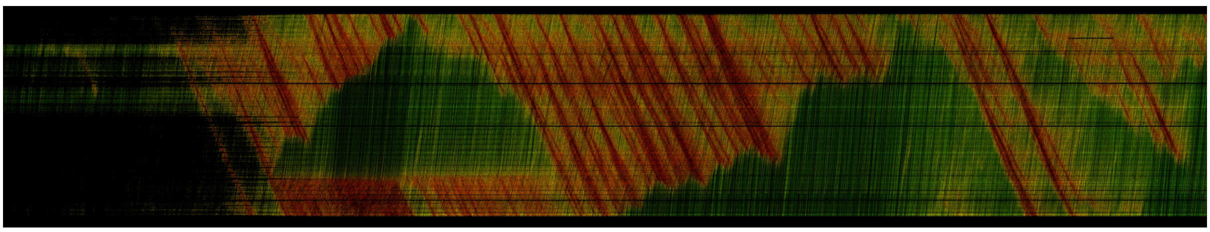


Figure 11: Time-Space Diagram of Westbound, Oct 17 (Thur), 2024

- **Jul 26 (Fri):** The time-space diagram of Friday eastbound clearly illustrates the typical afternoon/evening commute pattern. Congestion builds significantly starting mid-afternoon, driven by a bottleneck located upstream of the monitored segment (at or before MM 59.0). Within the main congested period, stop-and-go waves propagating downstream (against traffic flow) are clearly visible. The morning and midday periods remain largely free-flowing. Data quality is impacted by the known gap near MM 61.0-61.2 (Pole 25) and minor horizontal banding artifacts.

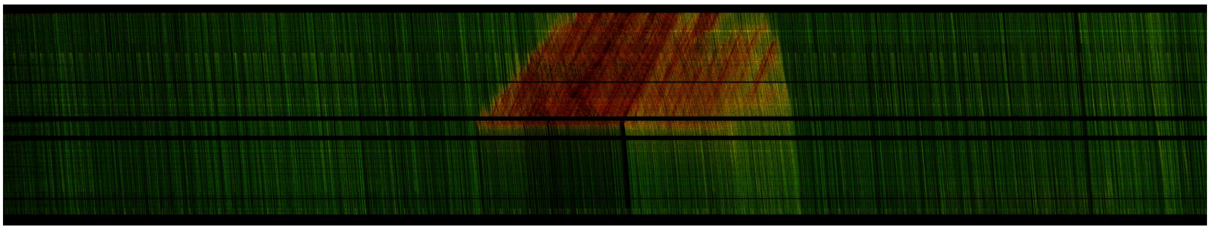


Figure 12: Time-Space Diagram of Eastbound, Jul 26 (Fri), 2024

- **Data Artifacts:** Across all days, issues like trajectory fragmentation and minor jitter were consistently present, appearing inherent to the data collection/processing method. On [Specific Date, e.g., Nov 23], there seemed to be a brief period around [Time] with slightly lower data density, potentially indicating a temporary issue with a subset of cameras or processing nodes, though overall coverage remained good.

This comparison highlights the variability of traffic patterns based on day-of-week and holiday influences, while also confirming the persistence of certain data characteristics and bottleneck locations.

8 Travel Time Analysis

Following the idea related to virtual trajectories [**?**], we aim to estimate the time taken for vehicles to traverse the entire segment using VT-tools [7].

1. The 4.2-mile segment was defined within the 'x_position' coordinate system, with start and end boundaries set at start X_{start} and X_{end}), respectively. These positions align with the longitudinal coordinates (in feet) used in the I-24 MOTION dataset.
2. Virtual trajectories were generated for each of the four lanes (Lane 1: HOV, Lane 2, Lane 3, Lane 4) using the VT-tools toolbox. Trajectories were spawned at 15-second intervals between 06:00 and 09:00 on November 21, 2022 (Westbound), resulting in 713 trajectories per lane (2,852 total).
3. For each virtual trajectory, the travel time (TT) was computed as the difference between the last timestamp and the first timestamp.
4. Trajectories were grouped into 5-minute departure time windows (e.g., 06:00-06:05, 06:05-06:10) to balance temporal resolution with statistical robustness, given the high number of trajectories per lane.
5. The average travel time for each 5-minute window was calculated by taking the mean of the travel times of all trajectories departing within that window.

The analysis of average travel time versus departure time for Nov 21, 2022 (Westbound) is shown in Figure 13.

- The plot shows significant variation during the morning hours, strongly correlating with congestion levels.
- Pre-peak travel times (around 06:00) and post-peak times (approaching 09:00) are relatively low, around 4-9 minutes, corresponding to higher, less congested speeds. True off-peak times outside this window would likely be lower.
- During the AM peak (roughly 06:15 to 07:45), average travel times increase significantly, reaching a maximum of approximately 36 minutes (observed in Lane 1, the HOV lane, around 06:30). Other lanes peak between 23-28 minutes shortly after.
- The provided figure focuses on the AM period (06:00-09:00). Analysis of any PM peak would require data from later in the day and is not depicted here.
- The shape of the travel time curve, with its sharp rise and subsequent fall, clearly mirrors the congestion patterns discussed in Section **??**, providing a quantitative measure of the delay experienced by drivers during the AM peak.

The "departure time" here refers to the initial time of virtual trajectory, in the context of real traffic, it refers to the time vehicle enters this stretch of highway.

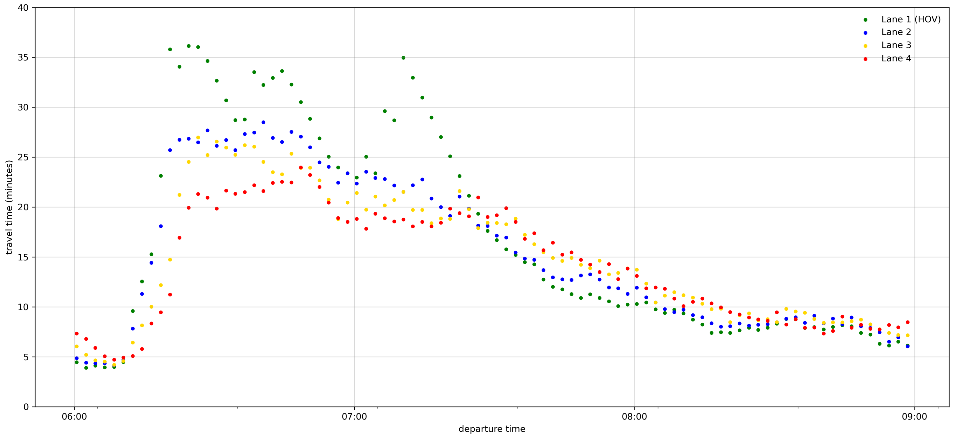


Figure 13: Travel time with different departure times for each virtual trajectory generated from each lane

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