Safety Assessment of UAV Operations in U-Space: A Comprehensive Study on Key Safety Metrics

Version 1.0

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Abstract

In this technical report, we introduce two categories of safety metrics including collision metrics and surveillance performance metrics. We also identify and classify influencing factors into three main categories consists of technical, environmental, and operational factors. We then analyze the impact of these factors on the defined metrics within the context of U-space.

1. Introductions

Unmanned Aerial Vehicles (UAVs), or drones, are increasingly used across various sectors and are expected to grow rapidly in civilian airspace in the coming years. In this context, effective traffic management becomes essential. UTM (Unmanned Traffic Management) and U-space are regulatory frameworks designed to manage drone traffic by providing various services. In U-space several strategic phase services (i.e., pre-flight) such as strategic conflict detection, strategic conflict resolution, and tactical phase services (i.e., in-flight) such as tactical conflict detection, and tracking are available to enhance the safety in this crowded and complex airspace.

Despite the availability of U-space services, defining reliable metrics to quantitatively assess operational safety and ensure the Target Level of Safety (TLS) under both normal and abnormal conditions remains a major challenge. This technical report presents an analysis of how abnormal conditions—such as GPS faults, IMU (Inertial Measurement Unit) faults, wind, and combinations of sensor faults with wind—affect These metrics.

These results can be useful for monitoring system to find the metrics which are more sensitive to the safety risk and analyzing the impact of the different factors on metrics to find which factor can have more impact on which metrics and finding the good metrics which are the metrics that are more sensitive to the risk of collision between drones.

2. Safety Factors

We categorized the safety metrics into three different factors including technical factors, environmental factors, and operational factors.

- Technical Factors: These involve system-related issues, where technical malfunctions or external intrusions in UAV components can lead to faults or failures, affecting overall operational safety. In this technical report we considered GPS Faults and IMU Faults as technical factors.
- Environmental Factors: These factors refer to the natural conditions that can affect UAV operations, such as wind.
- Operational Factors: These factors directly influence the safety of UAV operations based on both the operational environment and the performance of the UAVs. They include aspects such as different UAV speeds, different Update Intervals (UIs), and different air traffic density (high, medium, or low). We considered different levels of air traffic based on three features: (1) the distance between the target UAV and adjacent UAVs on its left and right sides: 10 meters for high traffic,100 meters for medium traffic, and 200 meters for low traffic; (2) the number of traffic layers: three layers with 10 meter spacing for high traffic, two layers with 100 meter spacing for medium traffic, and one layer with 200 meter spacing for low traffic; and (3) the flow rate, defined as a 0.4 second interval between consecutive flights, representing a worst-case scenario in which a drone is nearly always present at a fixed distance on both sides of the target UAV. These values for low, medium, and high traffic levels were defined based on extensive experimentation carried out both in this study and in our previous work.

3. Safety metrics

In this technical report, we classified the safety metrics into two different categories including the collision metrics and surveillance performance metrics.

- **Collision metrics:**
  we considered collision metrics as quantitative measures used to assess the frequency, likelihood, severity, and potential consequences of collisions or conflicts between drones. The following introduces these metrics.

  - **Number of Collisions:** The total number of UAV collisions along a flight path. A collision is defined when the distance between two drones becomes less than the sum of their motor-to-motor dimensions and propeller diameters.
  - **Number of Conflicts:** The Number of Conflicts metric counts instances where the safety zones, or "separation bubbles," of two UAVs overlap.
  - **Frequency of Collision:** Frequency of collision is calculated as all the collisions caused in the flight duration, divided by the sum of the flight time of each of the UAV involved, as shown in the Eq 1, where T_i is the total time flown by the number of drones n.

$$F_{Collisions} = \frac{N_{Collisions}}{\sum_{i=1}^{n} T_i}$$

  - **Frequency of Conflict**: Frequency of conflict is calculated as all the conflicts caused in the flight duration, divided by the sum of the flight time of each of the UAV involved, as shown in the Eq 2, where T_i is the total time flown by the number of drones n.

$$F_{Conflicts} = \frac{N_{Conflicts}}{\sum_{i=1}^{n} T_i}$$

  - **Incomplete missions' percentage (IMP):** This metric indicates the percentage of missions that were not successfully completed due to collisions, crashes, or the activation of fail-safe mechanisms, out of all faulty missions executed.
  - **Number of Inner Separation Minima Violations (ISMV):** The inner bubble size is calculated using a fixed formula, as shown in Equation 3, with all measurements standardized in meters for consistency. In this equation, D_O represents the drone's total dimensions, including wingspan, while D_S denotes the manufacturer's recommended safety distance. D_m denotes the maximum distance a drone can travel at peak speed between tracking intervals, remains constant for a mission but may vary by drone model and mission.

$$\text{Bubble}_{\text{inner}} = D_o + \max(D_s, D_m)$$

  - **Number of Outer Separation Minima Violations (OSMV):** The outer separation minima assign a protective bubble around each drone, influenced by factors like weight, speed, navigation, and communication with UTM/U-space, following U-space guidelines [?]. There is currently no standardized method for calculating these minima in urban airspace, emphasizing the need to define them for this study. Equation 4, calculates the dynamic bubble using current and previous airspeeds, $Sa(t_n)$ and $Sa(t_n-1)$ and the last distance covered by drone $D(t_n-1)$ represents the last distance covered by the drone, these parameters are used to compute the anticipated distance to be covered at time t_n:

$$D(t_n) = D(t_{n-1}) \times \frac{Sa(t_n)}{Sa(t_{n-1})}$$

The relative change in anticipated distance, based on airspeed variations (as in Equation 4), determines the extra space required beyond the drone's minimum inner bubble radius. Finally, as shown in Equation 5, The radius of the outer bubble is computed by multiplying the inner bubble radius by the calculated distance and a risk factor R (e.g., for simplicity in this study, R is set to 1), which accounts for factors like airspace density, weather, and U-space performance.

$$Bubble_{\text{outer}}(t) = R \times (Bubble_{\text{inner}} \times \max(1, D(t_n)))$$

- **Surveillance Performance Metric**

Measuring surveillance performance is vital for ensuring Target Level of Safety (TLS) in UAV operations, as it maintains separation and verifies telemetry data (Target Reports, TRs). To be effective in UTM systems or U-Space, telemetry must meet standards for completeness, precision, update rate, latency, and integrity. Surveillance performance is evaluated by classifying target reports based on their positional accuracy relative to a reference path, a necessary step before metric calculation. These reports are categorized into specific classes, as shown in figure 1 and explained below.

- **Number of True Target Report (NTTR)**: As shown in figure 1, TTR is a report received within the predefined bubble based on the drone's specifications, airspace density, and population type. It aligns with the reference path at the time the telemetry is received. A TTR occurs when the measured position is within a certain threshold distance from the reference trajectory at the same time.

- **Number of False Target Report (NFTR):** As show in 1, a FTR occurs when the distance between a UAV's actual position and its position on the reference trajectory exceeds a specified threshold.

- **Number of Ghost Target Report (NGTR):** A GTR occurs when an extra report is received within a given update interval (UI), beyond the expected number. For example, if two target reports are expected within a UI but a third report is received, that extra report is classified as a ghost target report.

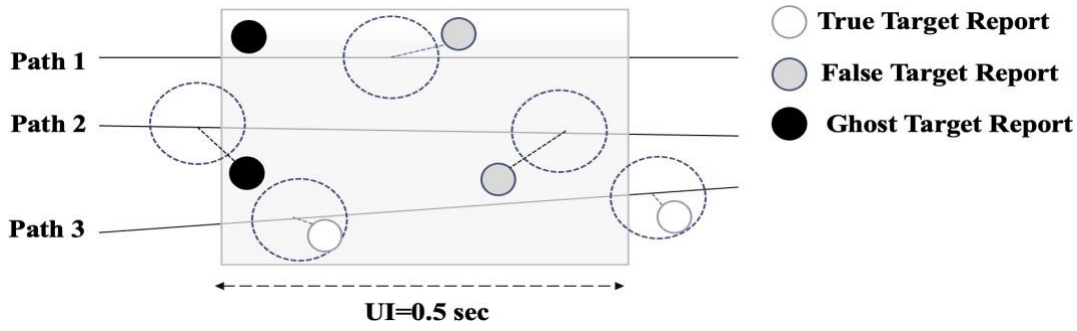


Figure 1 Visualization of Different Types of Target Reports.

- **Probability of Update (PU):** This metric quantifies the probability that a True Target Report (TTR) aligns with the reference trajectory during a specified Update Interval (UI) by calculating the proportion of time the UAS is tracked relative to its expected trajectory. Data loss, denoted by G, occurs when the time between two target reports meets or exceeds the UI, which calculates as follow, where UI is the Update Interval and N is the number of intervals.

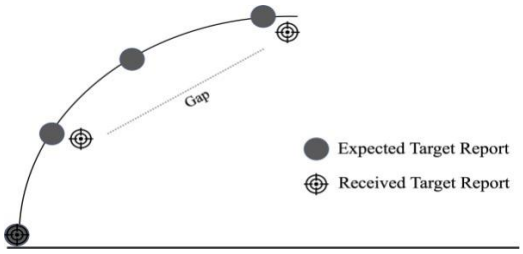
$$\text{Total Loss Period} = \sum_{t=1}^{N} L_t \quad L_t > 0,$$
$$\text{where} \quad L_t = G_t - UI$$
$$PU = 1 - \frac{\text{Total Loss Period}}{\text{Total Flight Duration}}$$

The Probability of Update, measures how consistently the UAV is tracked relative to its expected trajectory.

- **Probability of Long Gap (PLG):** As shown in Figure 2, this metric measures the probability of missing a True Target Report over consecutive Update Intervals (UIs). It is calculated based on the total loss periods, as defined below:

$$\text{Total Gap Period} = \sum_{t=1}^{N} G_t \qquad G_t > 2 * UI$$

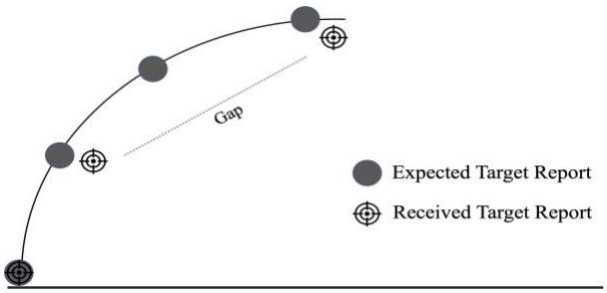
$$PLG = \frac{Total\ Gap\ Period}{Total\ Flight\ Duration}$$



- **Horizontal and Vertical Position Accuracy (HPA, VPA):** Surveillance systems with higher accuracy metrics, measured by the root mean square (RMS) of position errors in horizontal (HPA) and vertical (VPA) dimensions, improve the smoothness of data for traffic management in high-density airspace. Lower precision can necessitate adjustments to separation minima and flight plans. These accuracy metrics quantify the difference between received and expected target reports, Where erh_i^2 and erv_i^2 are the position errors in absolute value and N is the total number of true targets considered for the metric.

$$HPA_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} erh_i^2}$$

$$VPA_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} erv_i^2}$$



- **Density of False and Ghost Target Report (DFTR, DGTR):** The Density of False Target Reports DFTR is calculated as the ratio between the number of false targets and total number of target reports considered as can be seen in bellow:

$$DFTR = \frac{Total\ Target\ Reports_{False}}{Total\ Target\ Reports}$$

Similarly, the Density of Ghost Target Reports DGT R is calculated as the ratio between the number of ghost targets and total number of target reports considered as can be seen in bellow:

$$DGTR = \frac{Total\ Target\ Reports_{Ghost}}{Total\ Target\ Reports}$$

- **Probability of False or Ghost Track (PFT, PGT) :** The probability of false track is defined by dividing the total number of false UIs by the total number of UIs. A false UI is defined as an update interval in which at least one false target report is present alongside the true target report within it

$$Probability\ of\ False\ Track = \frac{Number\ Of\ UI_{False}}{Total\ Number\ of\ UI}$$

- the probability of Ghost Track is calculated by dividing the total number of ghost UIs by the total number of UIs. A ghost UI is defined as an update interval during which at least one ghost target report is present.

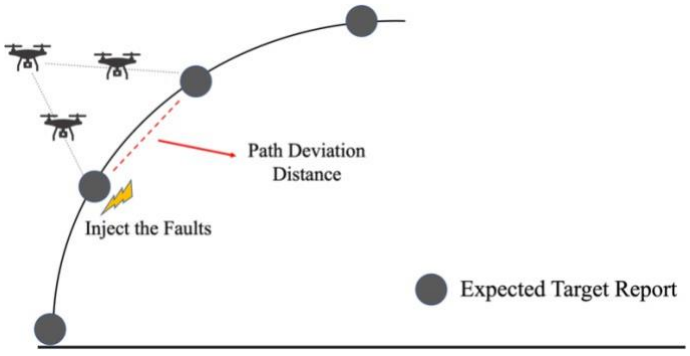
$$Probability\ Of\ Ghost\ Track = \frac{Number\ Of\ UI_{Ghost}}{Total\ Number\ of\ UI}$$

- **Flight Duration:** Flight Duration is a critical metric for operational efficiency and safety in UTM/U-space systems, as it directly impacts mission success in time-sensitive scenarios, measured from take-off to successful landing, or to the crash time if the drone failed.

- **Distance to be Traveled:** This metric represents the total distance, measured in meters, that a drone is expected to travel under both faulty Run or gold Run conditions. It helps assess the drone's performance in completing its flight path, accounting for any deviations or anomalies.

- **Battery Consumption:** This metric calculates the percentage of battery consumed during a flight, based on the Iris drone model's 15-minute capacity, offering insights into energy efficiency by comparing battery usage with flight duration, mission requirements, and operational conditions.

- **Path Deviation Distance (Dist. Dev (m)):** In this metric as shown in Figure 4, the distance between when a drone deviates from its intended path and when it returns to it is considered.



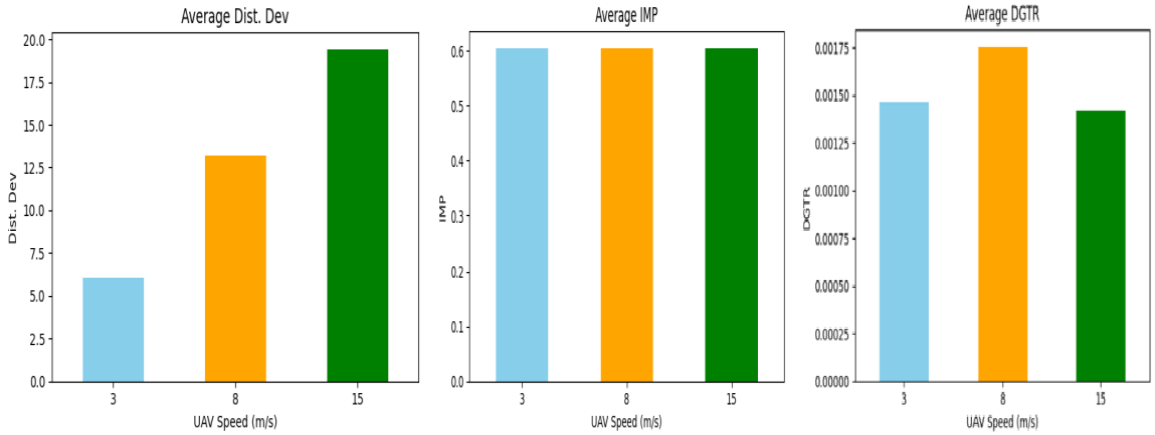
Results:

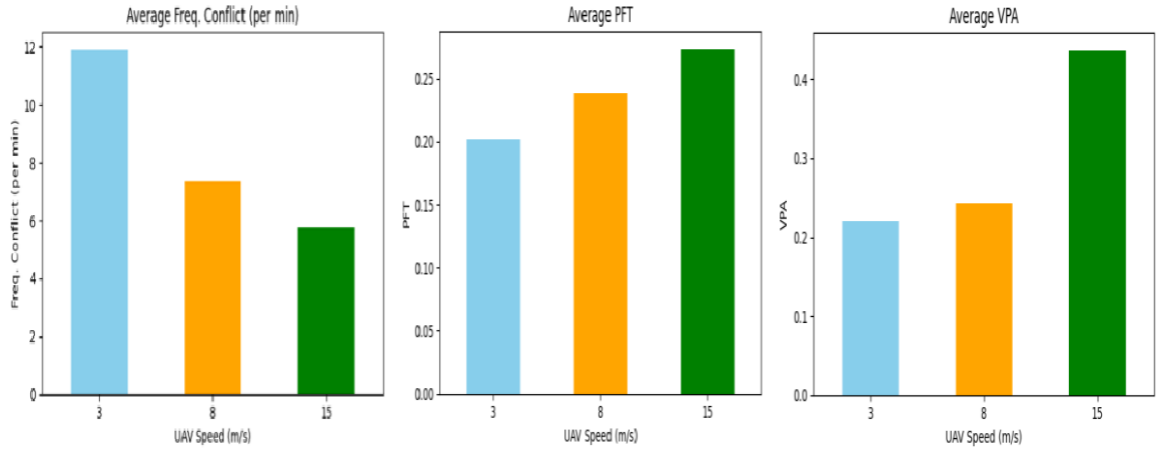
Impact of the different factors on GPS:

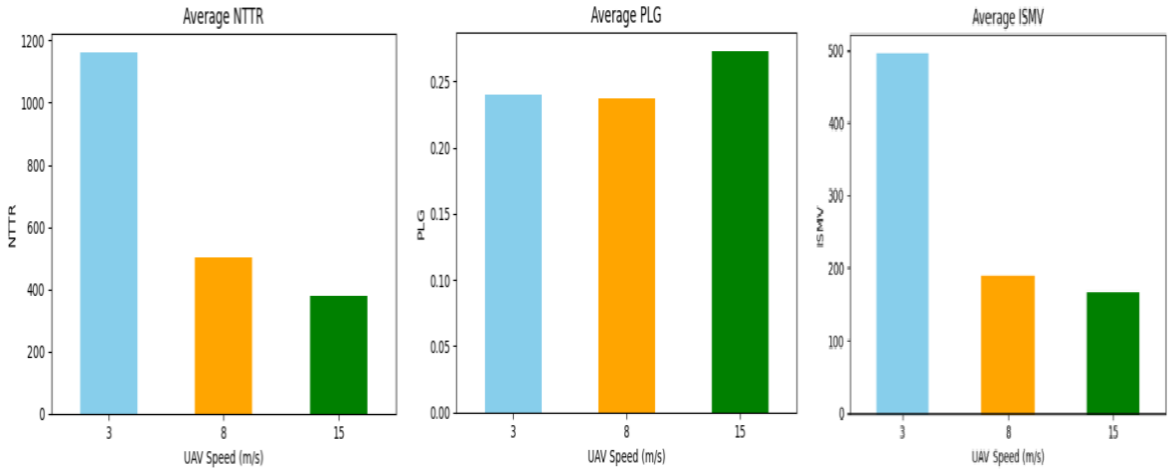
We injected three high-impact faults into the GPS module including Maximum Longitude, Maximum Latitude, and Random Value and analyzed their effects on various safety metrics. Following the fault injection, we further examined how different operational factors, including UAV speeds, update intervals (UIs), traffic levels, and injection durations, as well as an environmental factor (wind), influenced these metrics.

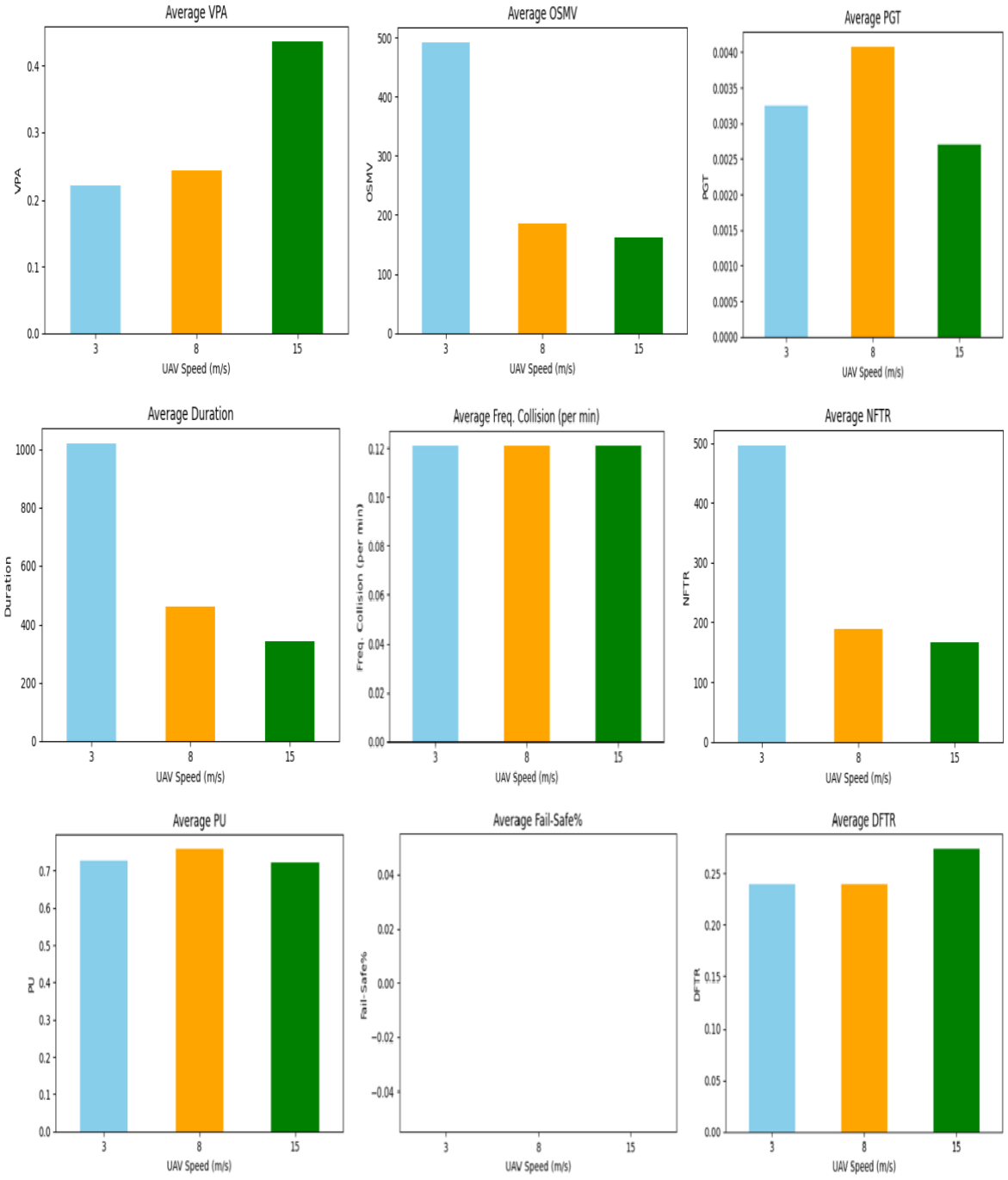
1) GPS Faults in light breeze wind

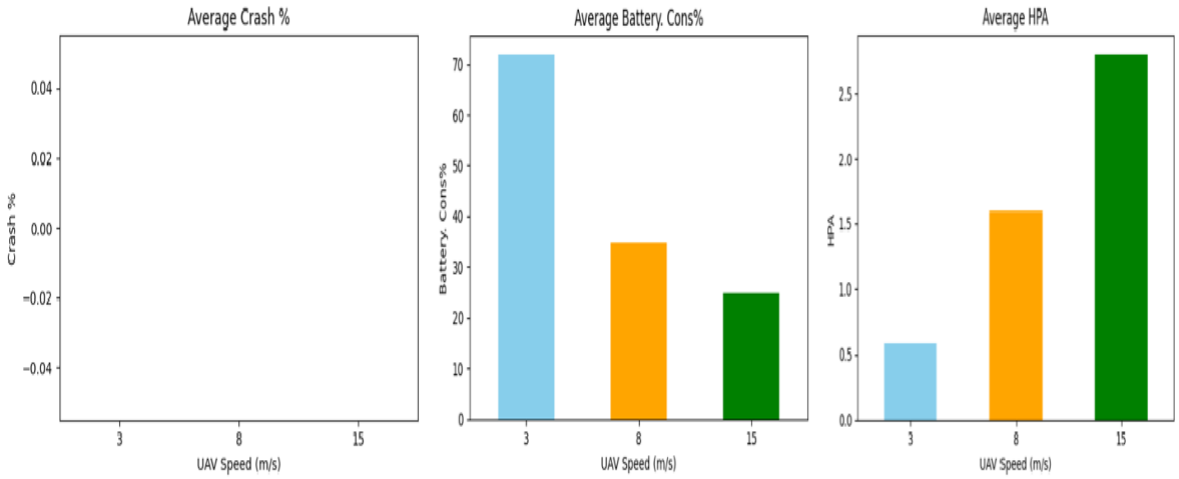
- **Impact of the different UAV Speeds:**



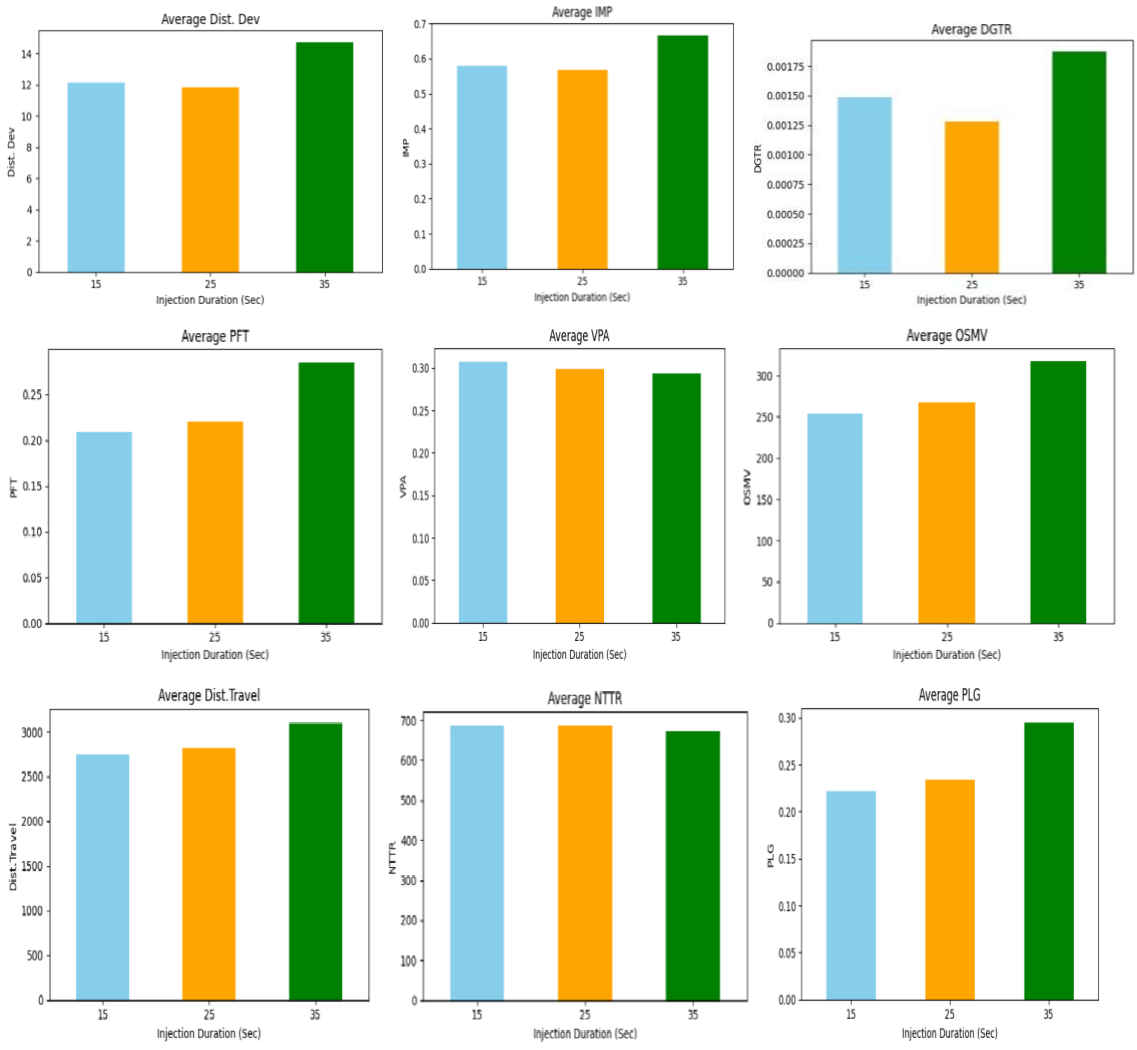


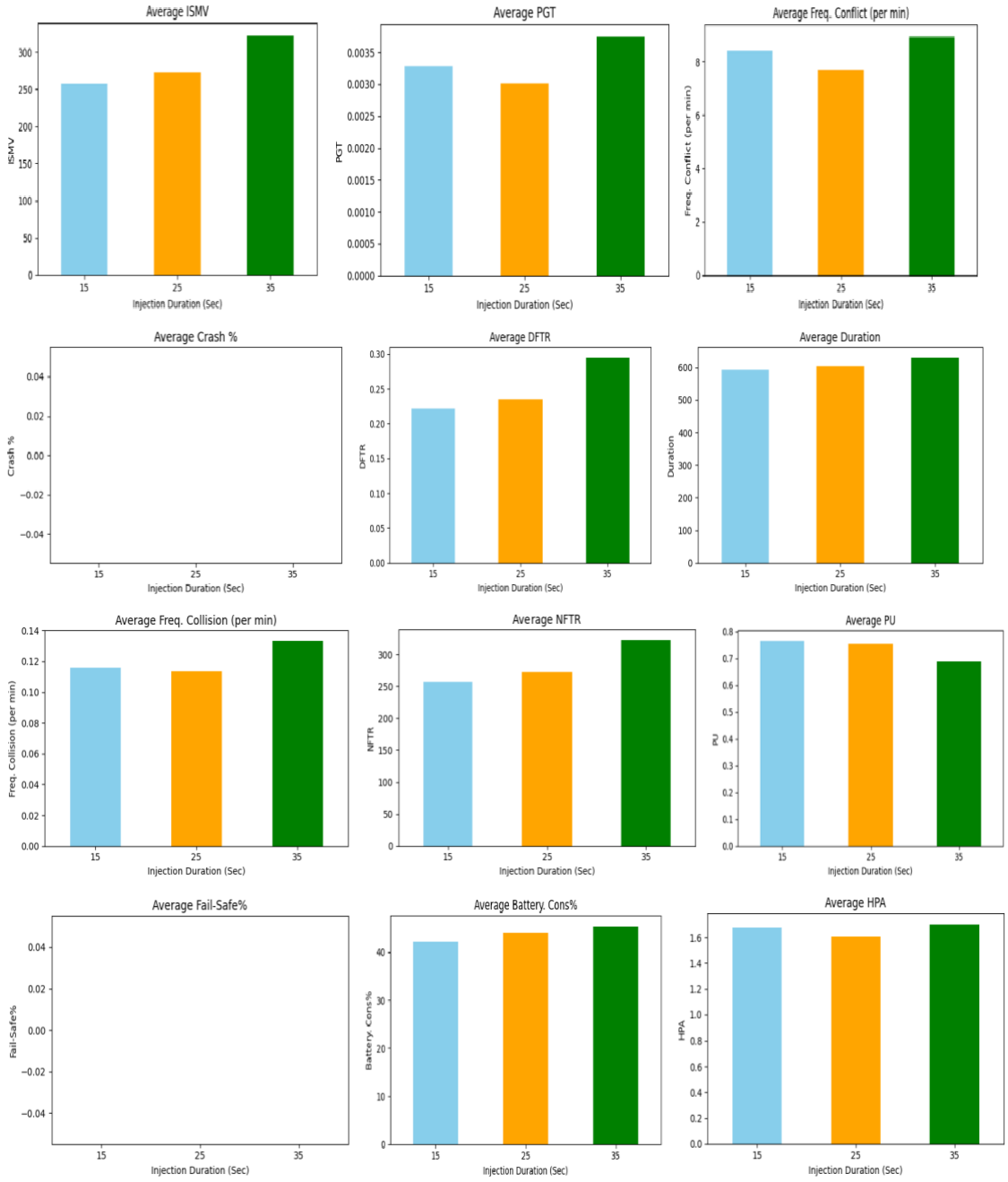



Average VPA
VPA
UAV Speed (m/s)
Average OSMV
OSMV
UAV Speed (m/s)
Average PGT
PGT
UAV Speed (m/s)
Average Duration
Duration
UAV Speed (m/s)
Average Freq. Collision (per min)
Freq. Collision (per min)
UAV Speed (m/s)
Average NFTR
NFTR
UAV Speed (m/s)
Average PU
PU
UAV Speed (m/s)
Average Fail-Safe%
Fail-Safe%
UAV Speed (m/s)
Average DFTR
DFTR
UAV Speed (m/s)

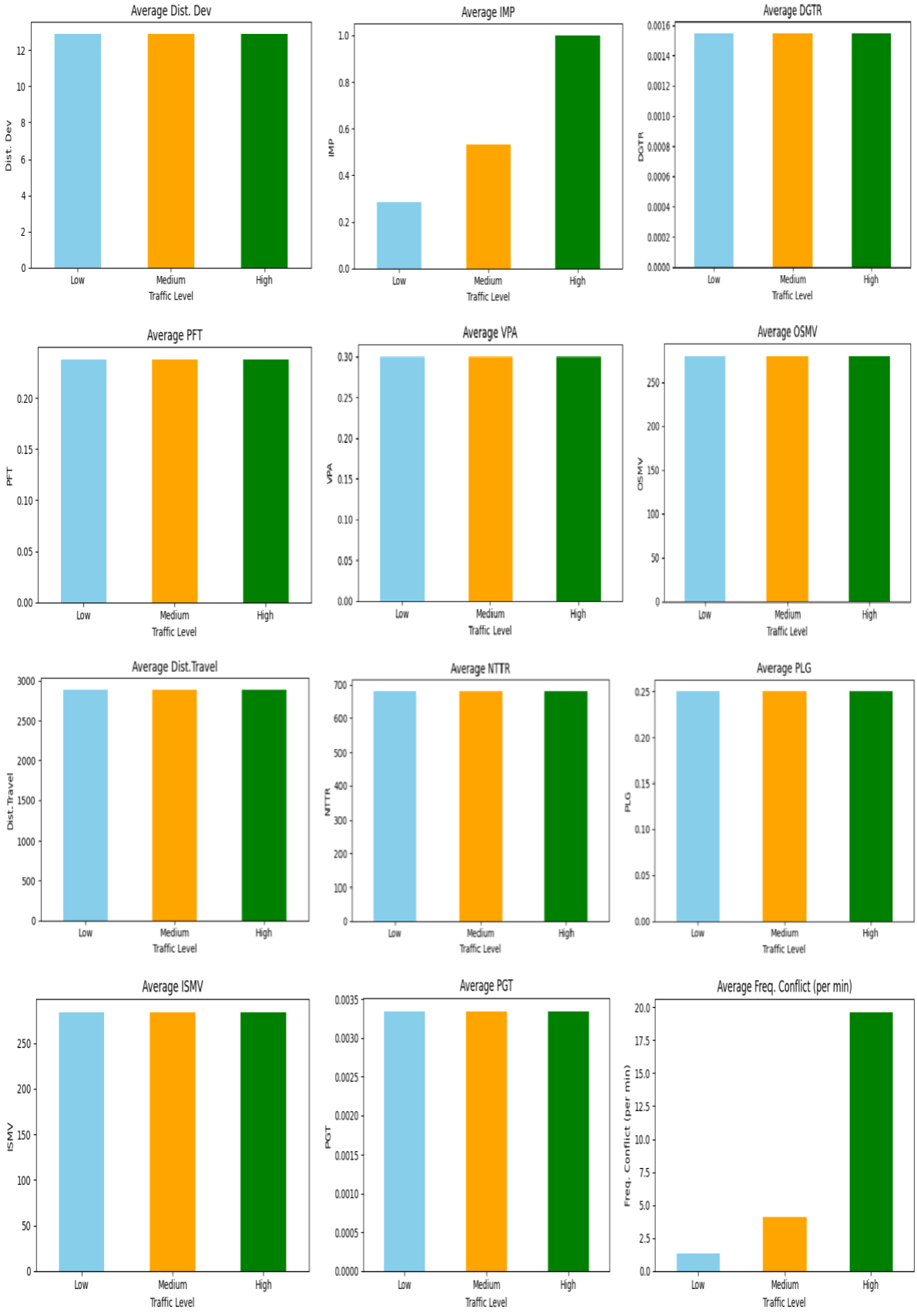


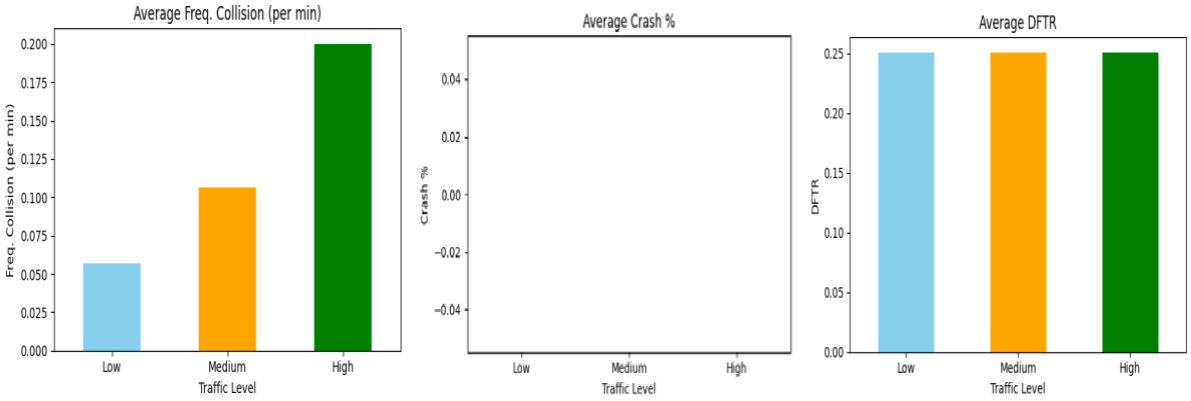
- **Impact of the different injection duration:**

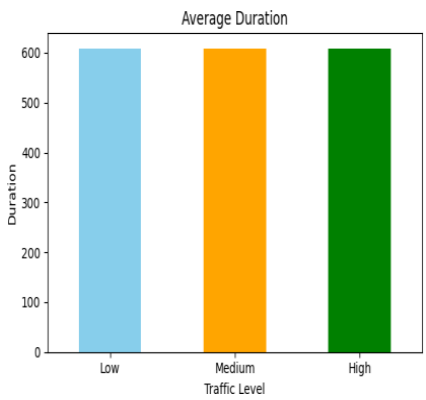


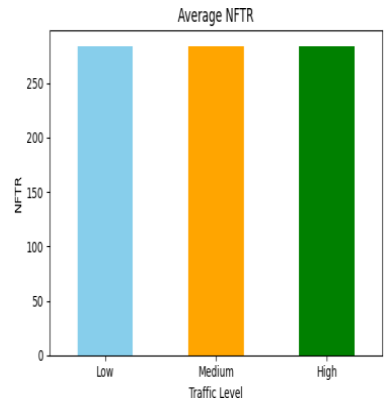


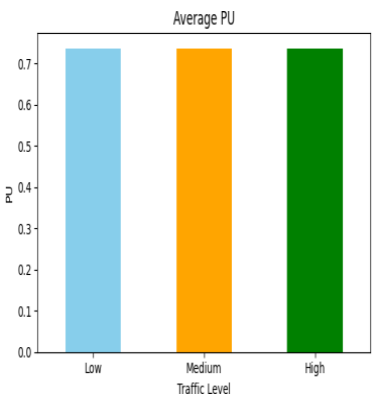
- **Impact of different Traffic Levels:**

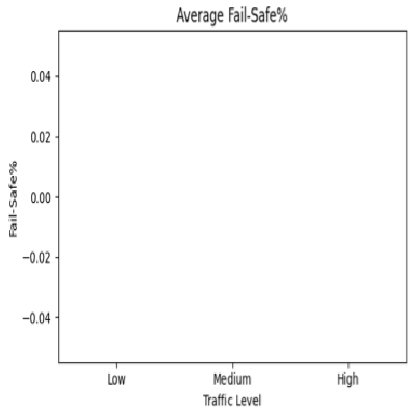

Average Dist. Dev
Dist. Dev
Traffic Level
Average IMP
IMP
Traffic Level
Average DGTR
DGTR
Traffic Level
Average PFT
PFT
Traffic Level
Average VPA
VPA
Traffic Level
Average OSMV
OSMV
Traffic Level
Average Dist.Travel
Dist.Travel
Traffic Level
Average NTTR
NTTR
Traffic Level
Average PLG
PLG
Traffic Level
Average ISMV
ISMV
Traffic Level
Average PGT
PGT
Traffic Level
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Traffic Level
Low
Medium
High

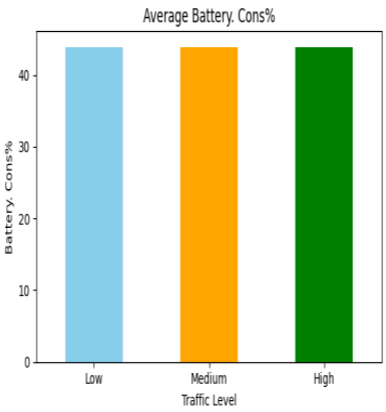


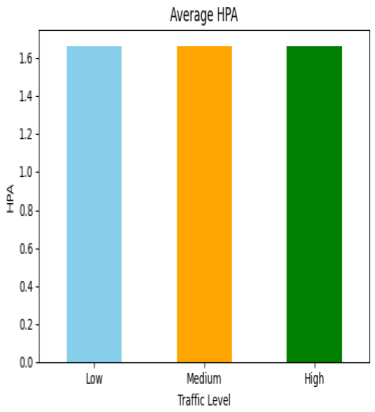




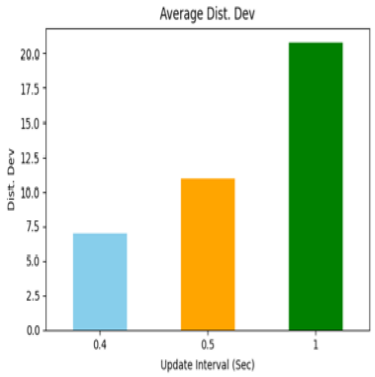


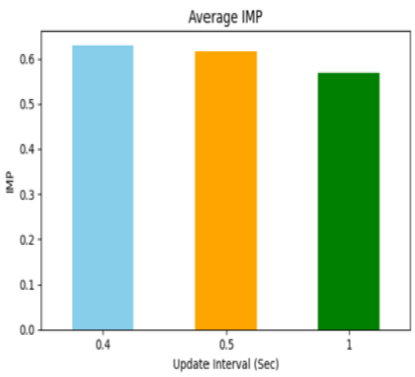


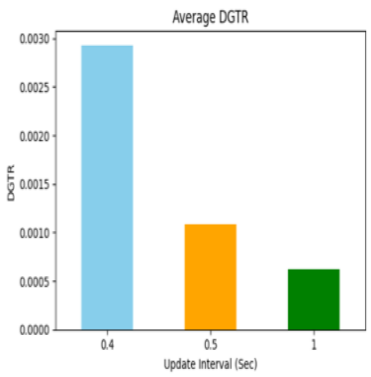


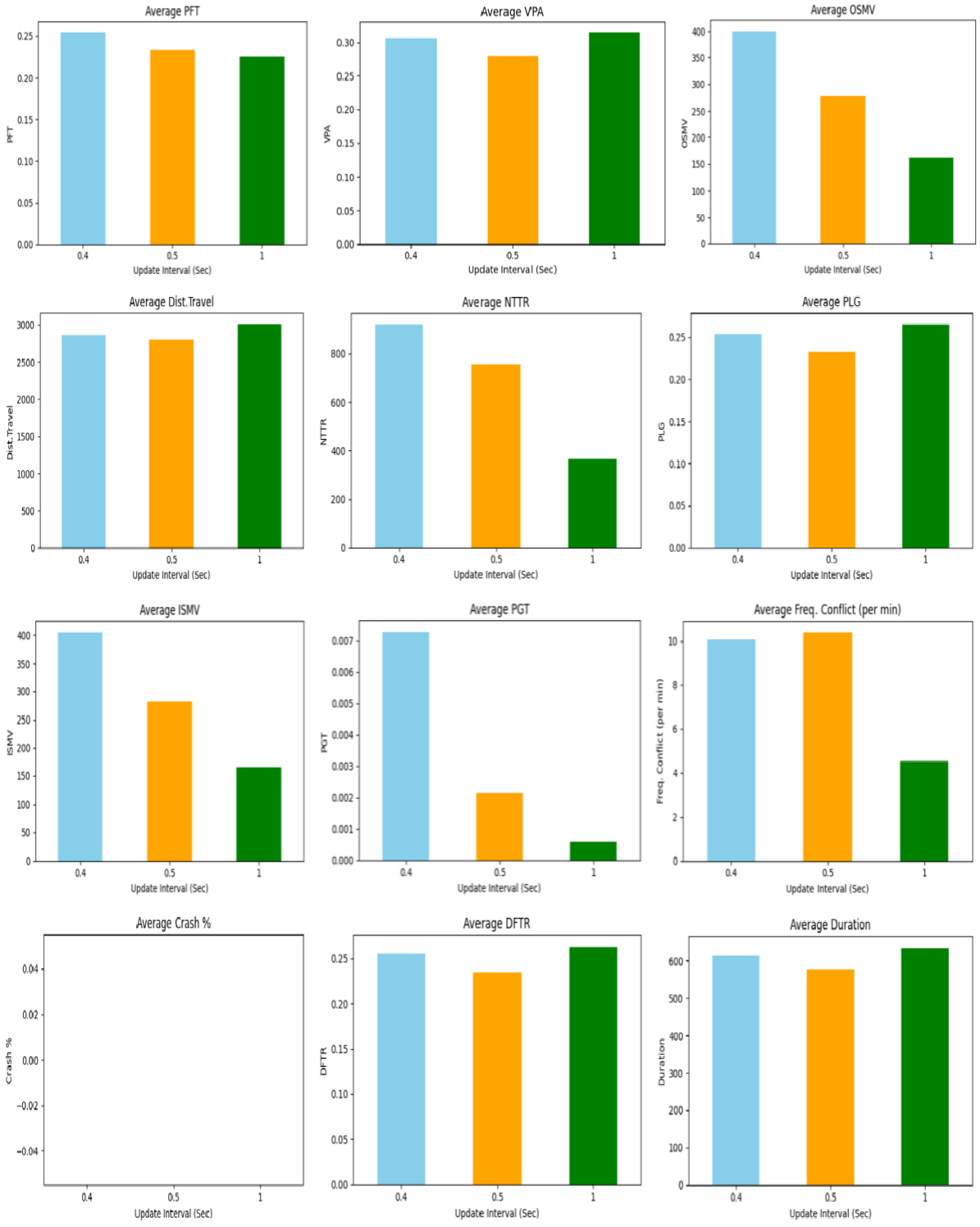


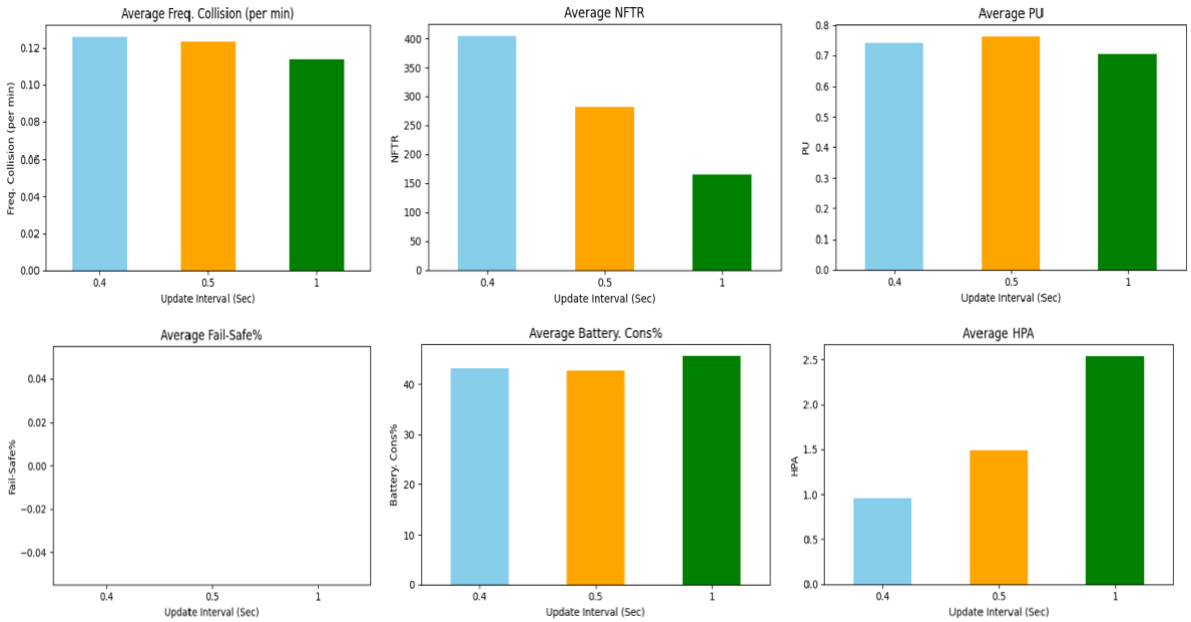
- **Impact of different update interval:**





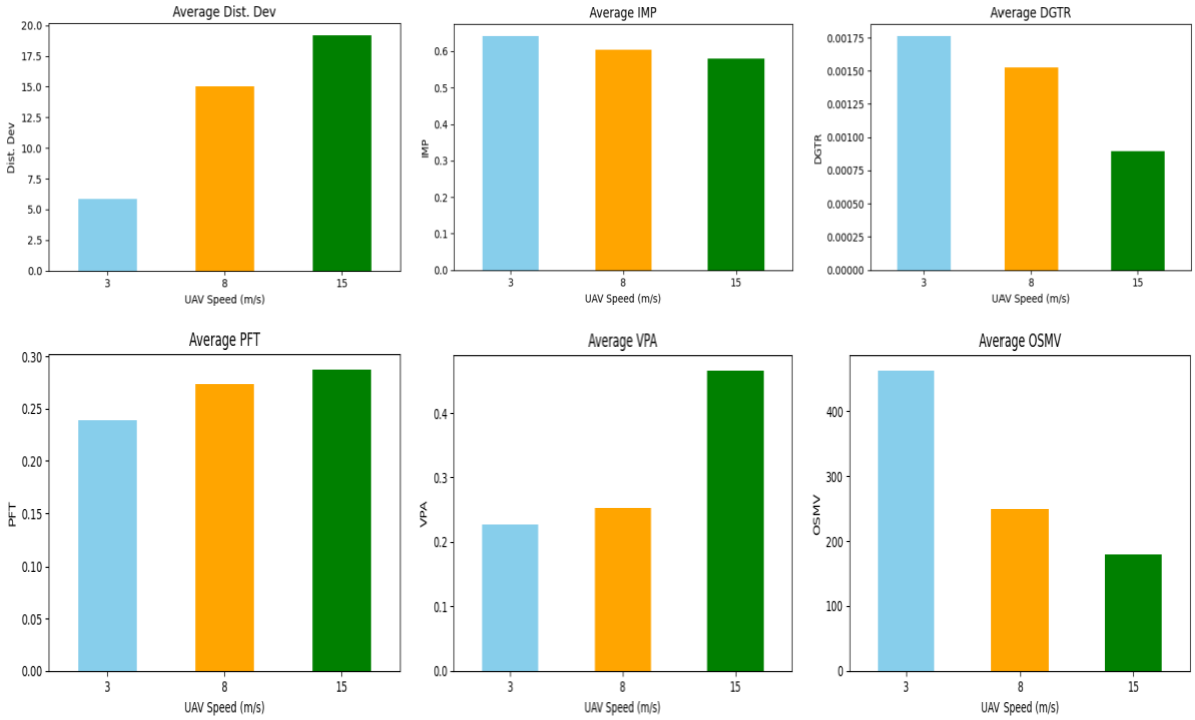


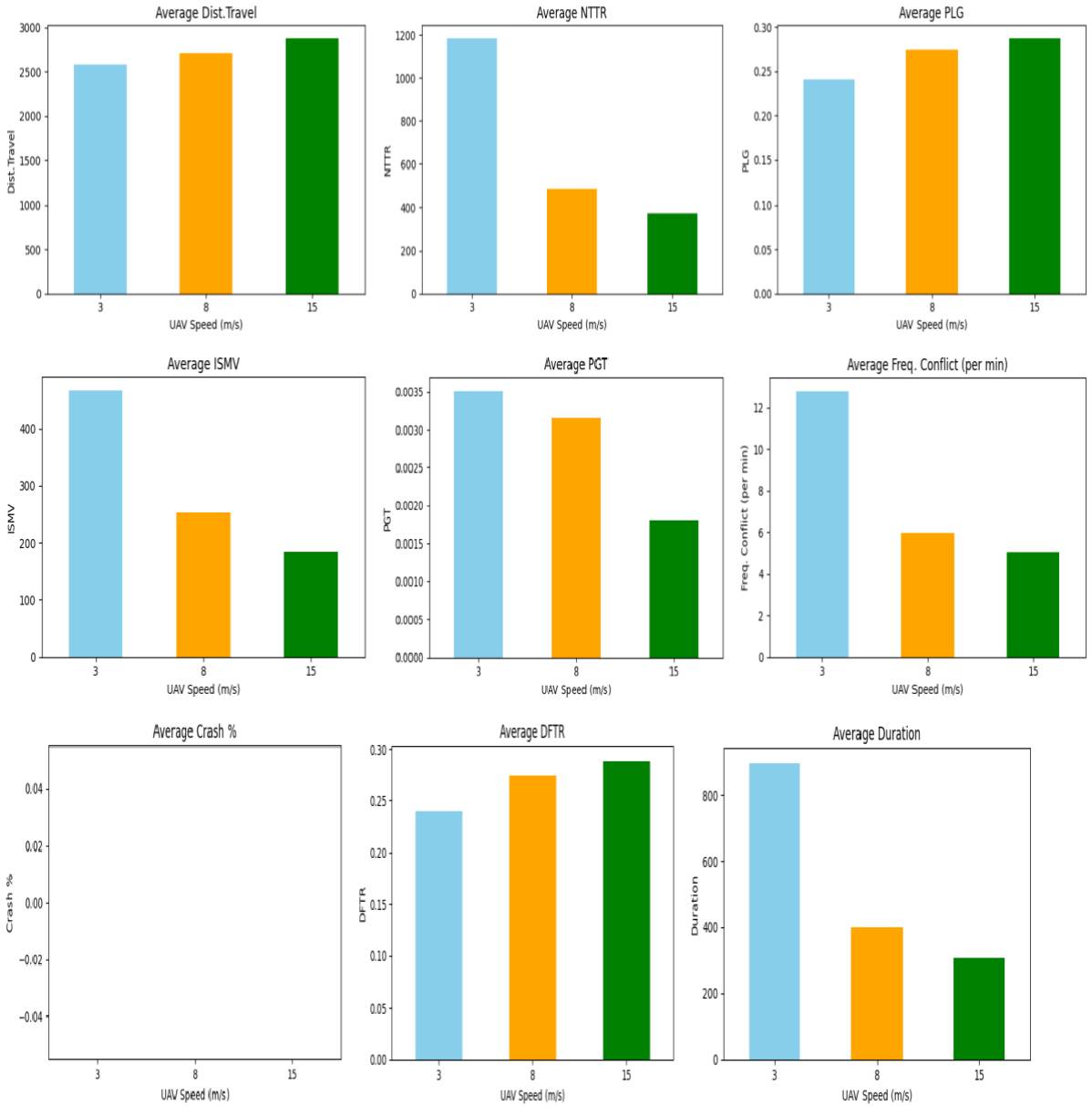

Average PFT
PFT
Update Interval (Sec)
Average VPA
VPA
Update Interval (Sec)
Average OSMV
OSMV
Update Interval (Sec)
Average Dist.Travel
Dist.Travel
Update Interval (Sec)
Average NTTR
NTTR
Update Interval (Sec)
Average PLG
PLG
Update Interval (Sec)
Average ISMV
ISMV
Update Interval (Sec)
Average PGT
PGT
Update Interval (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Update Interval (Sec)
Average Crash %
Crash %
Update Interval (Sec)
Average DFTR
DFTR
Update Interval (Sec)
Average Duration
Duration
Update Interval (Sec)

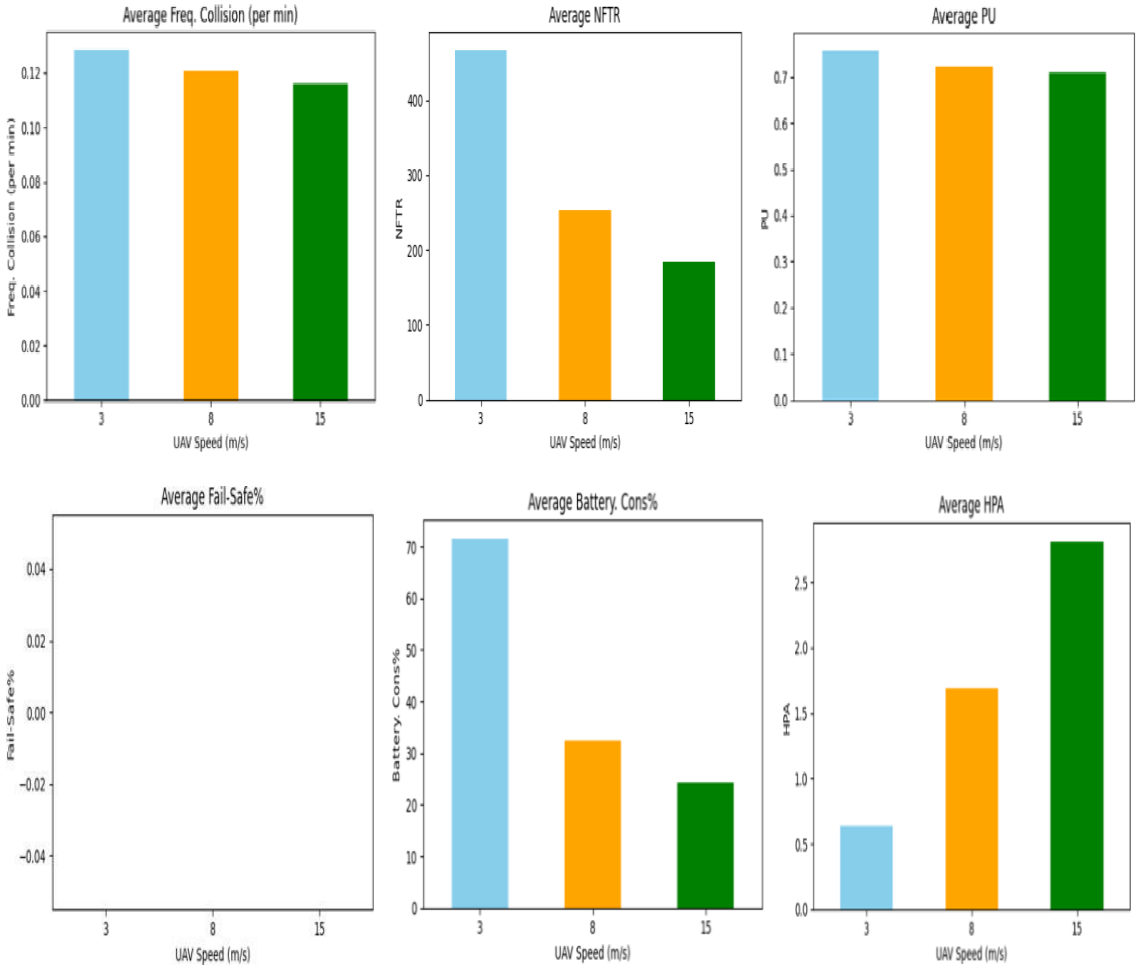


2) GPS Faults with moderate breeze:

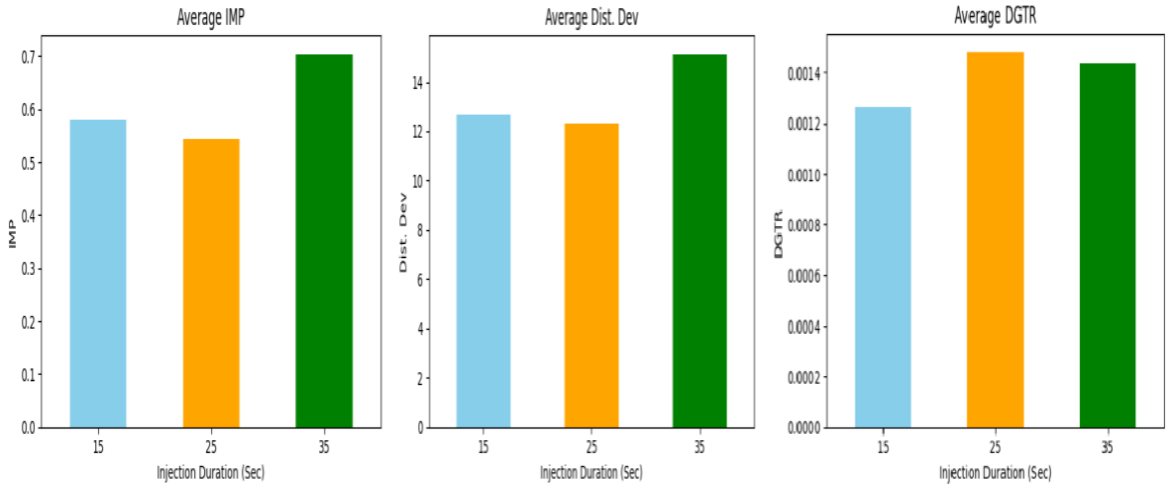
- **Impact of the different UAV speeds:**

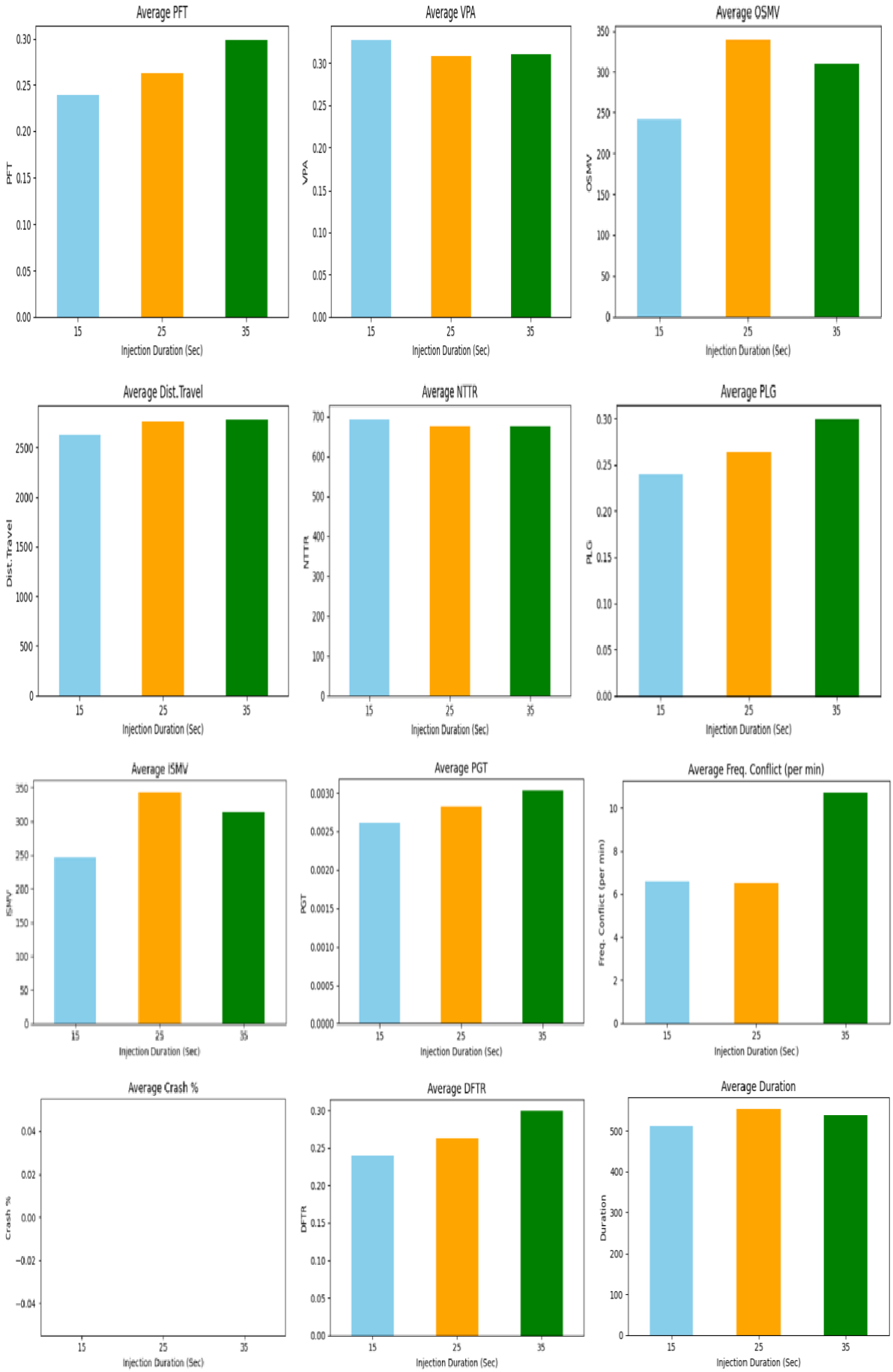


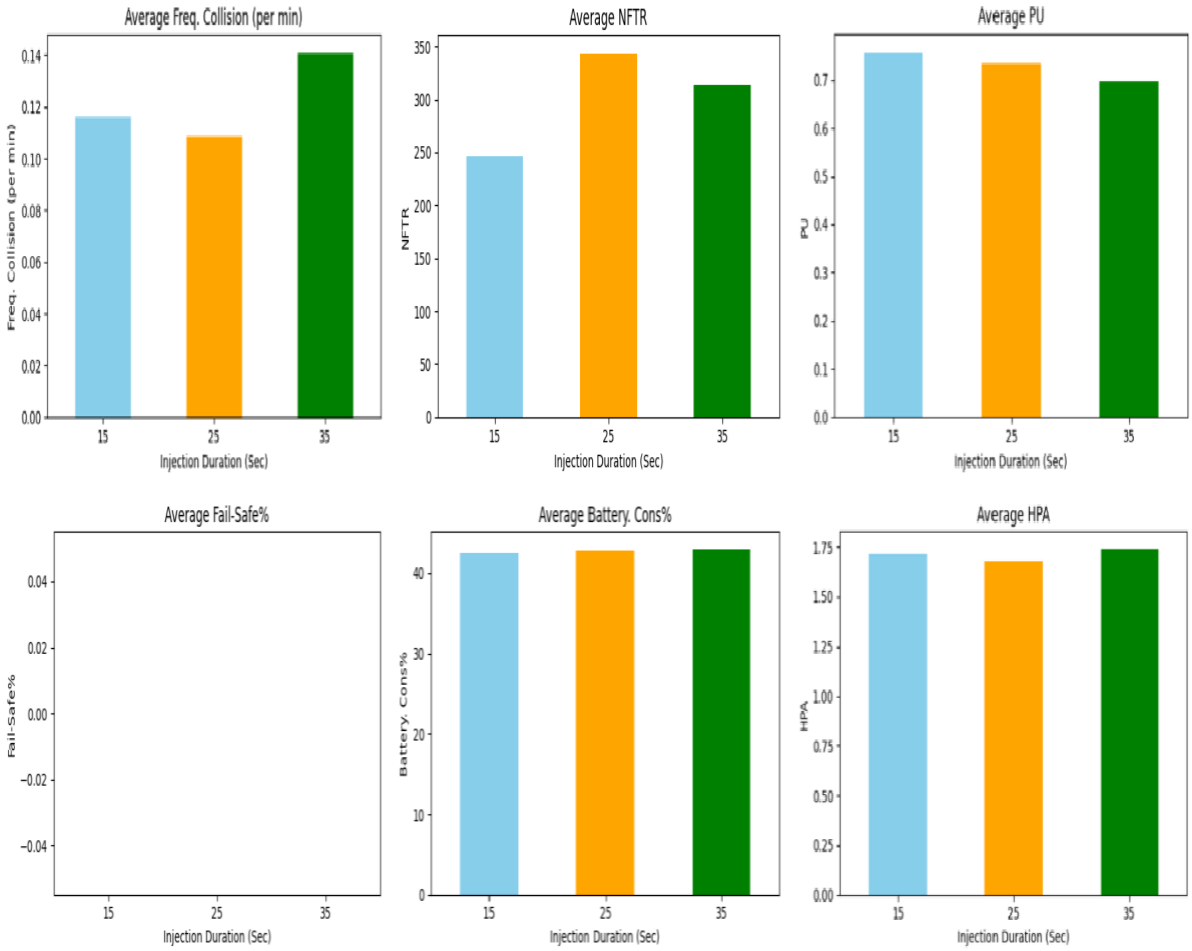

Average Dist.Travel
Dist.Travel
UAV Speed (m/s)
Average NTTR
NTTR
UAV Speed (m/s)
Average PLG
PLG
UAV Speed (m/s)
Average ISMV
ISMV
UAV Speed (m/s)
Average PGT
PGT
UAV Speed (m/s)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
UAV Speed (m/s)
Average Crash %
Crash %
UAV Speed (m/s)
Average DFTR
DFTR
UAV Speed (m/s)
Average Duration
Duration
UAV Speed (m/s)



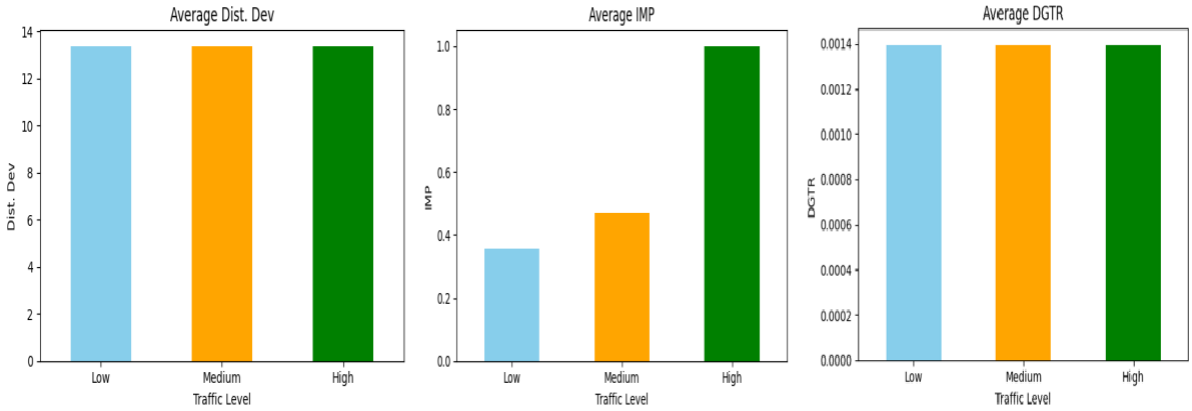
- **Impact of different injection durations:**

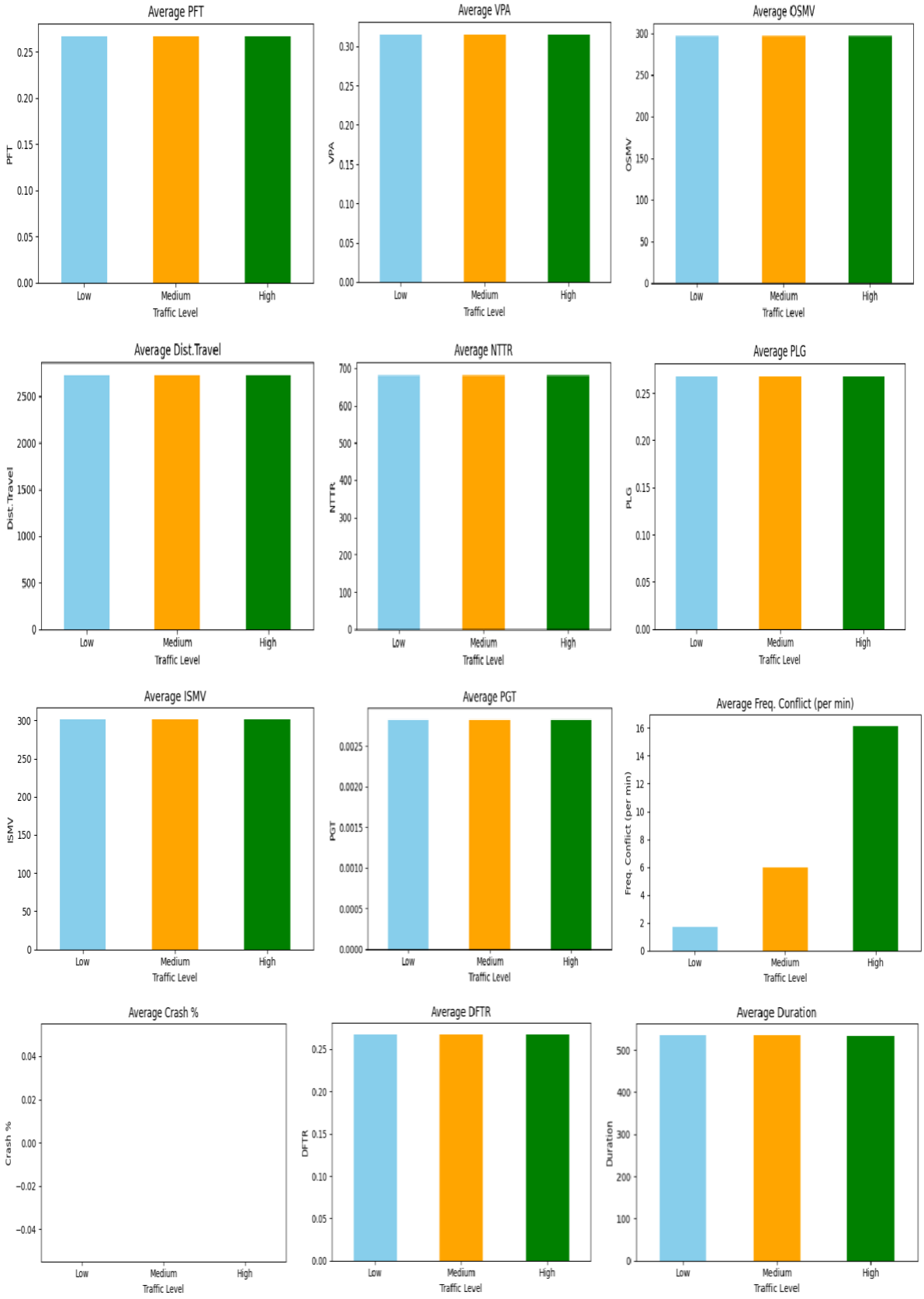


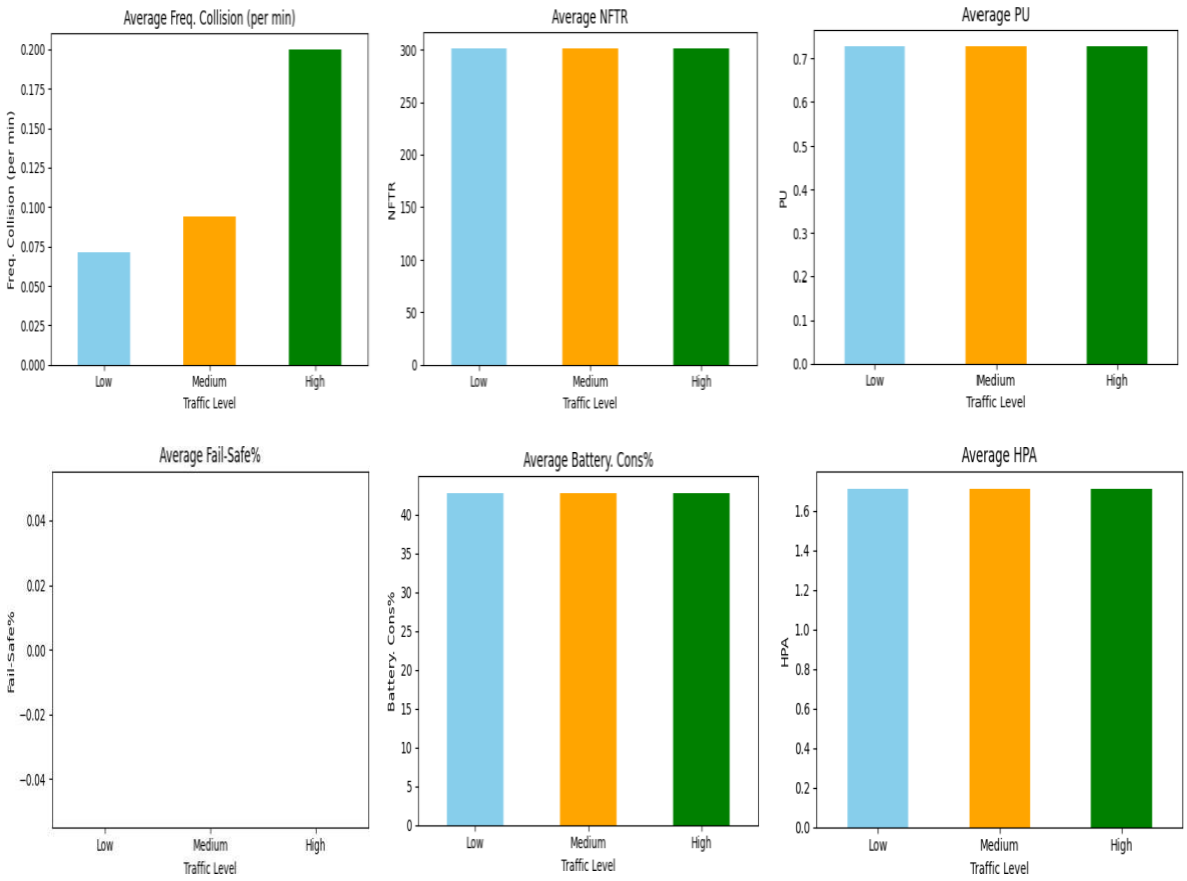

Average PFT
PFT
Injection Duration (Sec)
Average VPA
VPA
Injection Duration (Sec)
Average OSMV
OSMV
Injection Duration (Sec)
Average Dist.Travel
Dist.Travel
Injection Duration (Sec)
Average NTTR
NTTR
Injection Duration (Sec)
Average PLG
PLG
Injection Duration (Sec)
Average ISMV
ISMV
Injection Duration (Sec)
Average PGT
PGT
Injection Duration (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Injection Duration (Sec)
Average Crash %
Crash %
Injection Duration (Sec)
Average DFTR
DFTR
Injection Duration (Sec)
Average Duration
Duration
Injection Duration (Sec)



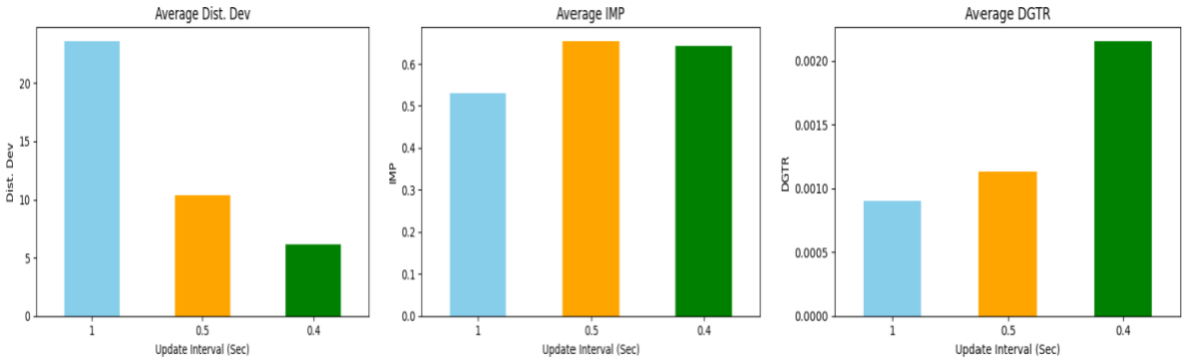
- **Impact of the different traffic levels:**

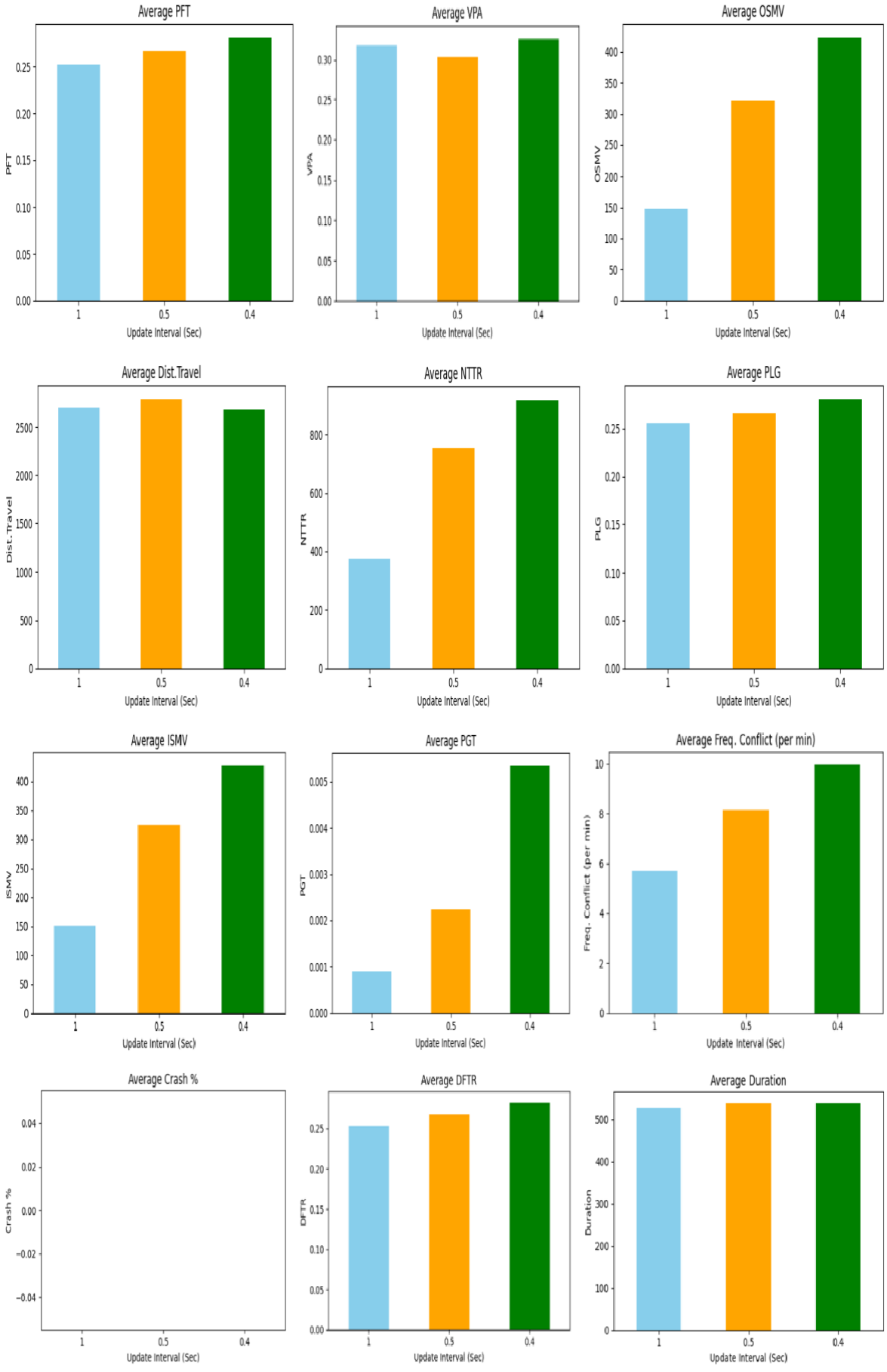


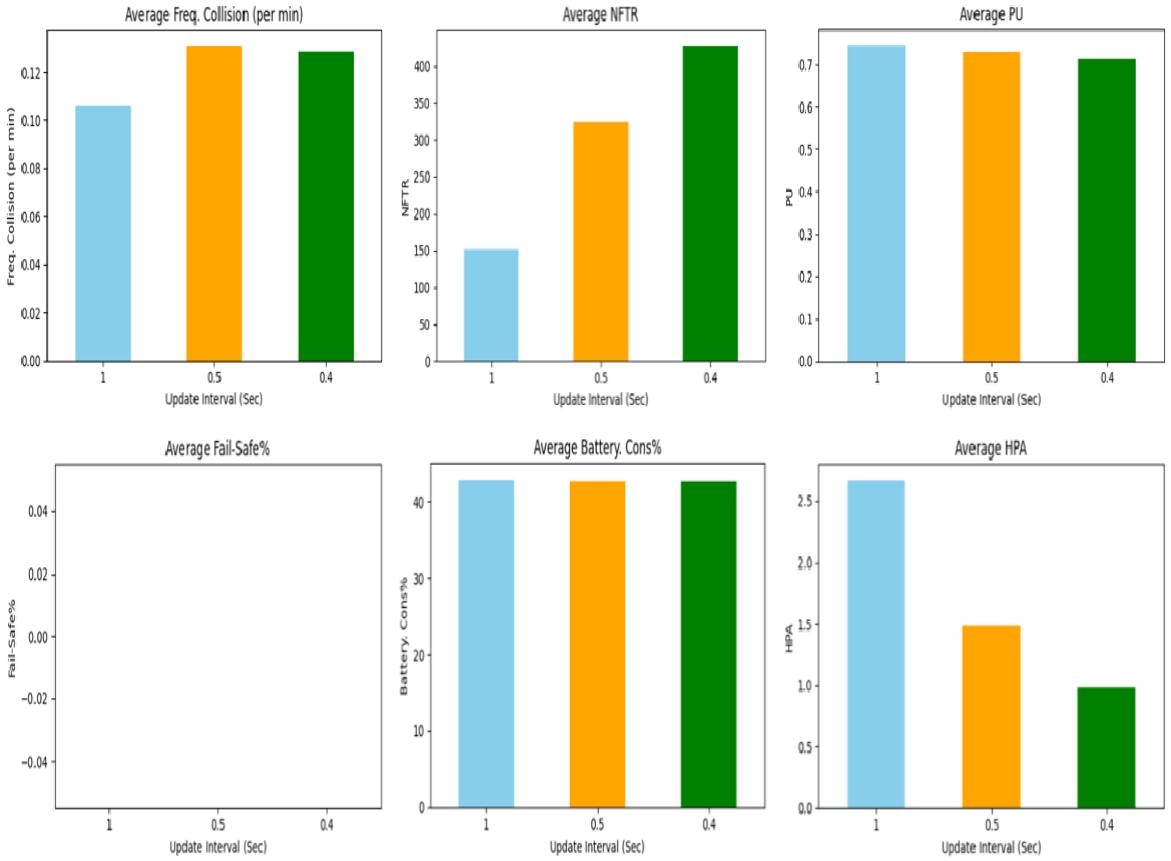

Average PFT
PFT
Traffic Level
Average VPA
VPA
Traffic Level
Average OSMV
OSMV
Traffic Level
Average Dist.Travel
Dist.Travel
Traffic Level
Average NTTR
NTTR
Traffic Level
Average PLG
PLG
Traffic Level
Average ISMV
ISMV
Traffic Level
Average PGT
PGT
Traffic Level
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Traffic Level
Average Crash %
Crash %
Traffic Level
Average DFTR
DFTR
Traffic Level
Average Duration
Duration
Traffic Level
Low
Medium
High



- **Impact of the different update intervals:**

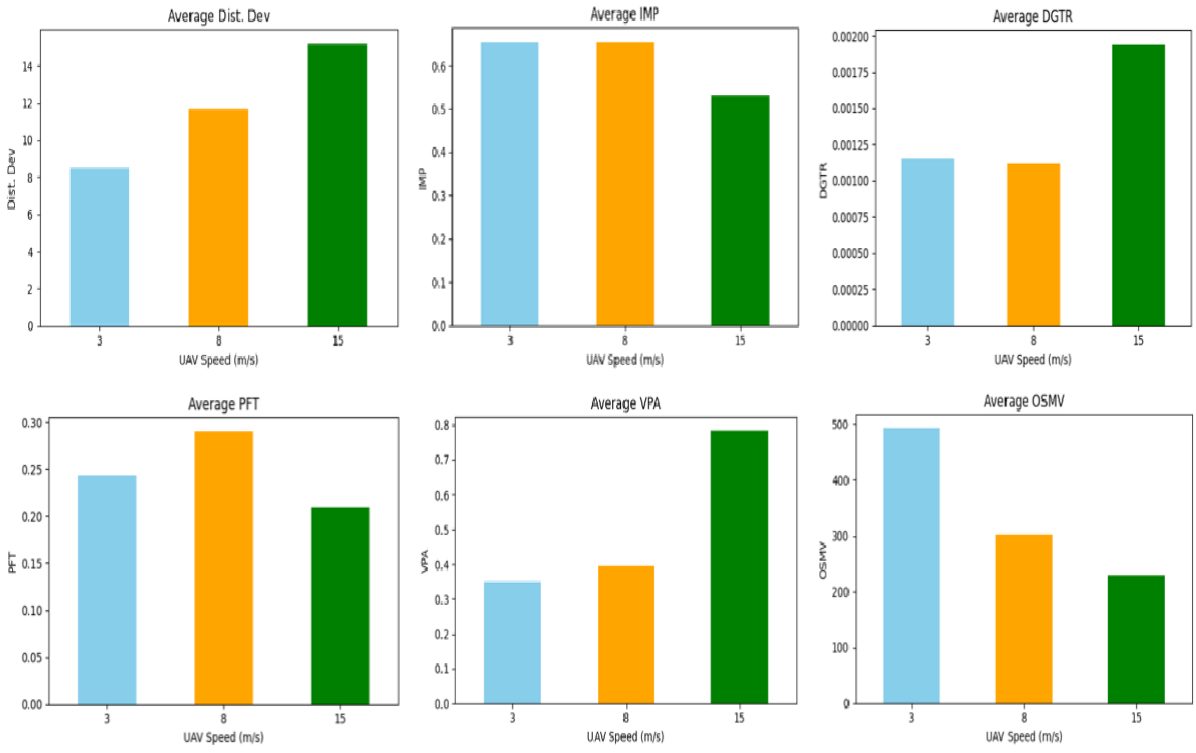


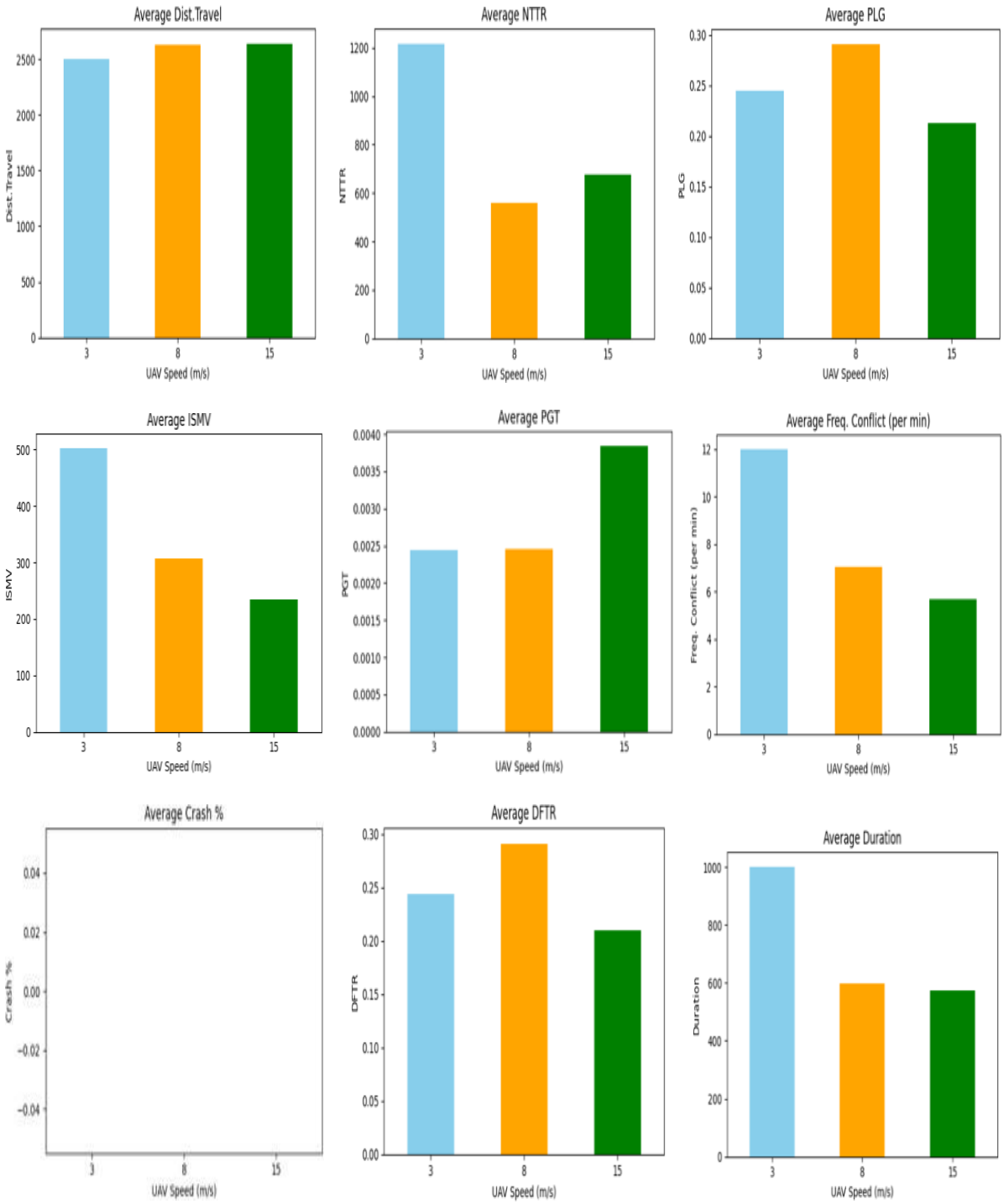

Average PFT
PFT
Update Interval (Sec)
Average VPA
VPA
Update Interval (Sec)
Average OSMV
OSMV
Update Interval (Sec)
Average Dist.Travel
Dist_Travel
Update Interval (Sec)
Average NTTR
NTTR
Update Interval (Sec)
Average PLG
PLG
Update Interval (Sec)
Average ISMV
ISMV
Update Interval (Sec)
Average PGT
PGT
Update Interval (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Update Interval (Sec)
Average Crash %
Crash %
Update Interval (Sec)
Average DFTR
DFTR
Update Interval (Sec)
Average Duration
Duration
Update Interval (Sec)

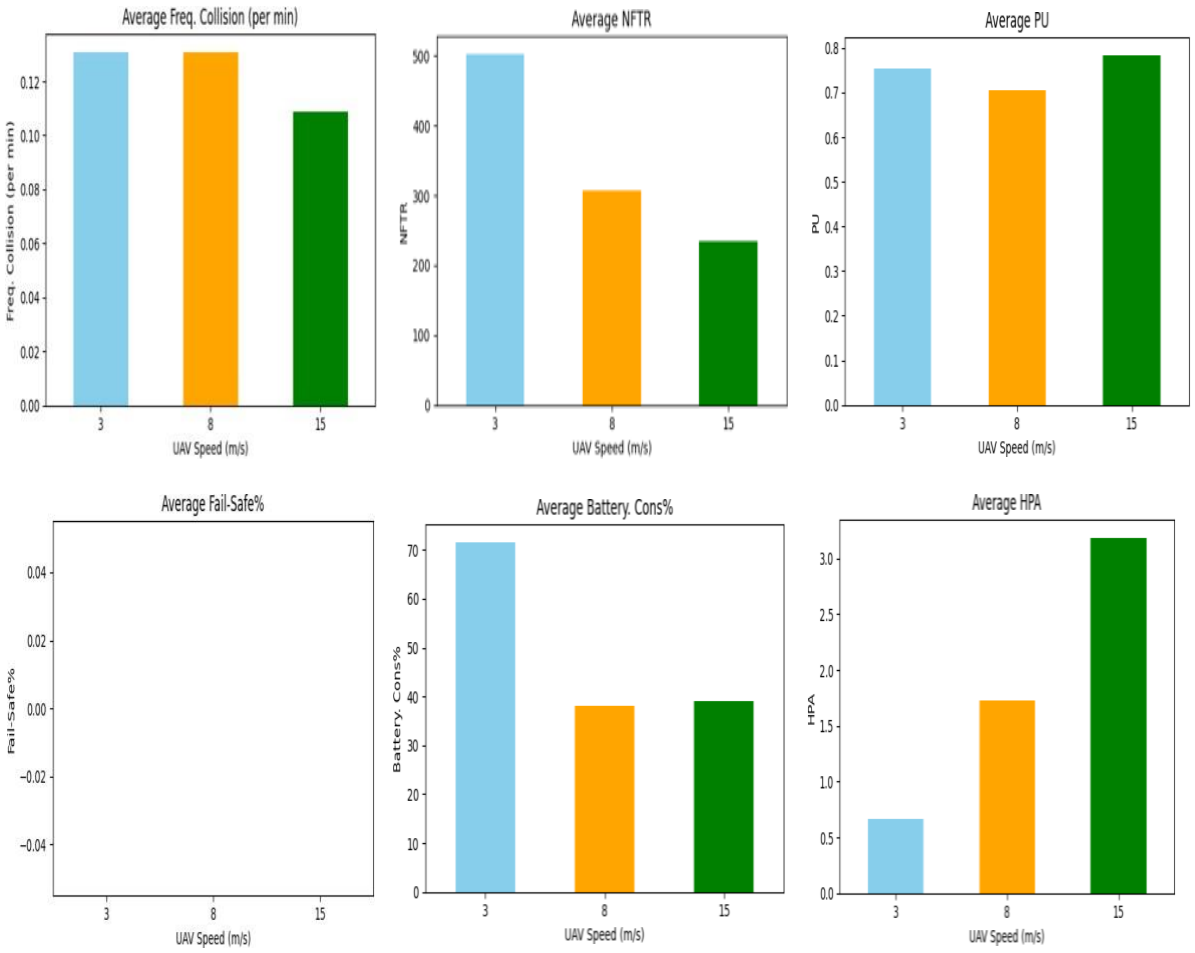


3) GPS Faults with near-gale wind conditions:

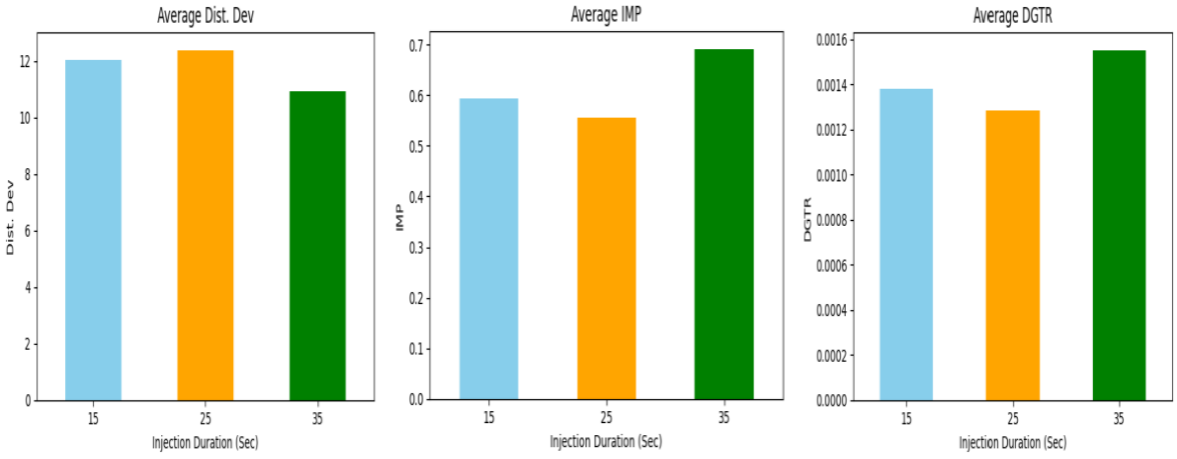
- **Impact of the different UAV speeds:**

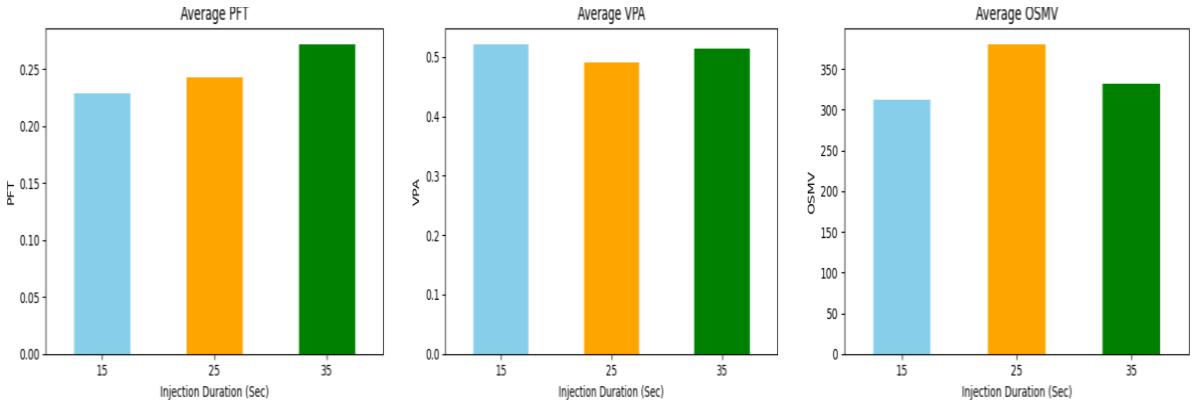


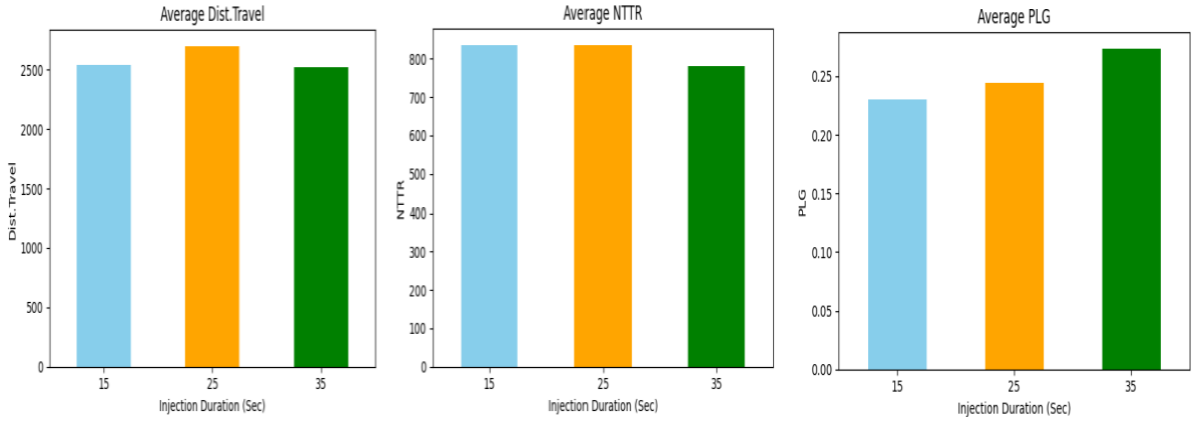

Average Dist.Travel
Dist.Travel
UAV Speed (m/s)
Average NTTR
NTTR
UAV Speed (m/s)
Average PLG
PLG
UAV Speed (m/s)
Average ISMV
ISMV
UAV Speed (m/s)
Average PGT
PGT
UAV Speed (m/s)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
UAV Speed (m/s)
Average Crash %
Crash %
UAV Speed (m/s)
Average DFTR
DFTR
UAV Speed (m/s)
Average Duration
Duration
UAV Speed (m/s)

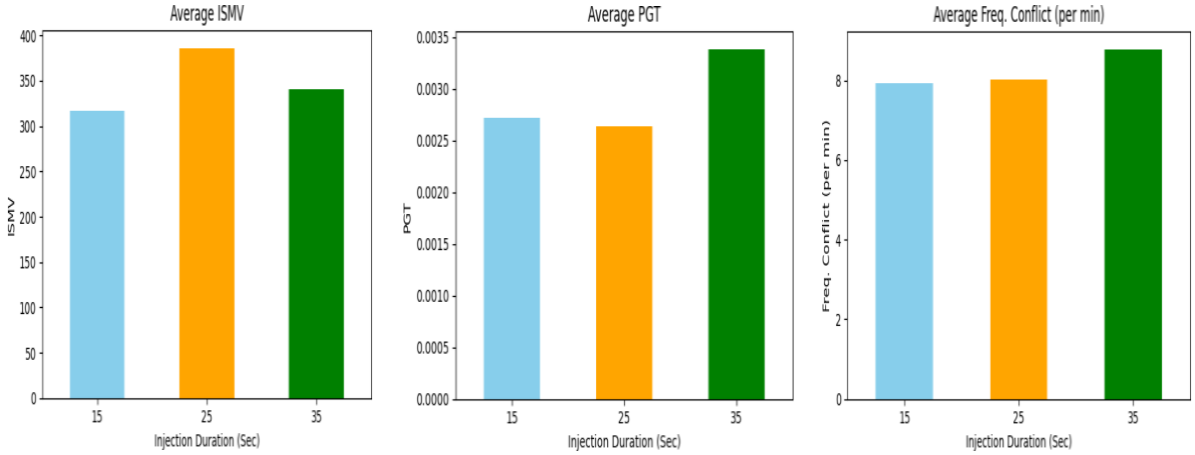


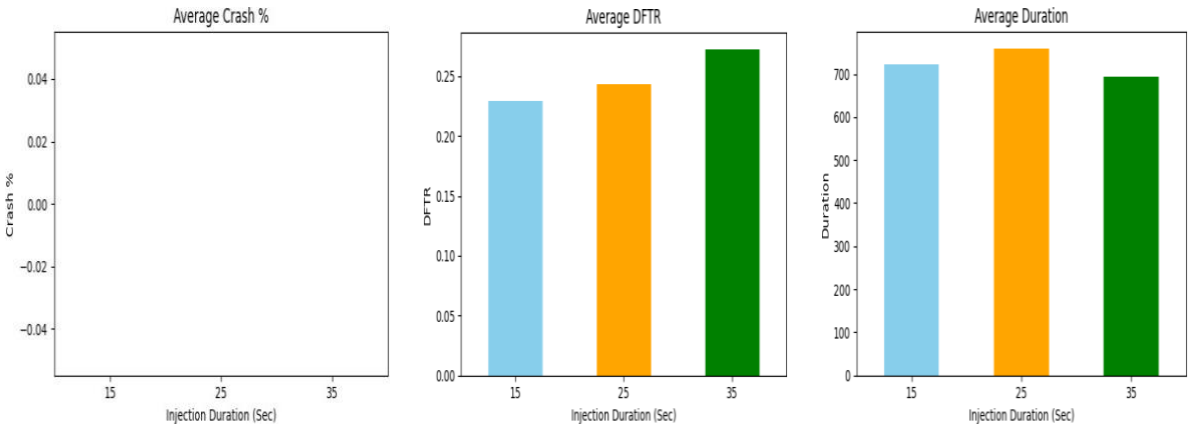
- **Impact of different injection durations:**

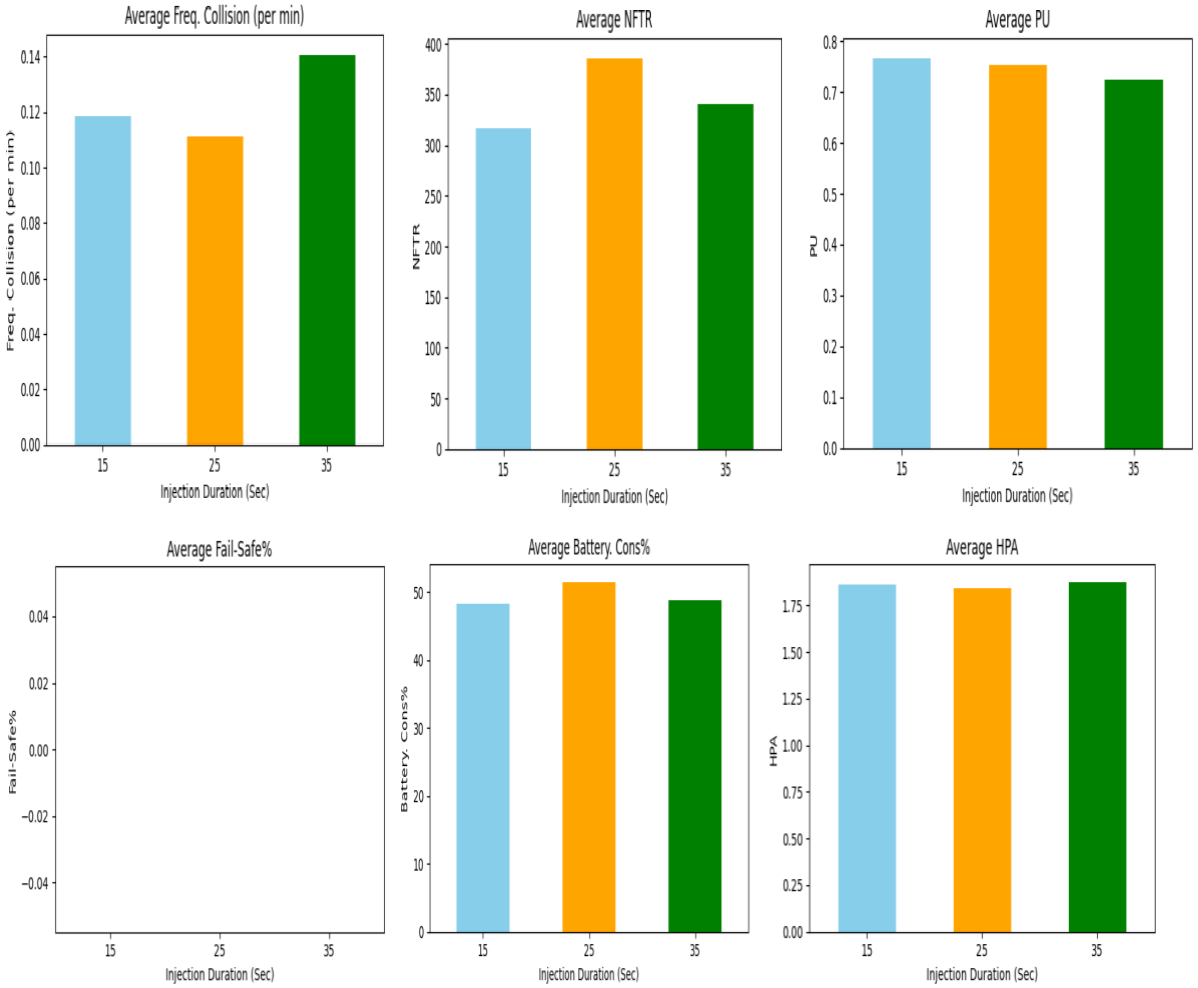



Average PFT
PFT
Injection Duration (Sec)
Average VPA
VPA
Injection Duration (Sec)
Average OSMV
OSMV
Injection Duration (Sec)

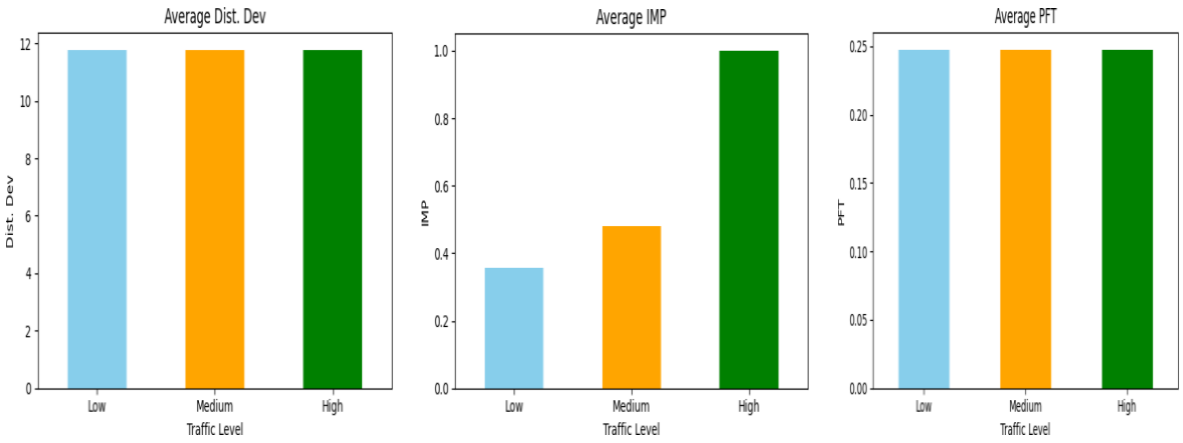

Average Dist.Travel
Dist.Travel
Injection Duration (Sec)
Average NTTR
NTTR
Injection Duration (Sec)
Average PLG
PLG
Injection Duration (Sec)

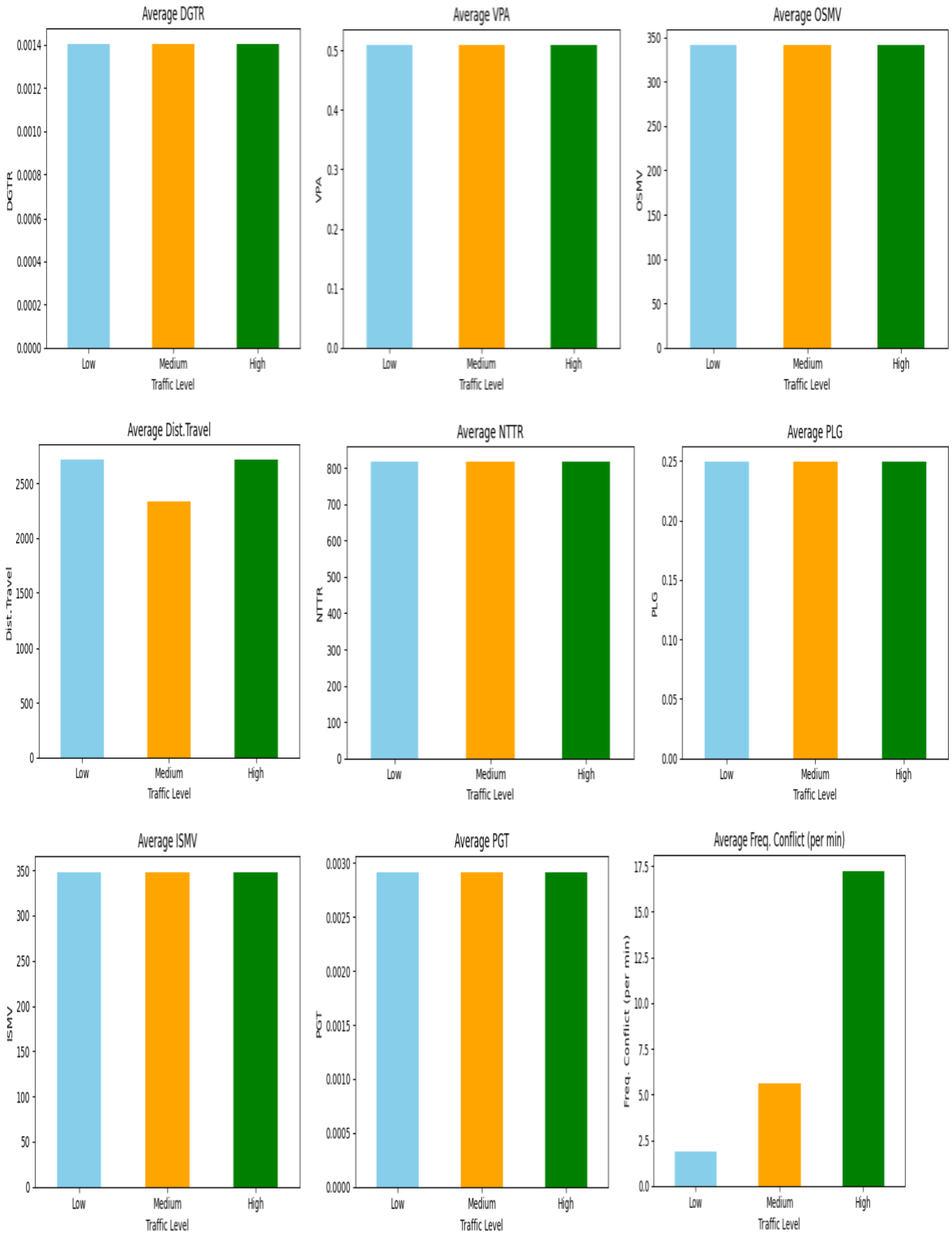

Average ISMV
ISMV
Injection Duration (Sec)
Average PGT
PGT
Injection Duration (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Injection Duration (Sec)

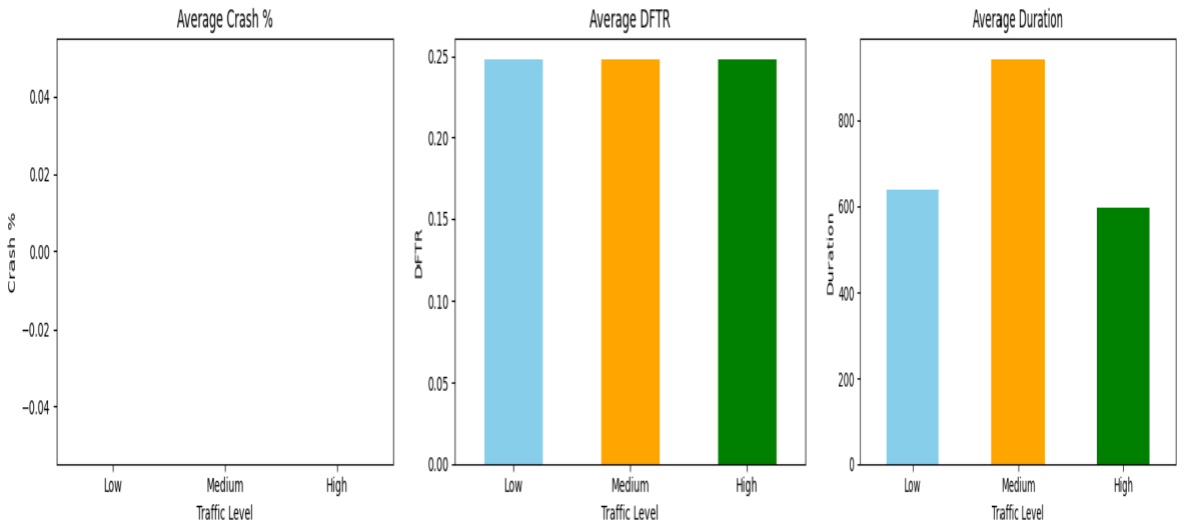

Average Crash %
Crash %
Injection Duration (Sec)
Average DFTR
DFTR
Injection Duration (Sec)
Average Duration
Duration
Injection Duration (Sec)

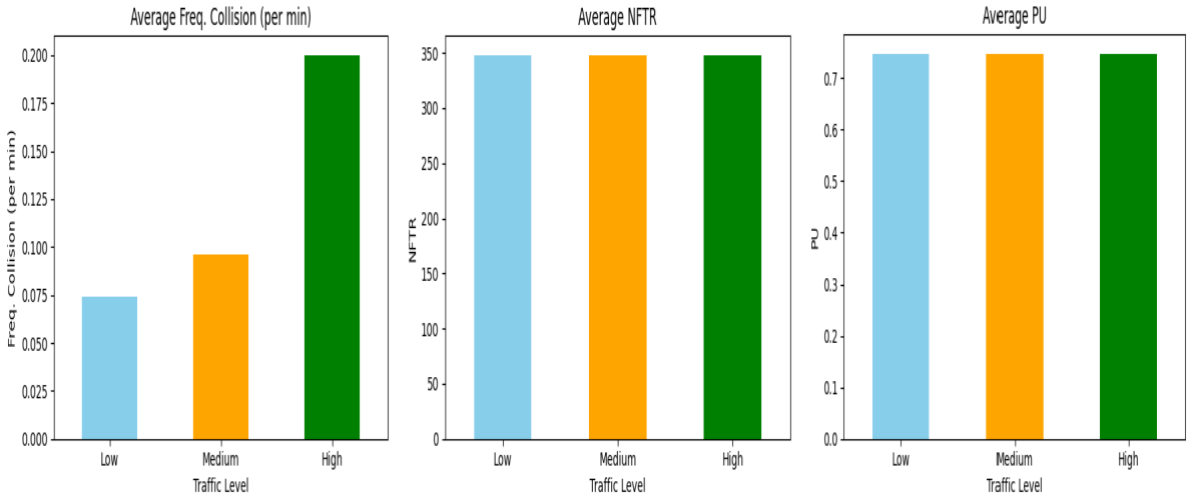


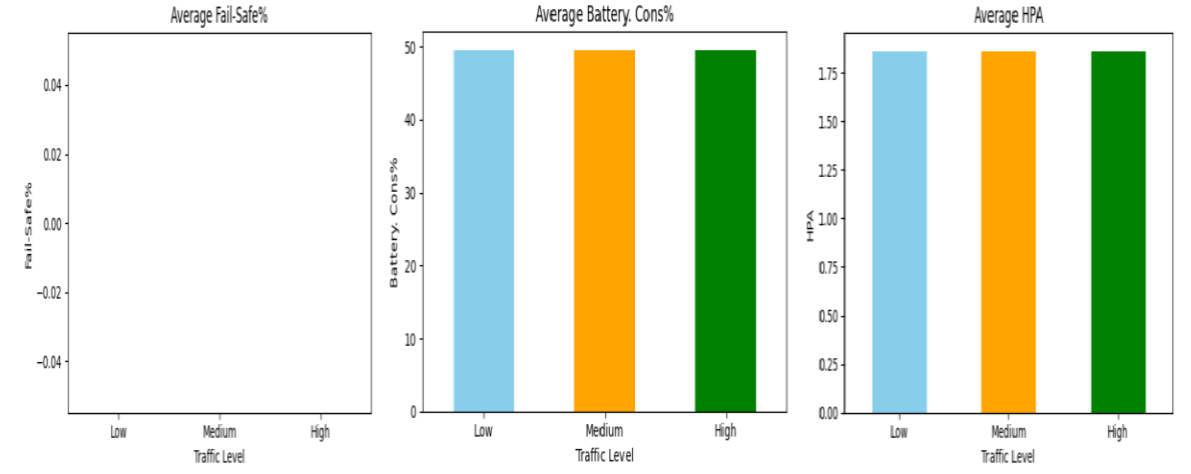
- **Impact of different traffic levels:**



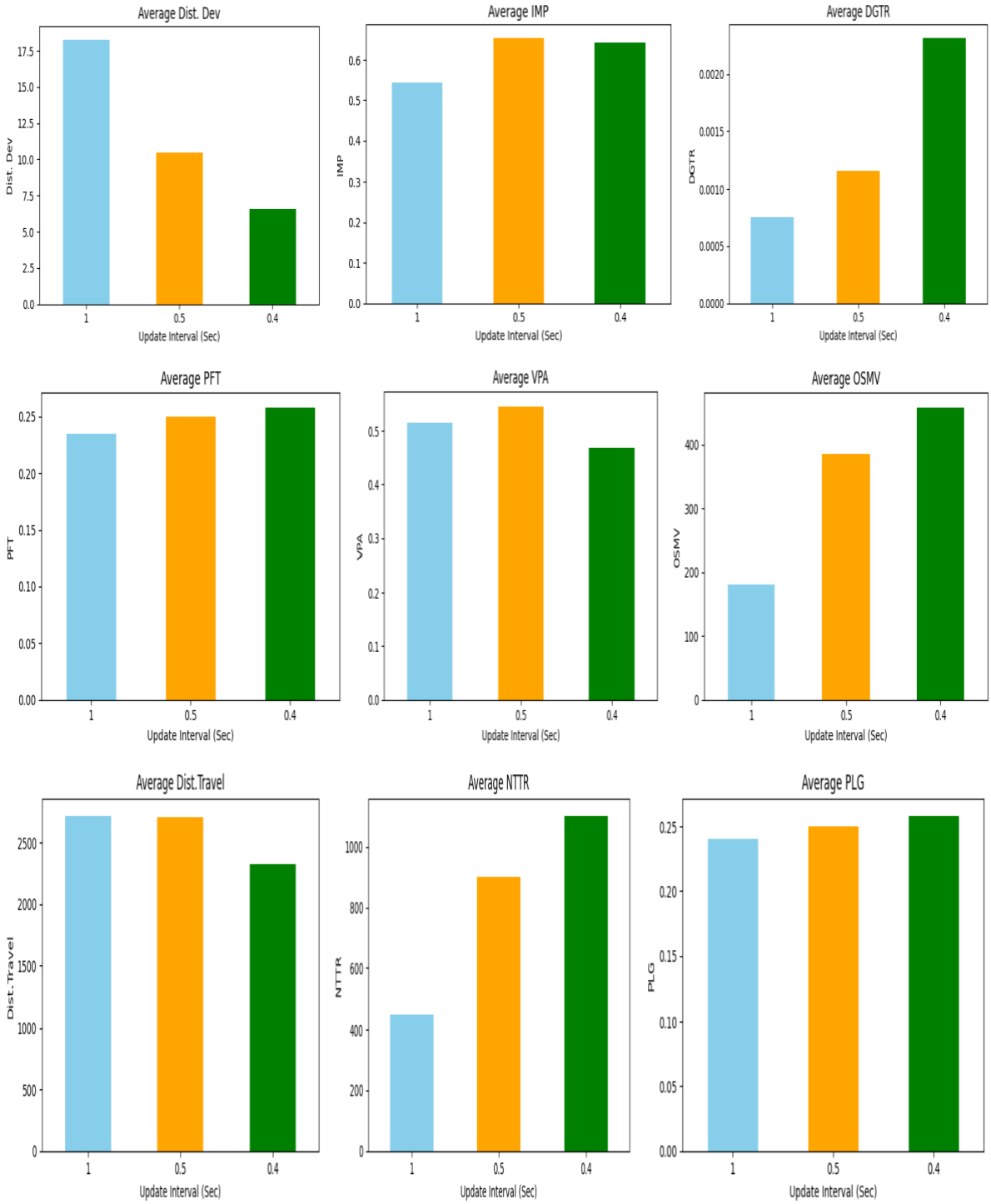

Average DGTR
DGTR
Traffic Level
Low
Medium
High
Average VPA
VPA
Average OSMV
OSMV
Average Dist.Travel
Dist.Travel
Average NTTR
NTTR
Average PLG
PLG
Average ISMV
ISMV
Average PGT
PGT
Average Freq. Conflict (per min)
Freq. Conflict (per min)

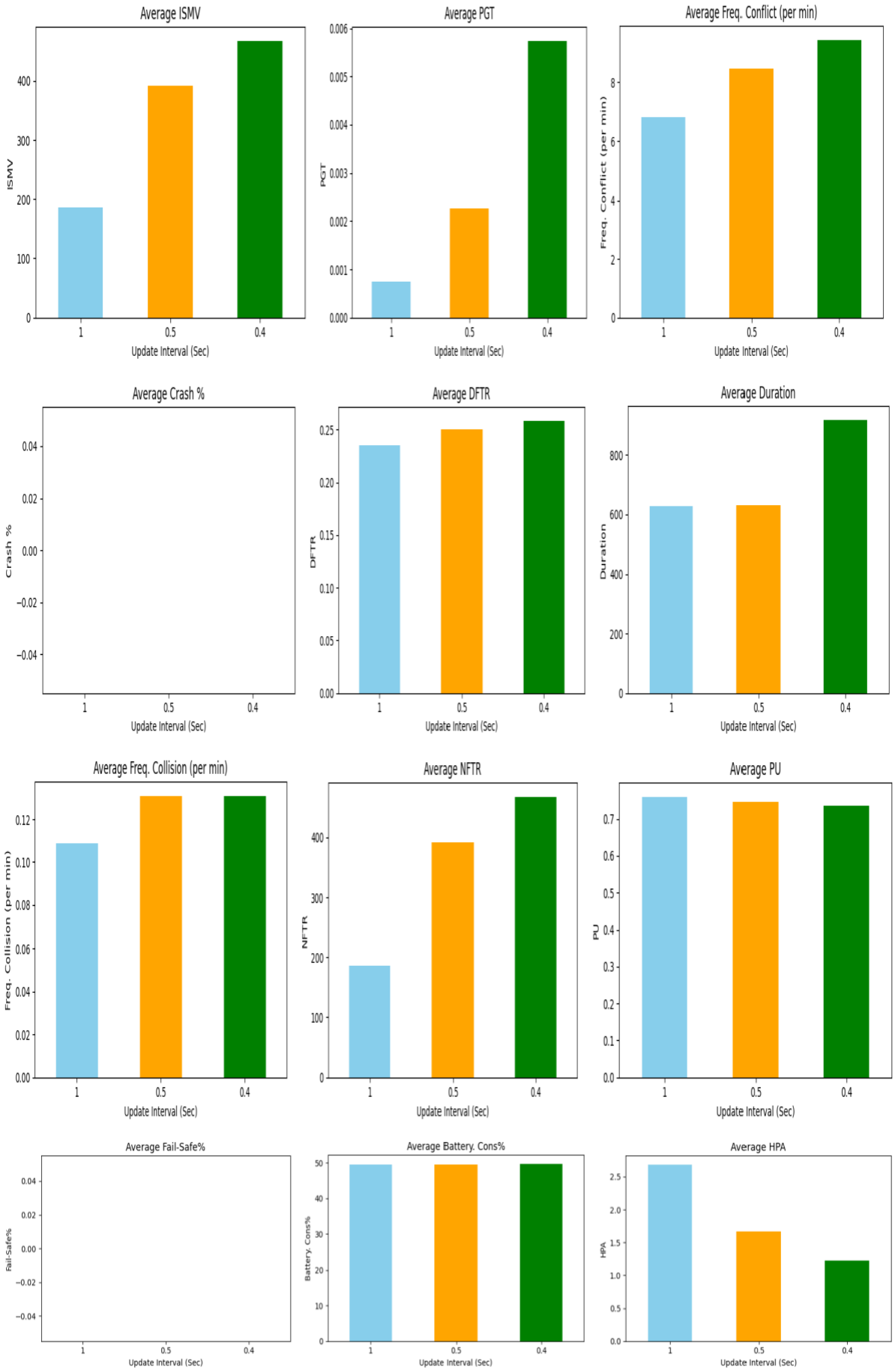

Average Crash %
Crash %
0.04
0.02
0.00
−0.02
−0.04
Low
Medium
High
Traffic Level
Average DFTR
DFTR
0.25
0.20
0.15
0.10
0.05
0.00
Low
Medium
High
Traffic Level
Average Duration
Duration
800
600
400
200
0
Low
Medium
High
Traffic Level


Average Freq. Collision (per min)
Freq. Collision (per min)
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
Low
Medium
High
Traffic Level
Average NFTR
NFTR
350
300
250
200
150
100
50
0
Low
Medium
High
Traffic Level
Average PU
PU
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Low
Medium
High
Traffic Level


Average Fail-Safe%
Fail-Safe%
0.04
0.02
0.00
−0.02
−0.04
Low
Medium
High
Traffic Level
Average Battery. Cons%
Battery. Cons%
50
40
30
20
10
0
Low
Medium
High
Traffic Level
Average HPA
HPA
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Low
Medium
High
Traffic Level

- **Impact of different update intervals:**



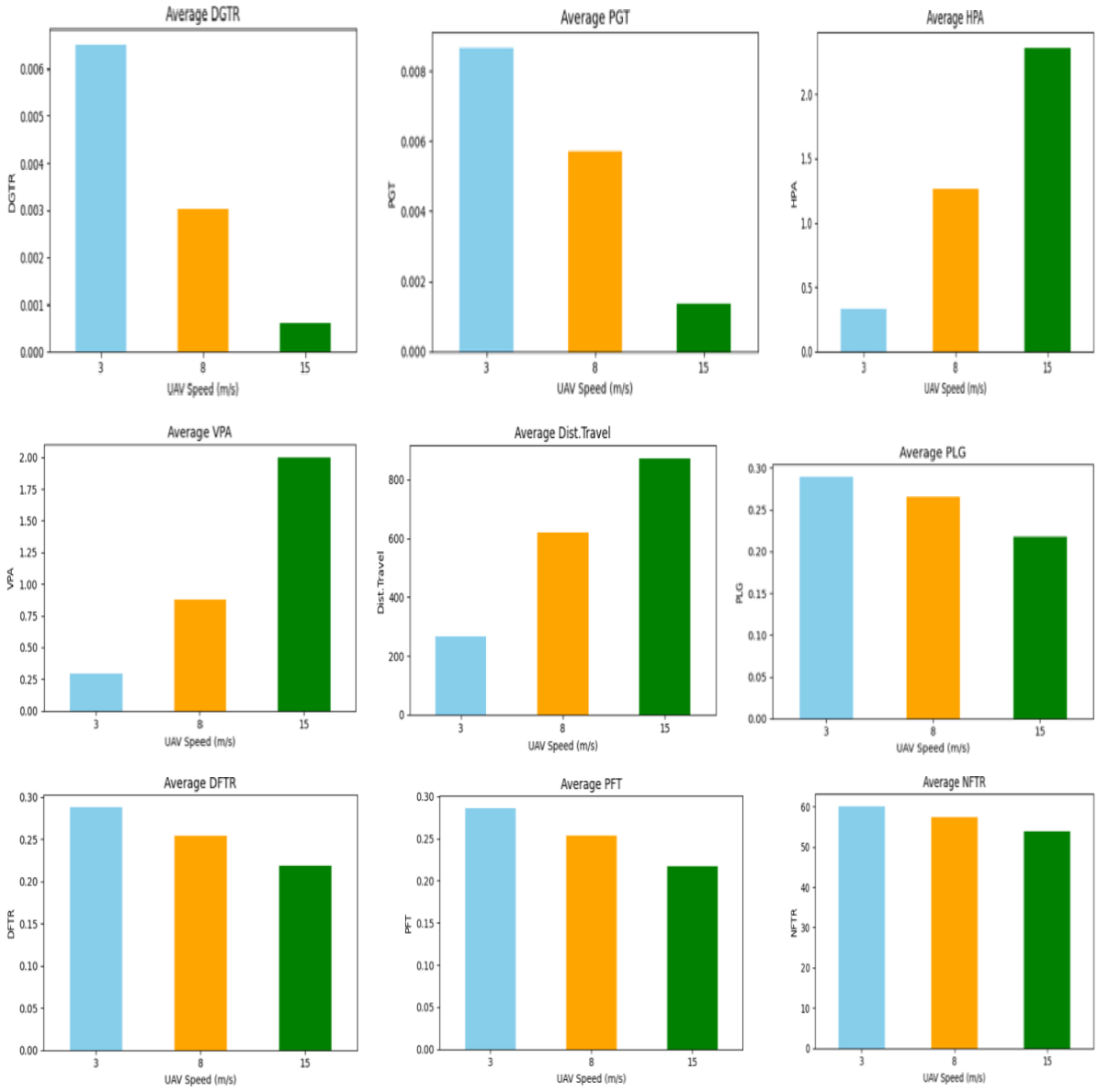

Average ISMV
ISMV
Update Interval (Sec)
Average PGT
PGT
Update Interval (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Update Interval (Sec)
Average Crash %
Crash %
Update Interval (Sec)
Average DFTR
DFTR
Update Interval (Sec)
Average Duration
Duration
Update Interval (Sec)
Average Freq. Collision (per min)
Freq. Collision (per min)
Update Interval (Sec)
Average NFTR
NFTR
Update Interval (Sec)
Average PU
PU
Update Interval (Sec)
Average Fail-Safe%
Fail-Safe%
Update Interval (Sec)
Average Battery. Cons%
Battery. Cons%
Update Interval (Sec)
Average HPA
HPA
Update Interval (Sec)

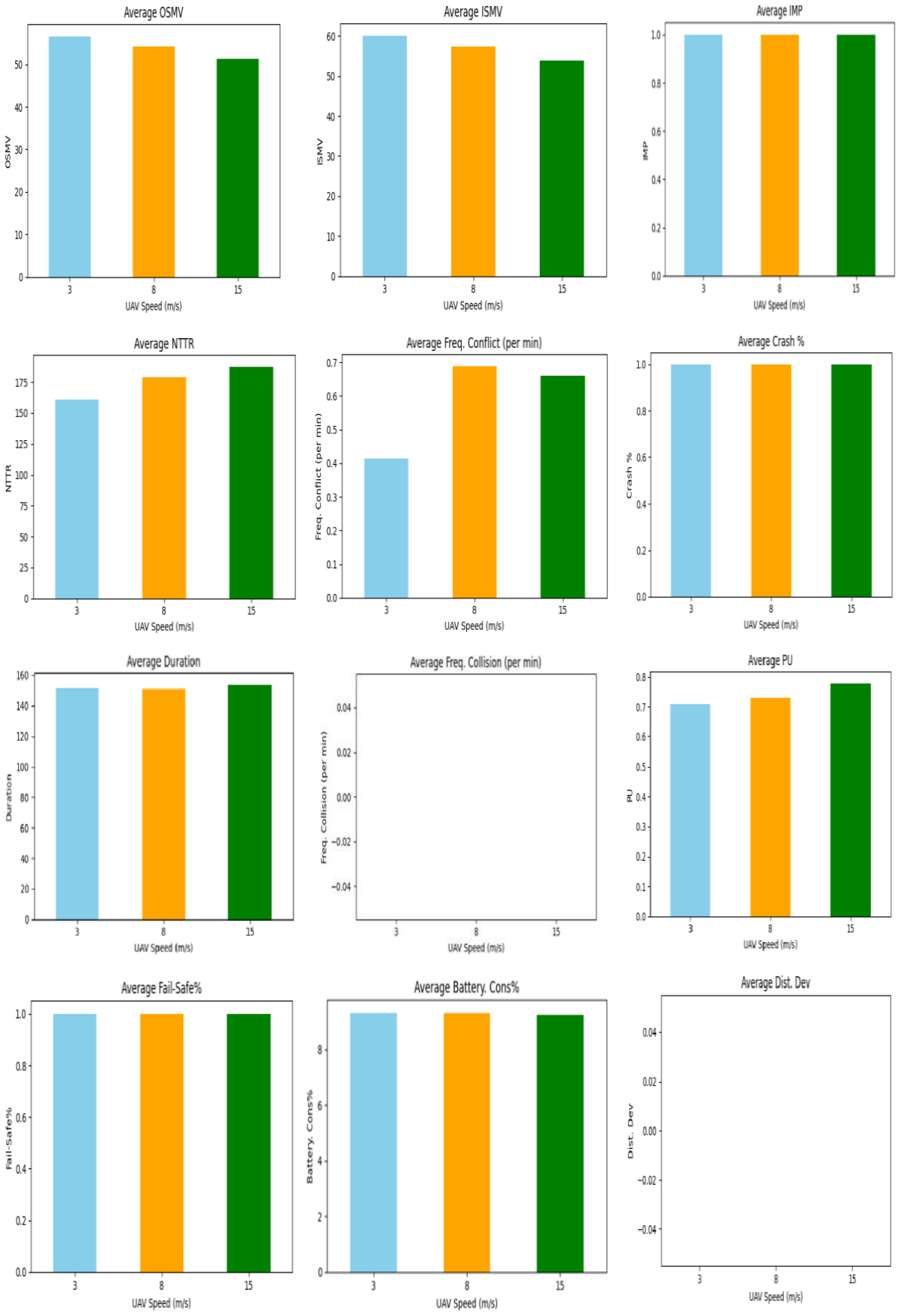
Impact of the different factors on IMU:

We injected three faults into the accelerometer and gyroscope including Maximum Value, Freeze Value, and Random Value and analyzed their effects on various safety metrics. Following the fault injection, we further examined how different operational factors, including UAV speeds, update intervals (UIs), traffic levels, and injection durations, as well as an environmental factor (wind), influenced these metrics.

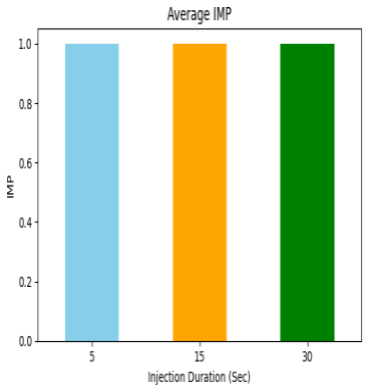
1) Accelerometer faults with light breeze wind:

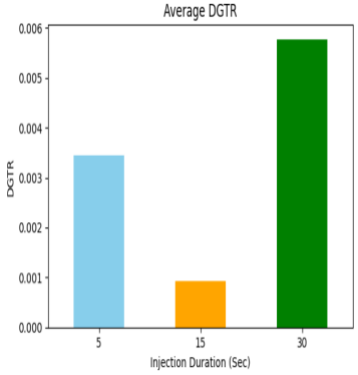
- **Impact of the different UAV speeds:**

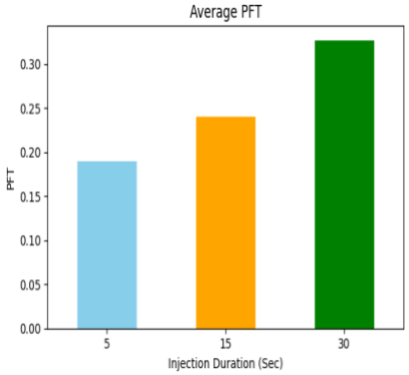


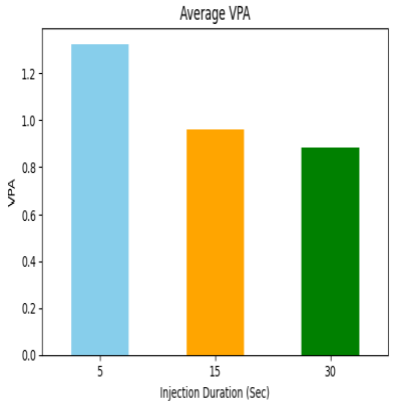

Average OSMV
OSMV
UAV Speed (m/s)
Average ISMV
ISMV
UAV Speed (m/s)
Average IMP
IMP
UAV Speed (m/s)
Average NTTR
NTTR
UAV Speed (m/s)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
UAV Speed (m/s)
Average Crash %
Crash %
UAV Speed (m/s)
Average Duration
Duration
UAV Speed (m/s)
Average Freq. Collision (per min)
Freq. Collision (per min)
UAV Speed (m/s)
Average PU
PU
UAV Speed (m/s)
Average Fail-Safe%
Fail-Safe%
UAV Speed (m/s)
Average Battery. Cons%
Battery. Cons%
UAV Speed (m/s)
Average Dist. Dev
Dist. Dev
UAV Speed (m/s)

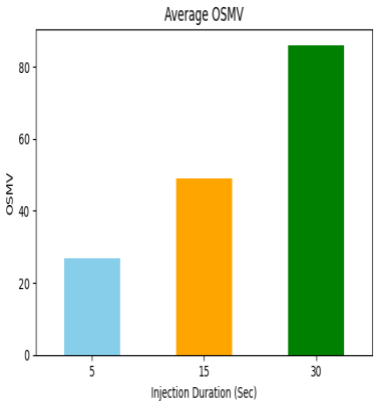
- **Impact of the different injection durations:**

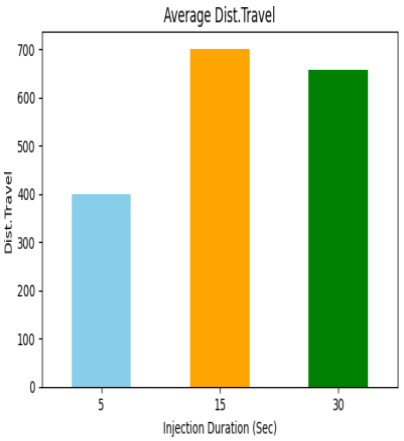


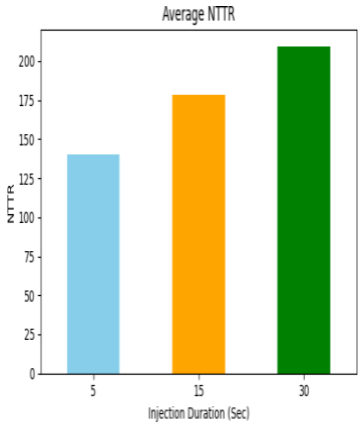


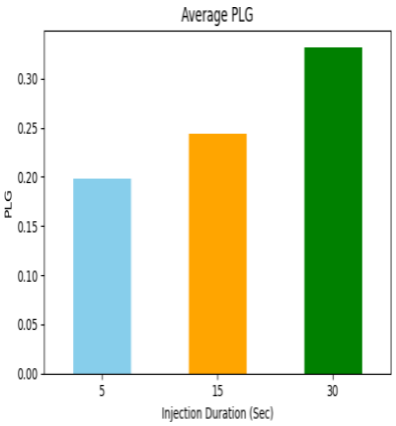


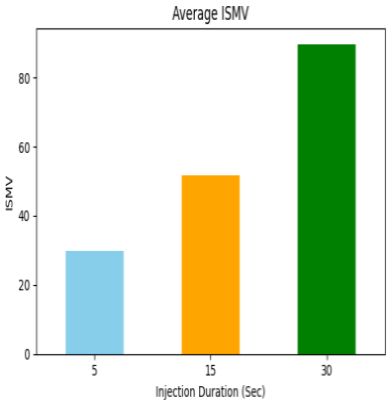


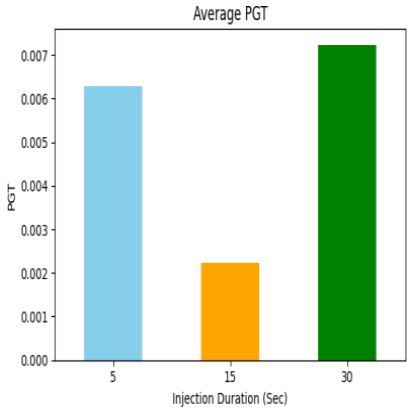


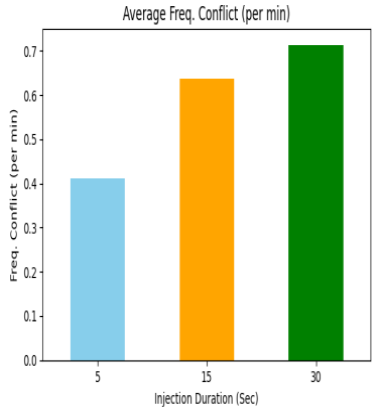


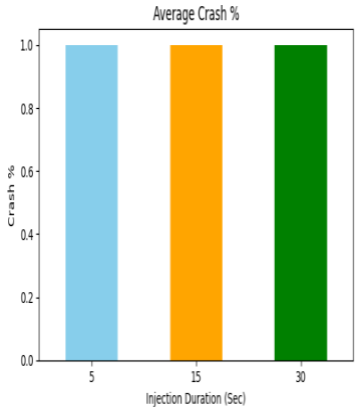


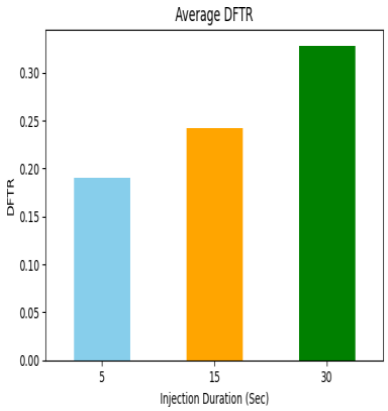


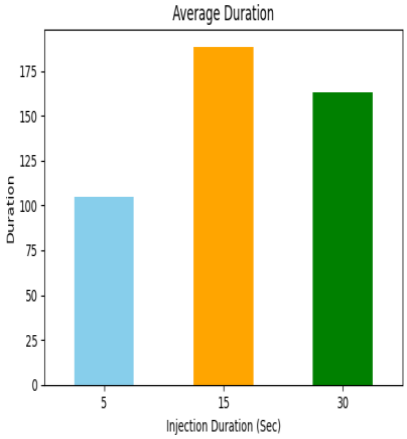


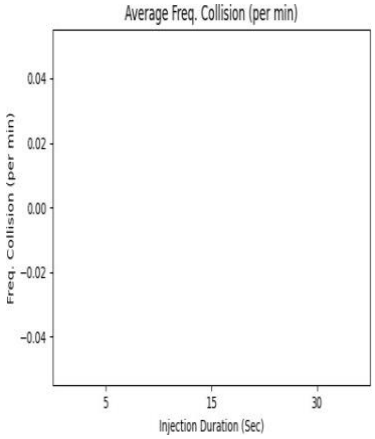

Average PGT
PGT
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
5
15
30
Injection Duration (Sec)

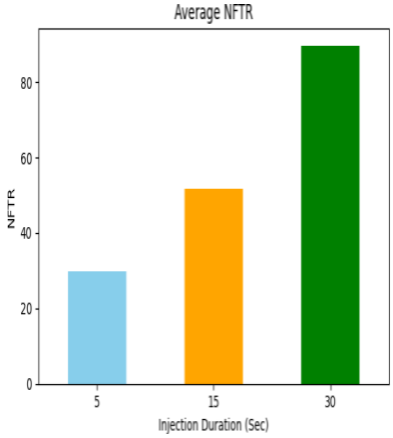

Average Freq. Conflict (per min)
Freq. Conflict (per min)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
5
15
30
Injection Duration (Sec)

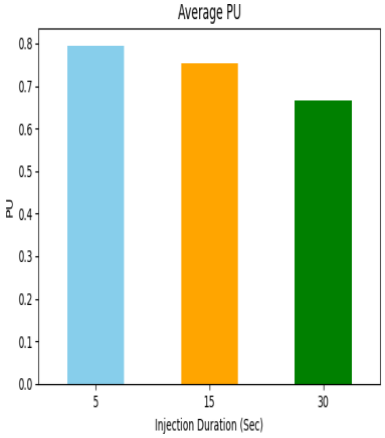

Average Crash %
Crash %
0.0
0.2
0.4
0.6
0.8
1.0
5
15
30
Injection Duration (Sec)

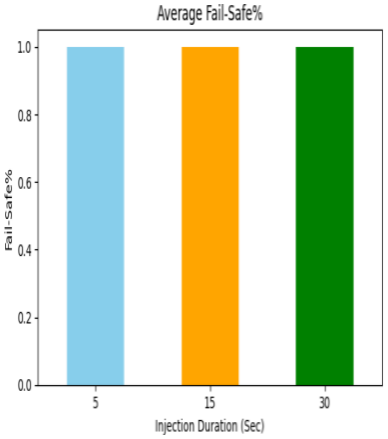

Average DFTR
DFTR
0.00
0.05
0.10
0.15
0.20
0.25
0.30
5
15
30
Injection Duration (Sec)

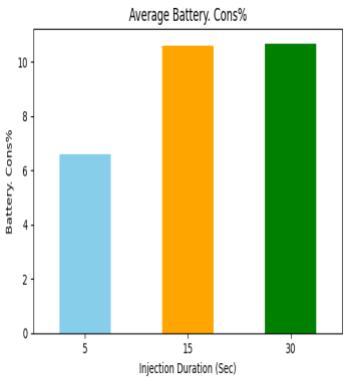

Average Duration
Duration
0
25
50
75
100
125
150
175
5
15
30
Injection Duration (Sec)

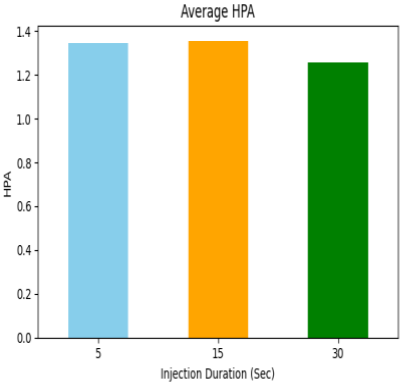

Average Freq. Collision (per min)
Freq. Collision (per min)
−0.04
−0.02
0.00
0.02
0.04
5
15
30
Injection Duration (Sec)

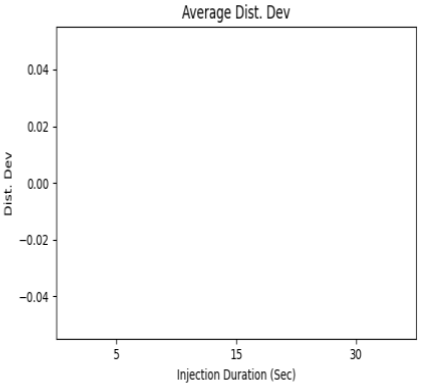

Average NFTR
NFTR
0
20
40
60
80
5
15
30
Injection Duration (Sec)


Average PU
PU
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
5
15
30
Injection Duration (Sec)

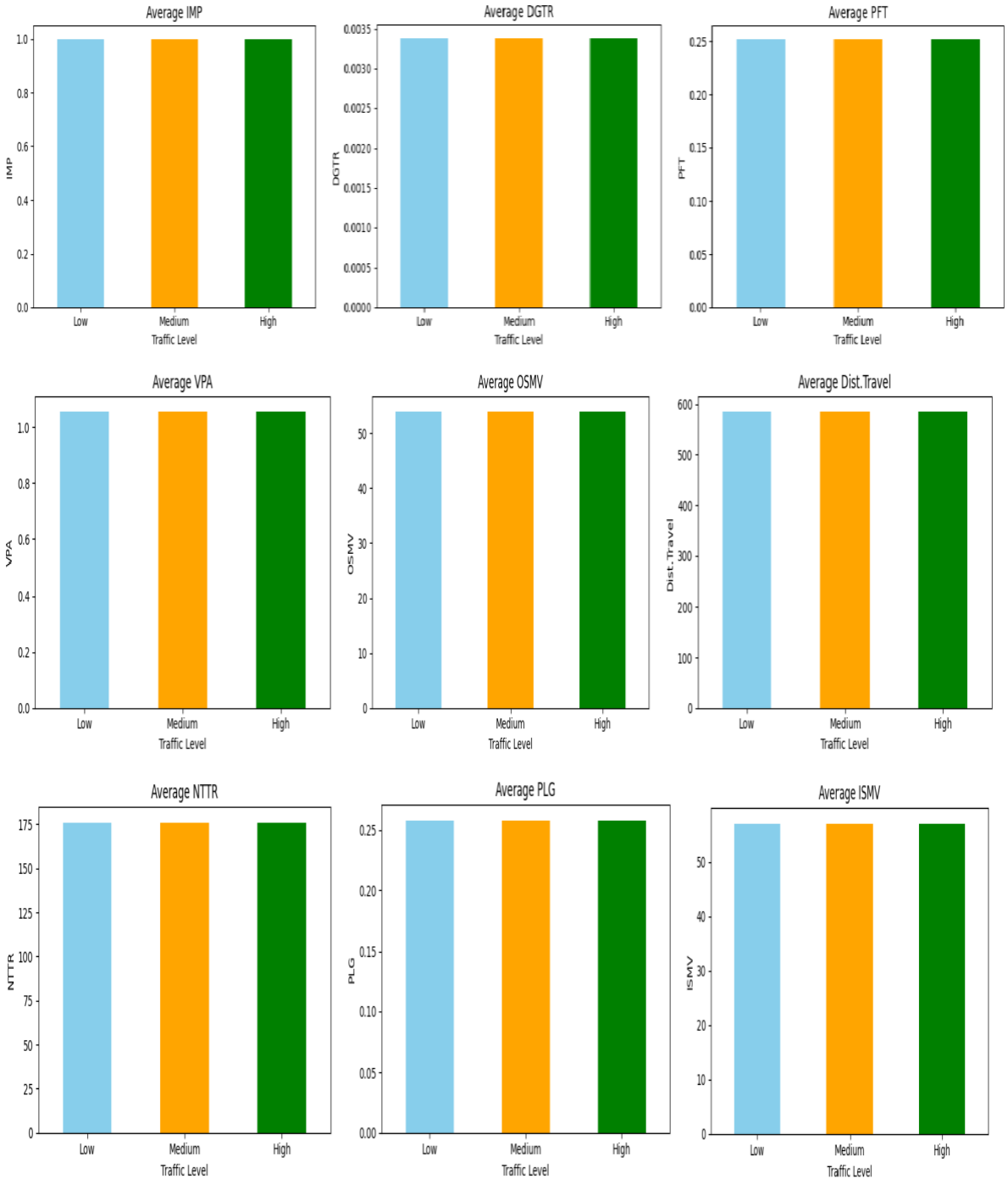

Average Fail-Safe%
Fail-Safe%
0.0
0.2
0.4
0.6
0.8
1.0
5
15
30
Injection Duration (Sec)

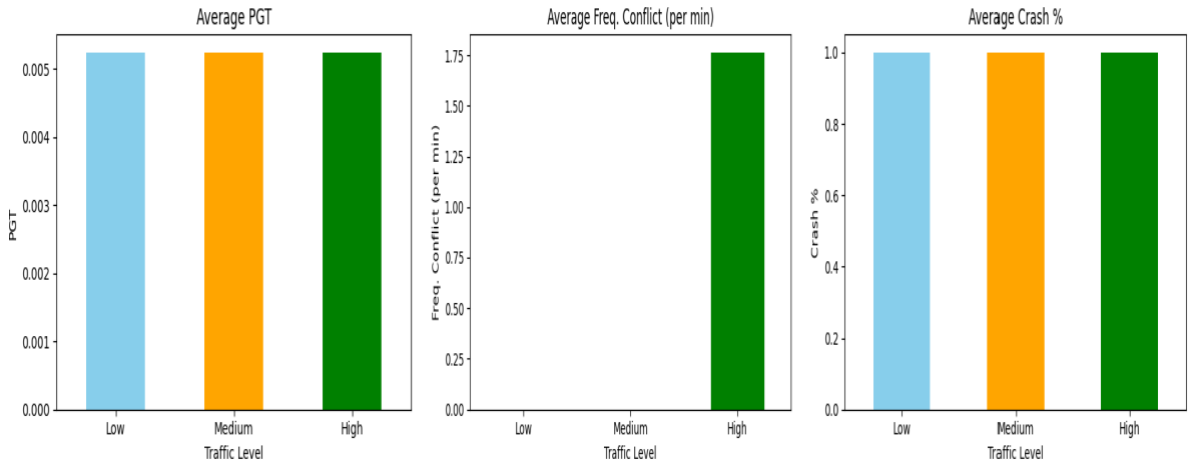

Average Battery. Cons%
Battery. Cons%
0
2
4
6
8
10
5
15
30
Injection Duration (Sec)


Average HPA
HPA
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
5
15
30
Injection Duration (Sec)


Average Dist. Dev
Dist. Dev
−0.04
−0.02
0.00
0.02
0.04
5
15
30
Injection Duration (Sec)

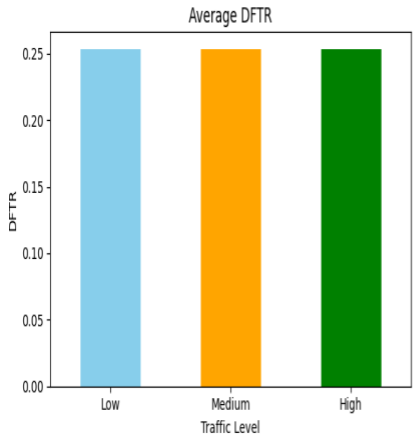
- **Impact of the different traffic levels:**

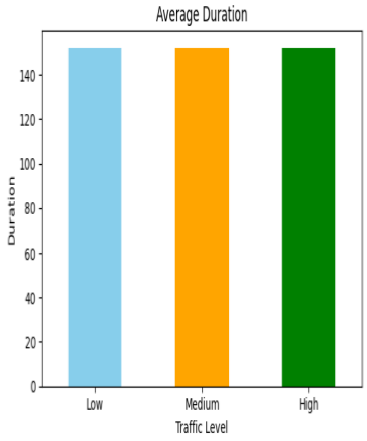


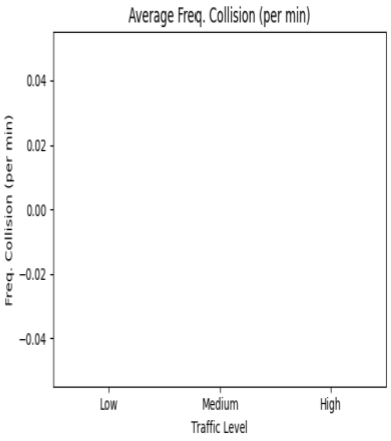

Average PGT
PGT
0.000
0.001
0.002
0.003
0.004
0.005
Low
Medium
High
Traffic Level

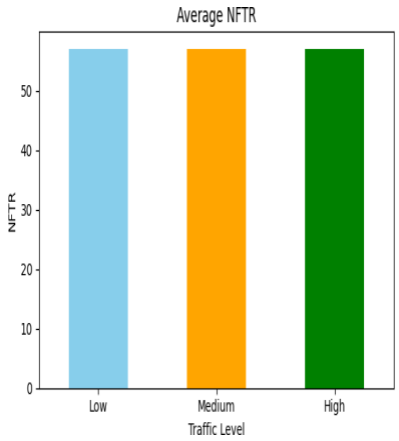
Average Freq. Conflict (per min)
Freq. Conflict (per min)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
Low
Medium
High
Traffic Level

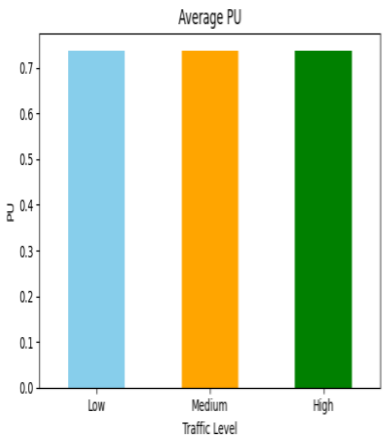
Average Crash %
Crash %
0.0
0.2
0.4
0.6
0.8
1.0
Low
Medium
High
Traffic Level

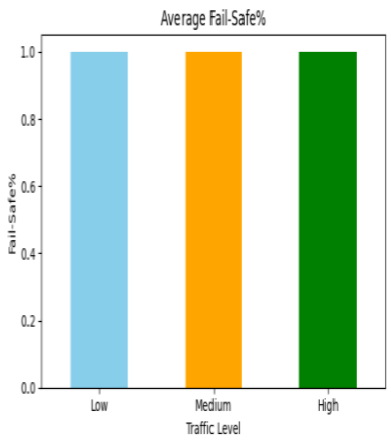

Average DFTR
DFTR
0.00
0.05
0.10
0.15
0.20
0.25
Low
Medium
High
Traffic Level

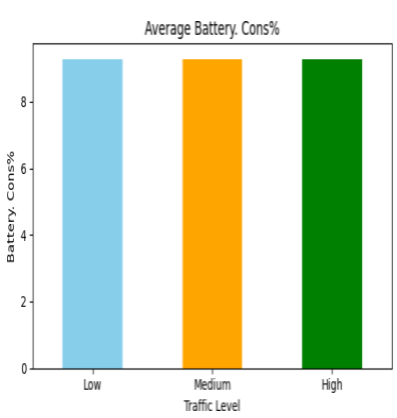

Average Duration
Duration
0
20
40
60
80
100
120
140
Low
Medium
High
Traffic Level

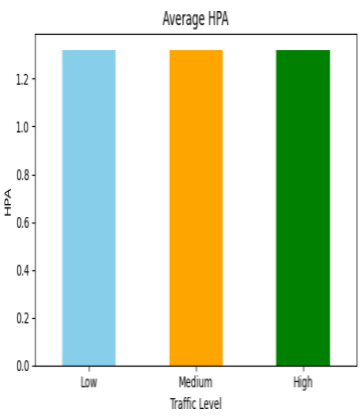

Average Freq. Collision (per min)
Freq. Collision (per min)
−0.04
−0.02
0.00
0.02
0.04
Low
Medium
High
Traffic Level

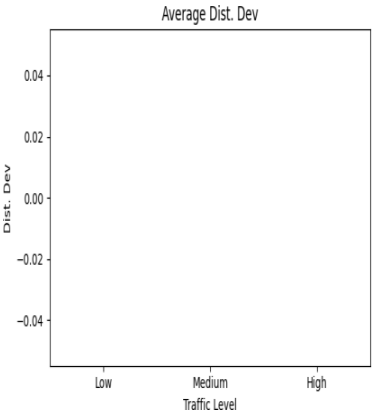

Average NFTR
NFTR
0
10
20
30
40
50
Low
Medium
High
Traffic Level


Average PU
PU
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Low
Medium
High
Traffic Level

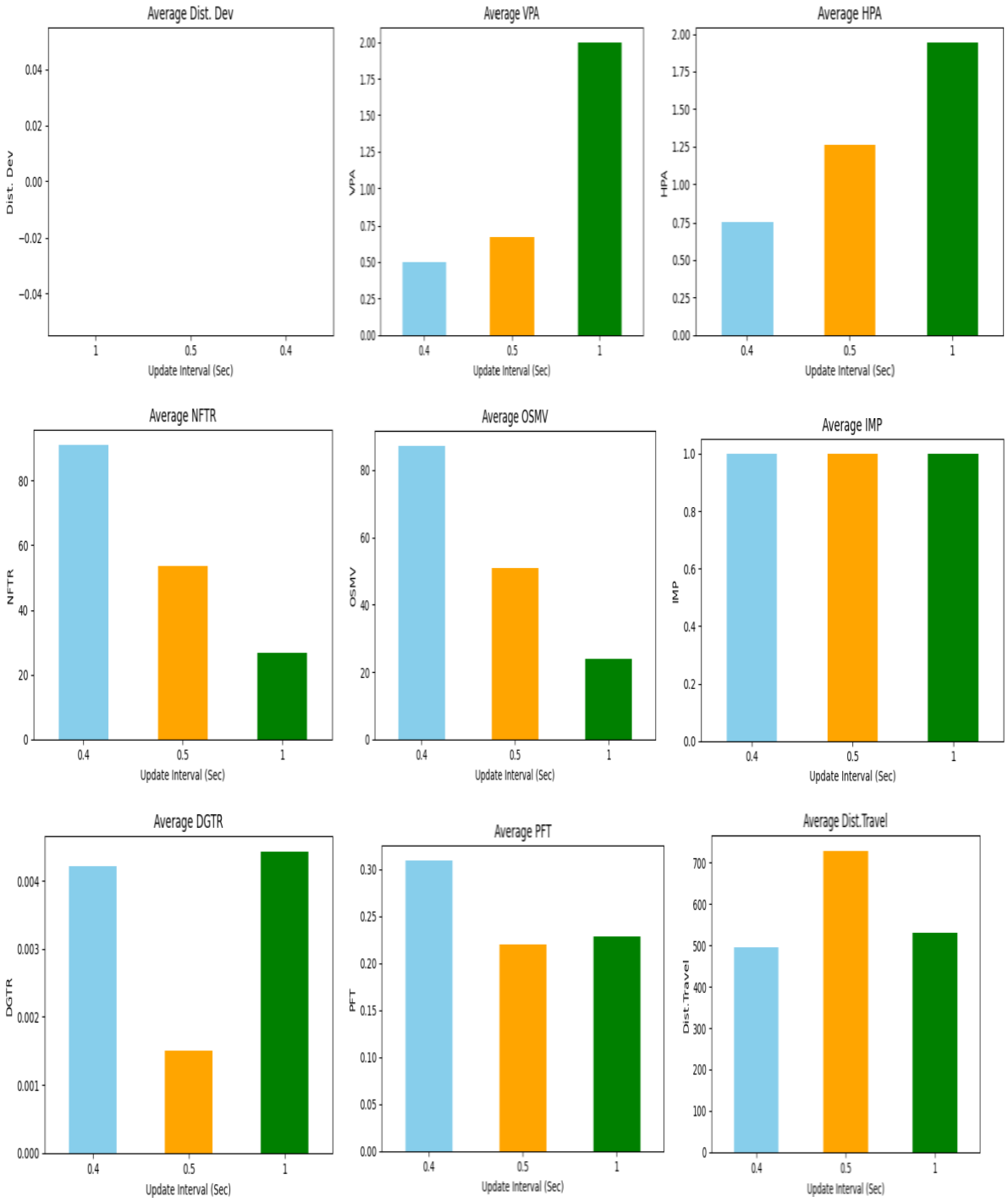

Average Fail-Safe%
Fail-Safe%
0.0
0.2
0.4
0.6
0.8
1.0
Low
Medium
High
Traffic Level

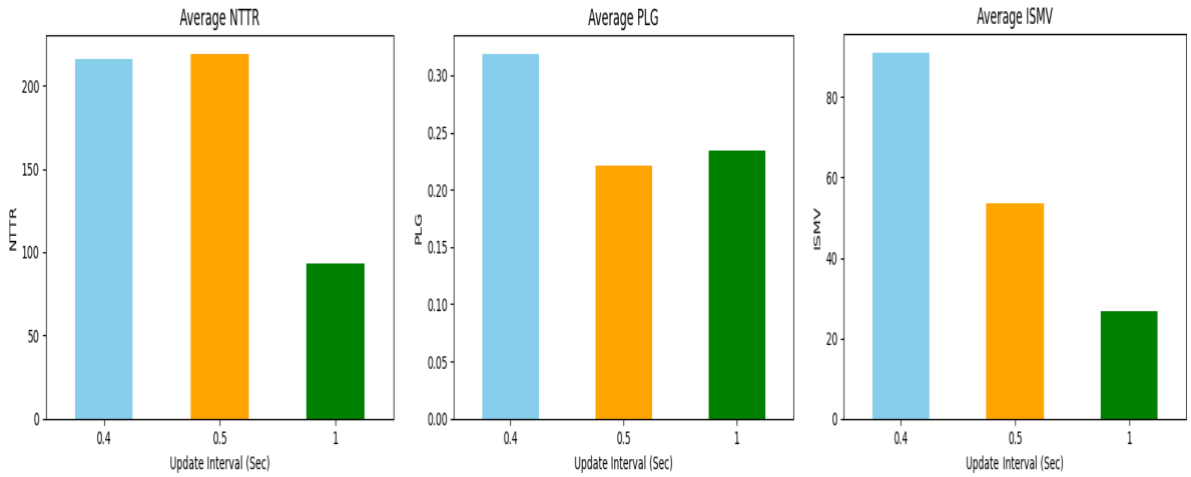

Average Battery. Cons%
Battery. Cons%
0
2
4
6
8
Low
Medium
High
Traffic Level

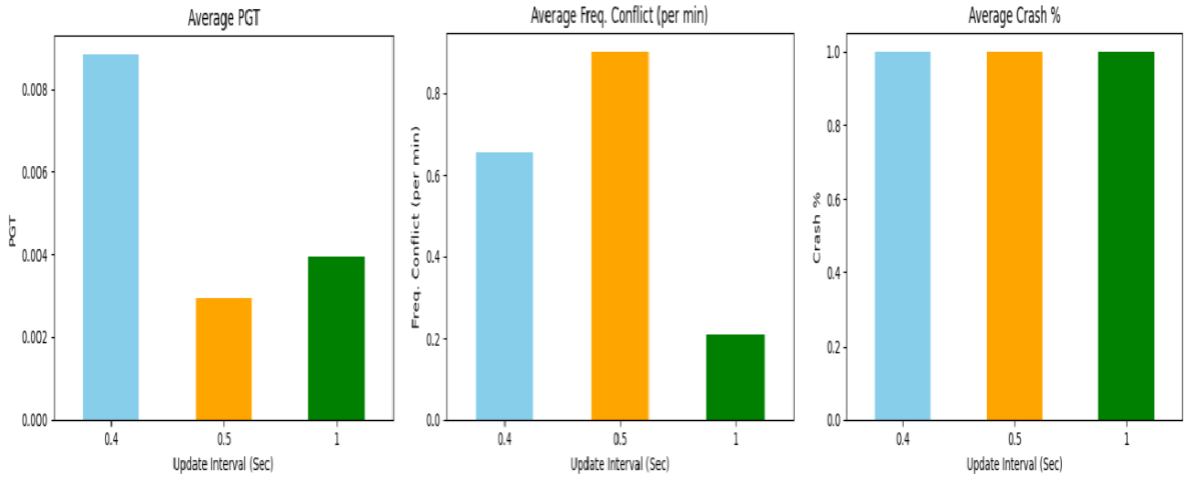

Average HPA
HPA
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Low
Medium
High
Traffic Level

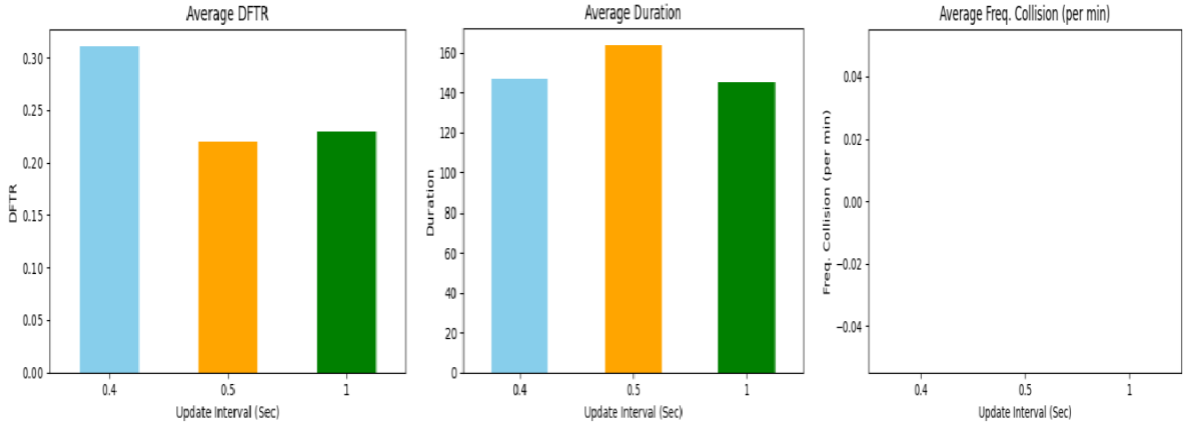

Average Dist. Dev
Dist. Dev
−0.04
−0.02
0.00
0.02
0.04
Low
Medium
High
Traffic Level

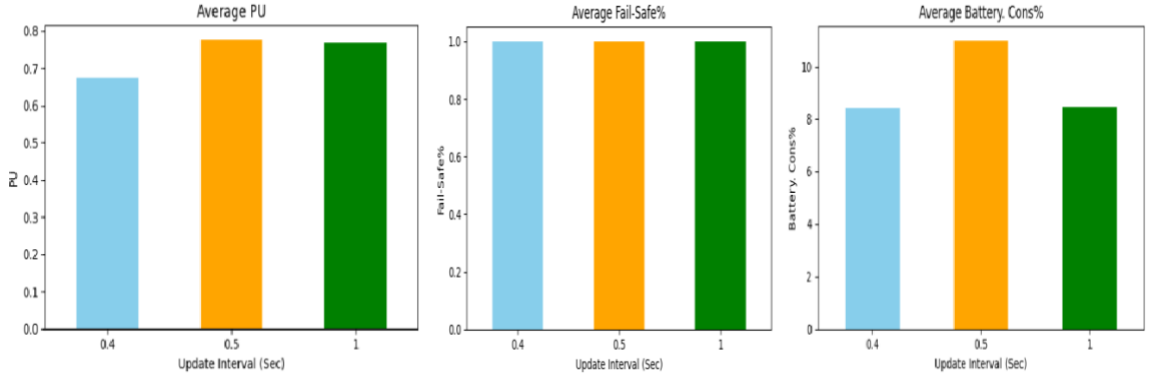
- **Impact of the different Update Intervals:**




Average NTTR
NTTR
Update Interval (Sec)
Average PLG
PLG
Update Interval (Sec)
Average ISMV
ISMV
Update Interval (Sec)

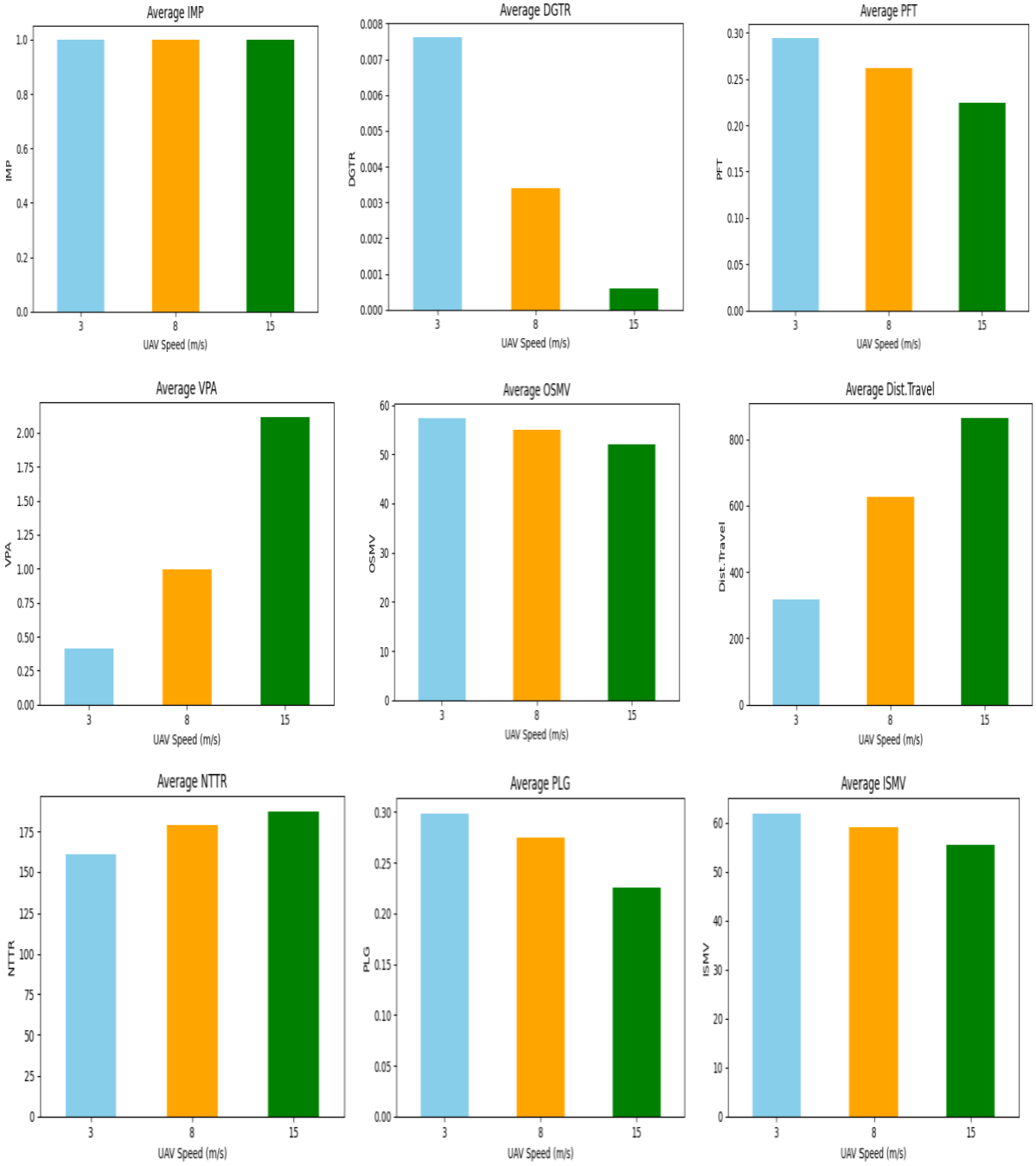

Average PGT
PGT
Update Interval (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Update Interval (Sec)
Average Crash %
Crash %
Update Interval (Sec)

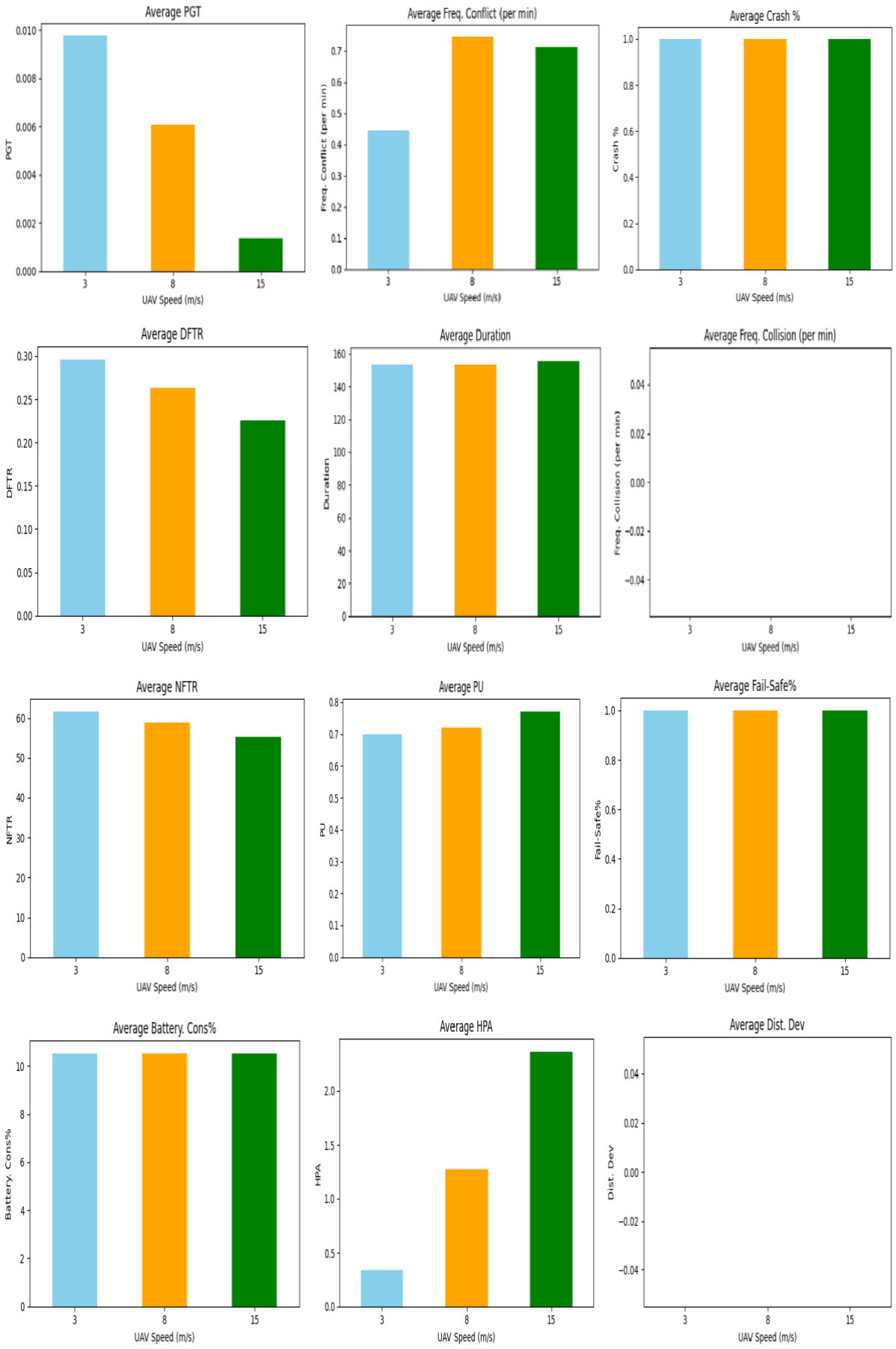

Average DFTR
DFTR
Update Interval (Sec)
Average Duration
Duration
Update Interval (Sec)
Average Freq. Collision (per min)
Freq. Collision (per min)
Update Interval (Sec)


Average PU
PU
Update Interval (Sec)
Average Fail-Safe%
Fail-Safe%
Update Interval (Sec)
Average Battery. Cons%
Battery. Cons%
Update Interval (Sec)

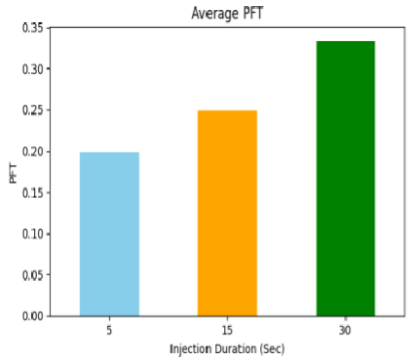
2) Accelerometer faults with moderate breeze wind:

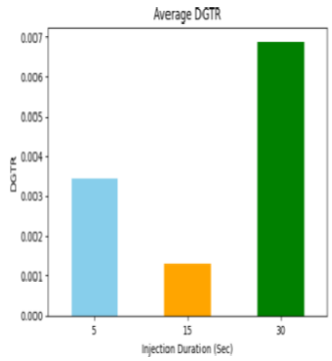
- **Impact of different UAV speeds:**

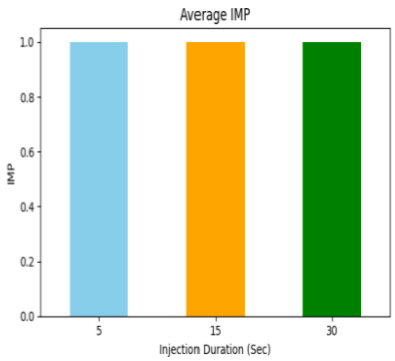


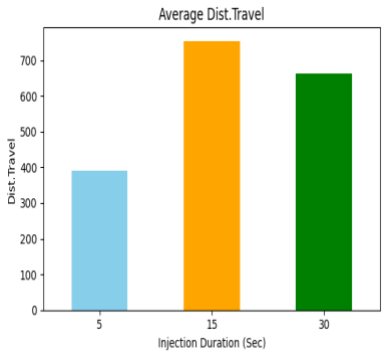

Average PGT
PGT
UAV Speed (m/s)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
UAV Speed (m/s)
Average Crash %
Crash %
UAV Speed (m/s)
Average DFTR
DFTR
UAV Speed (m/s)
Average Duration
Duration
UAV Speed (m/s)
Average Freq. Collision (per min)
Freq. Collision (per min)
UAV Speed (m/s)
Average NFTR
NFTR
UAV Speed (m/s)
Average PU
PU
UAV Speed (m/s)
Average Fail-Safe%
Fail-Safe%
UAV Speed (m/s)
Average Battery. Cons%
Battery. Cons%
UAV Speed (m/s)
Average HPA
HPA
UAV Speed (m/s)
Average Dist. Dev
Dist. Dev
UAV Speed (m/s)

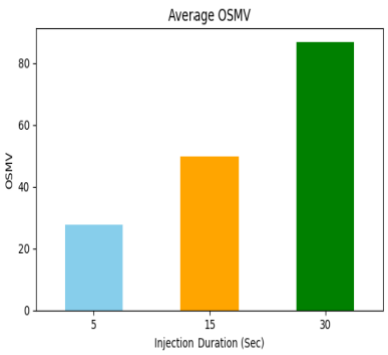
- **Impact of different injection durations:**

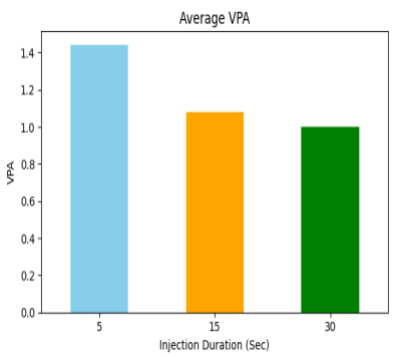


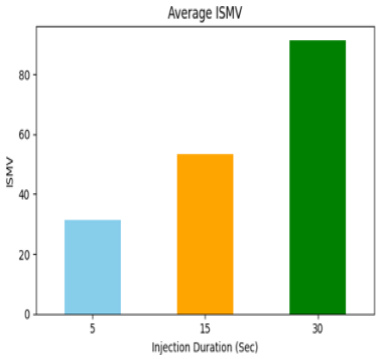


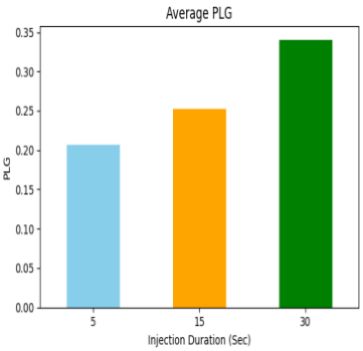


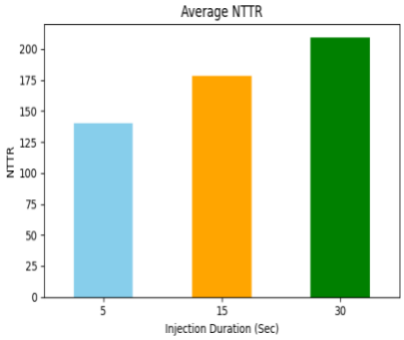


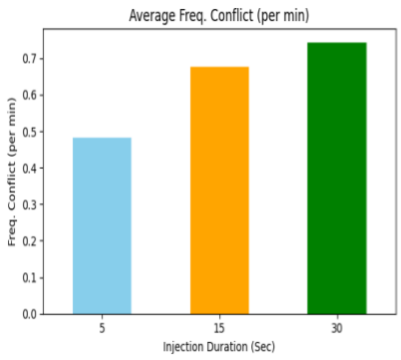


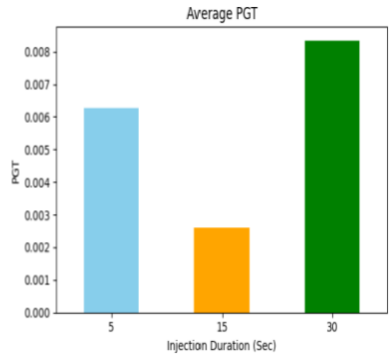


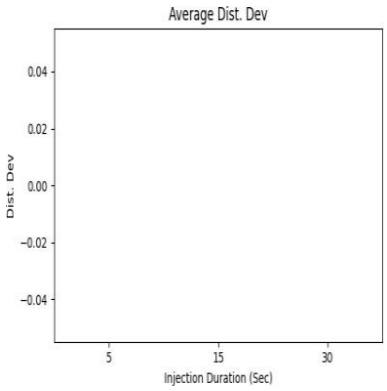


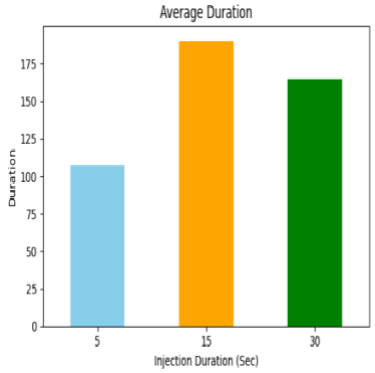


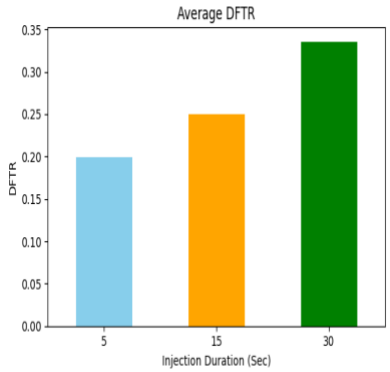


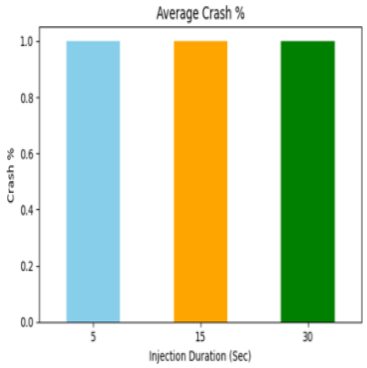


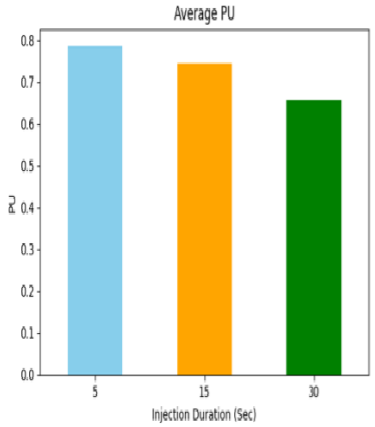


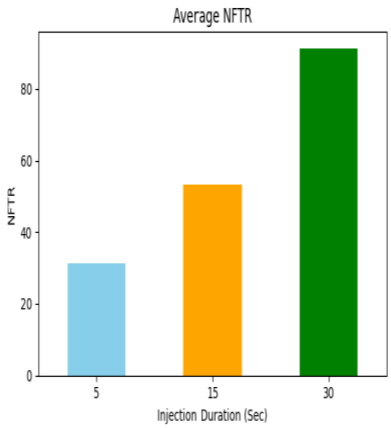


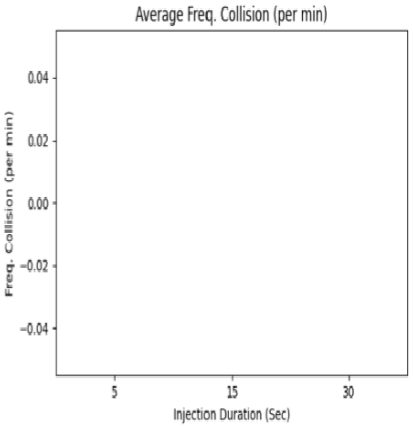

Average Duration
Duration
Injection Duration (Sec)

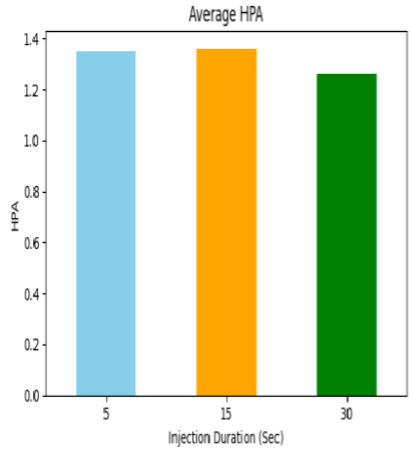

Average DFTR
DFTR
Injection Duration (Sec)

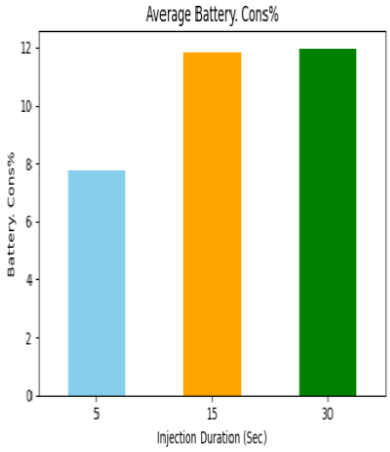

Average Crash %
Crash %
Injection Duration (Sec)

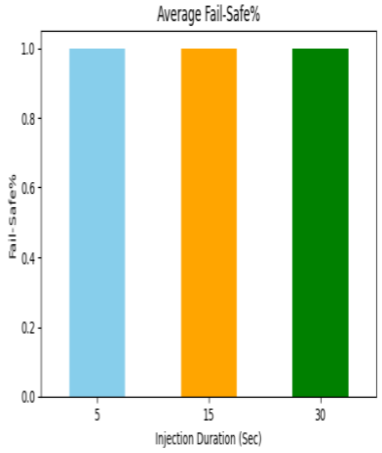

Average PU
PU
Injection Duration (Sec)


Average NFTR
NFTR
Injection Duration (Sec)

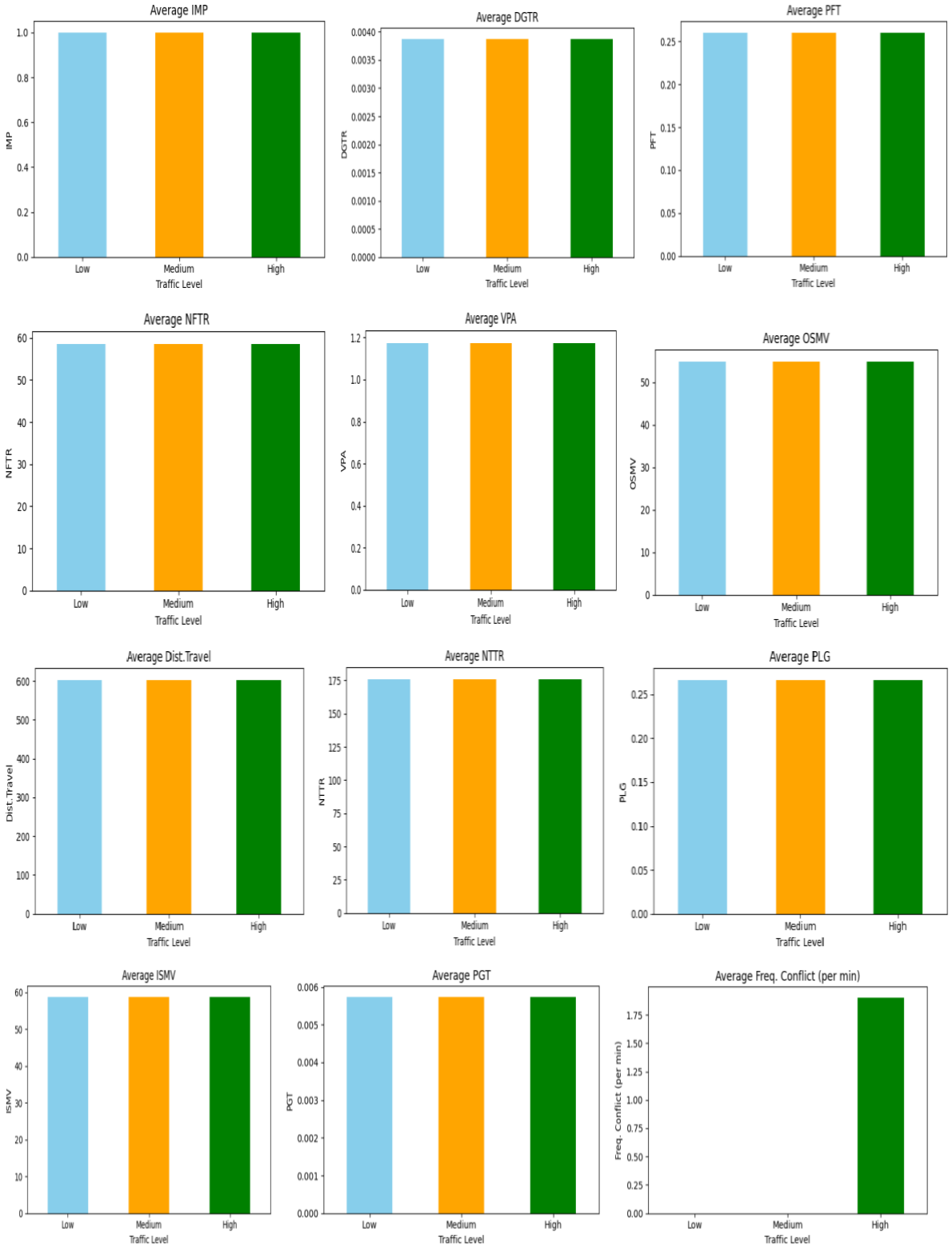

Average Freq. Collision (per min)
Freq. Collision (per min)
Injection Duration (Sec)

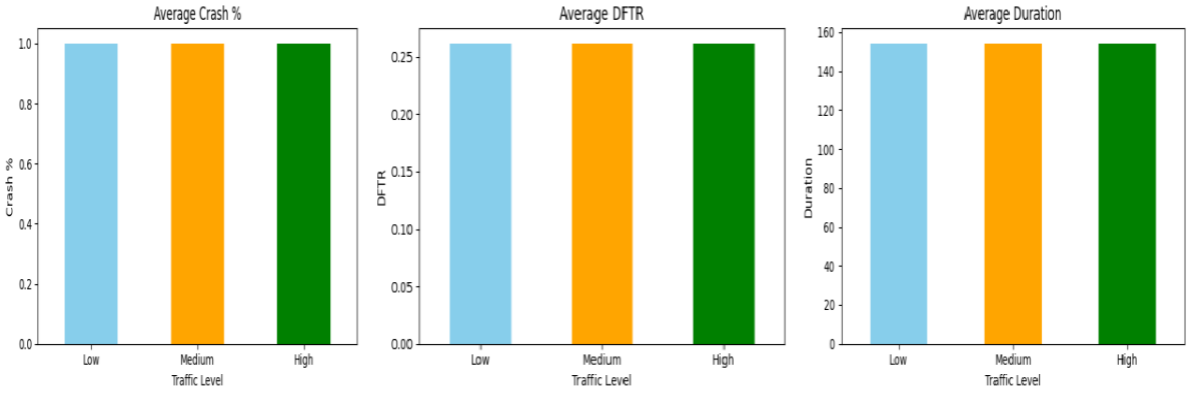

Average HPA
HPA
Injection Duration (Sec)

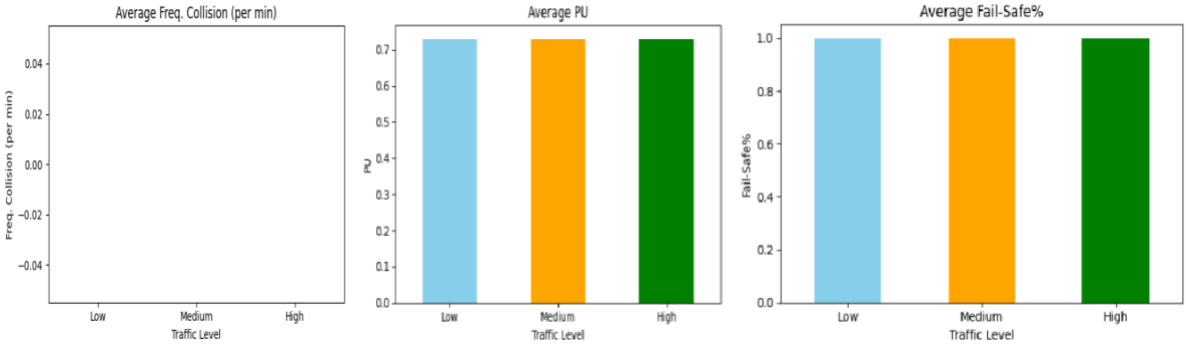

Average Battery. Cons%
Battery. Cons%
Injection Duration (Sec)

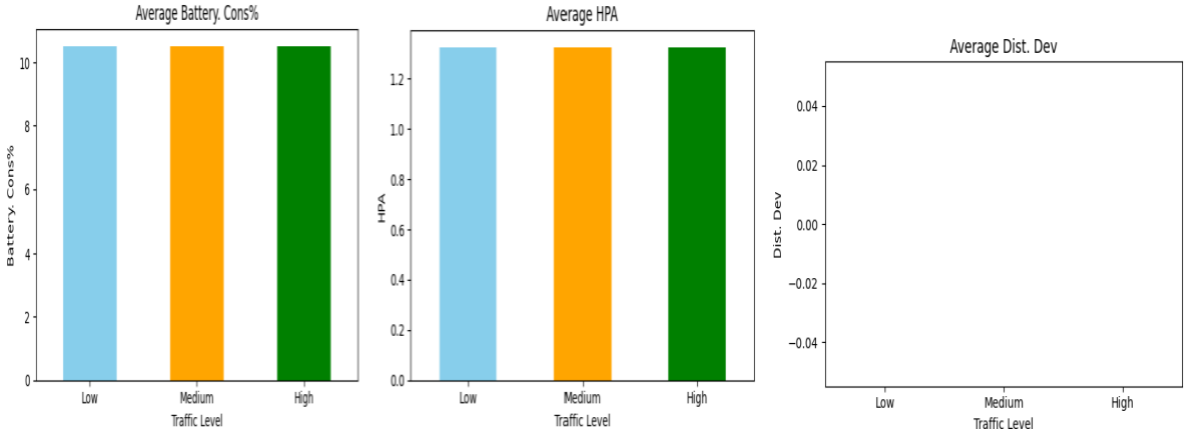

Average Fail-Safe%
Fail-Safe%
Injection Duration (Sec)

- **Impact of different traffic levels:**

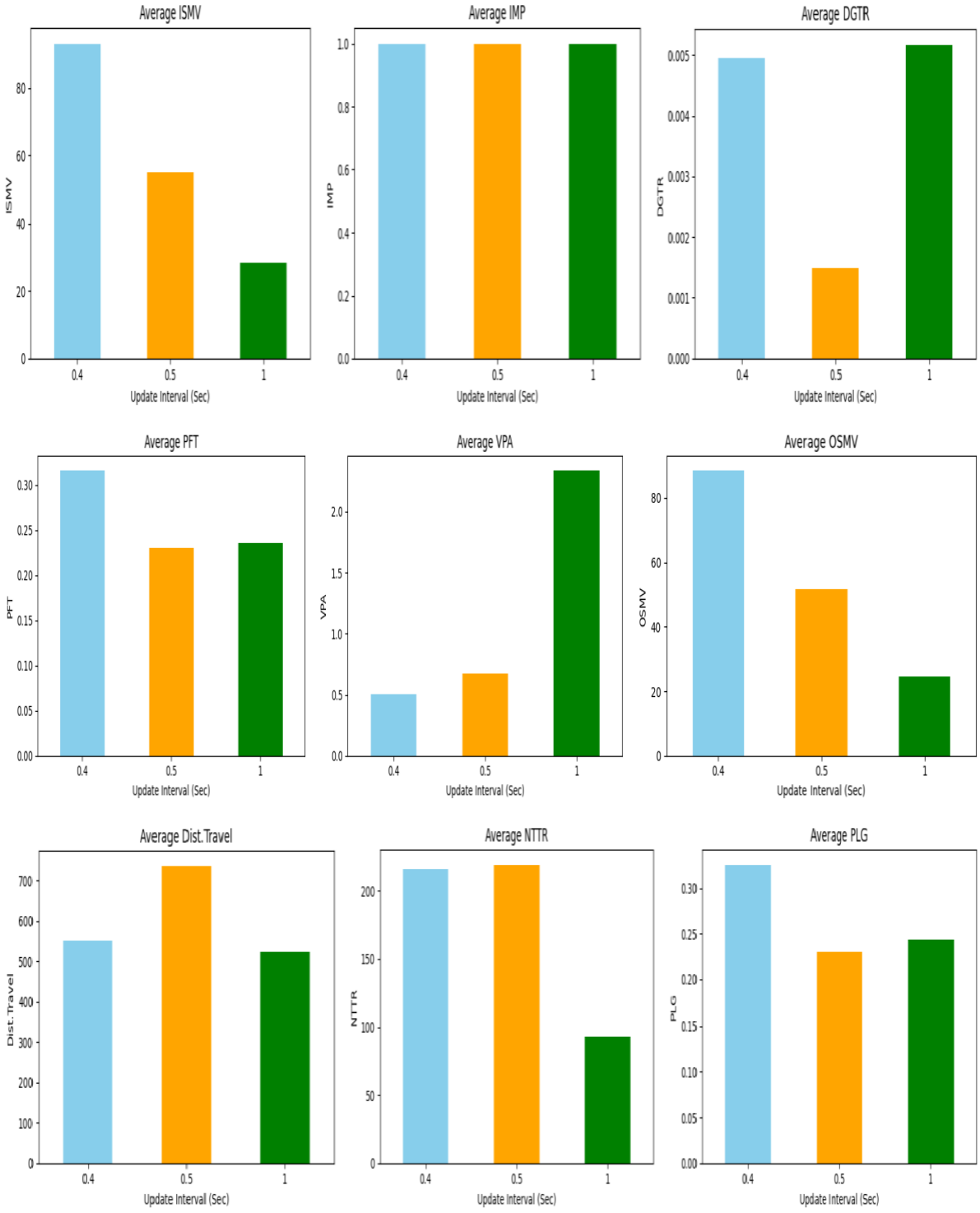


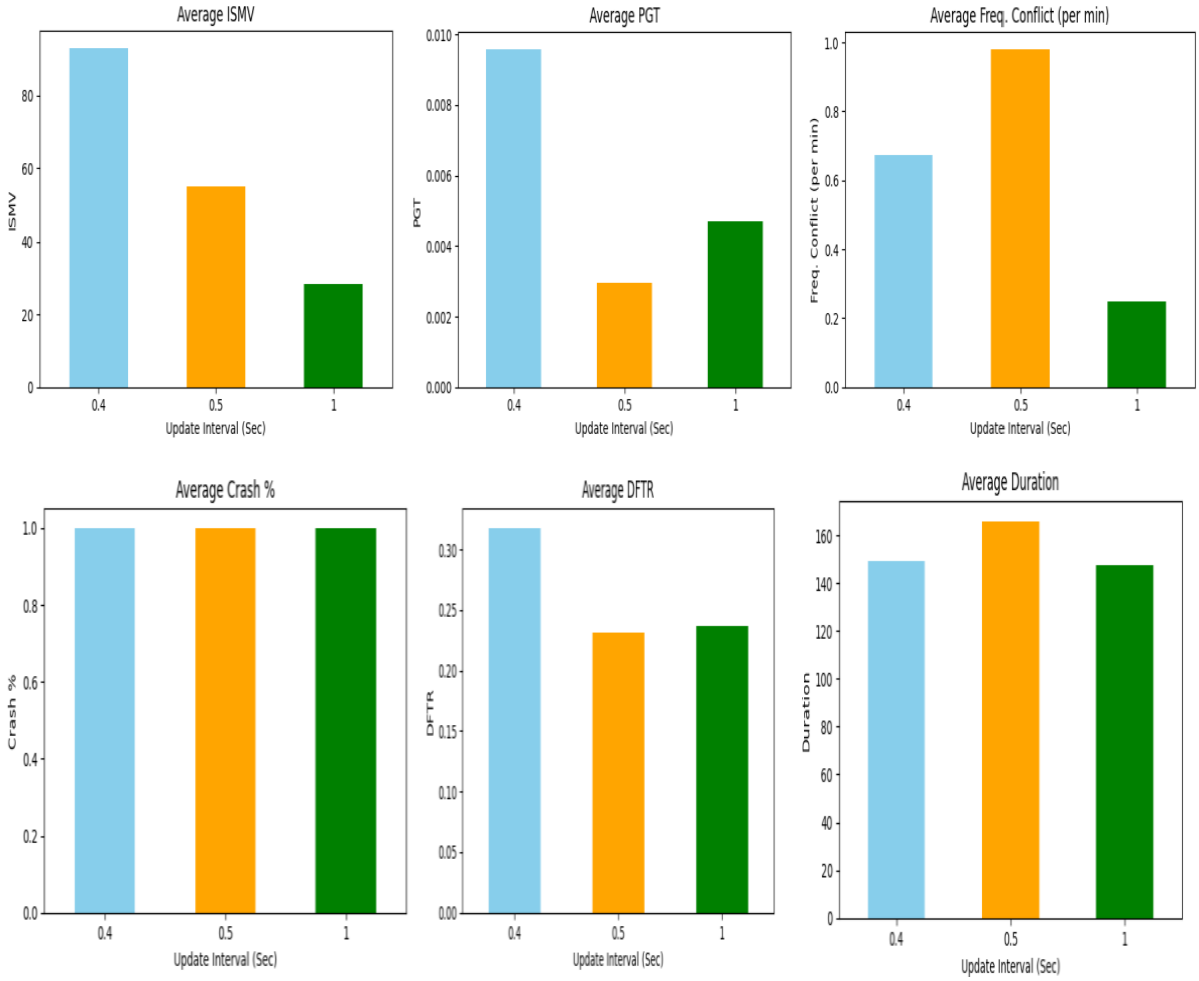

Average Crash %
Crash %
Traffic Level
Low
Medium
High
Average DFTR
DFTR
Average Duration
Duration

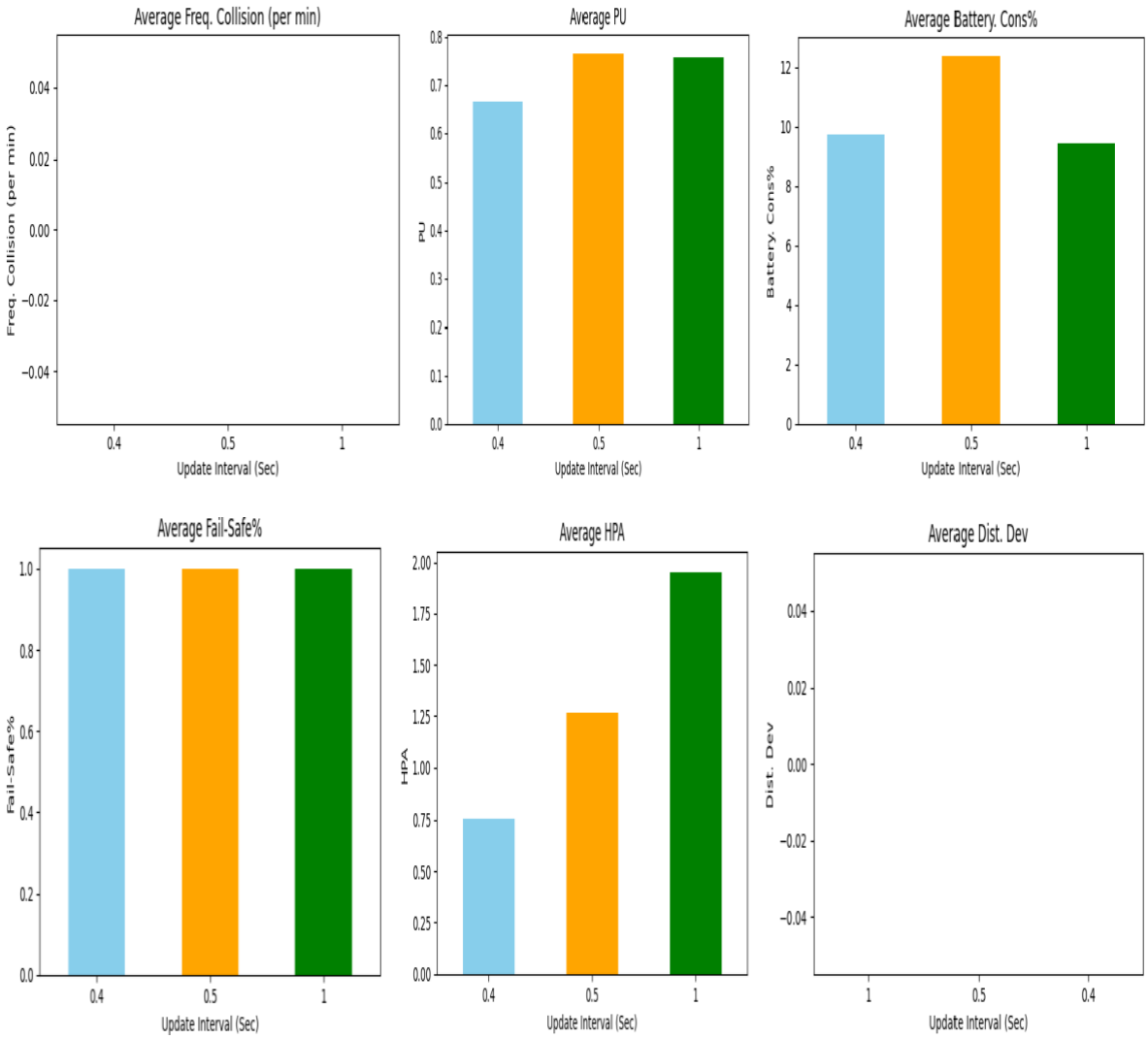

Average Freq. Collision (per min)
Freq. Collision (per min)
Average PU
PU
Average Fail-Safe%
Fail-Safe%
Traffic Level


Average Battery. Cons%
Battery. Cons%
Average HPA
HPA
Average Dist. Dev
Dist. Dev
Traffic Level

- **Impact of different update intervals:**

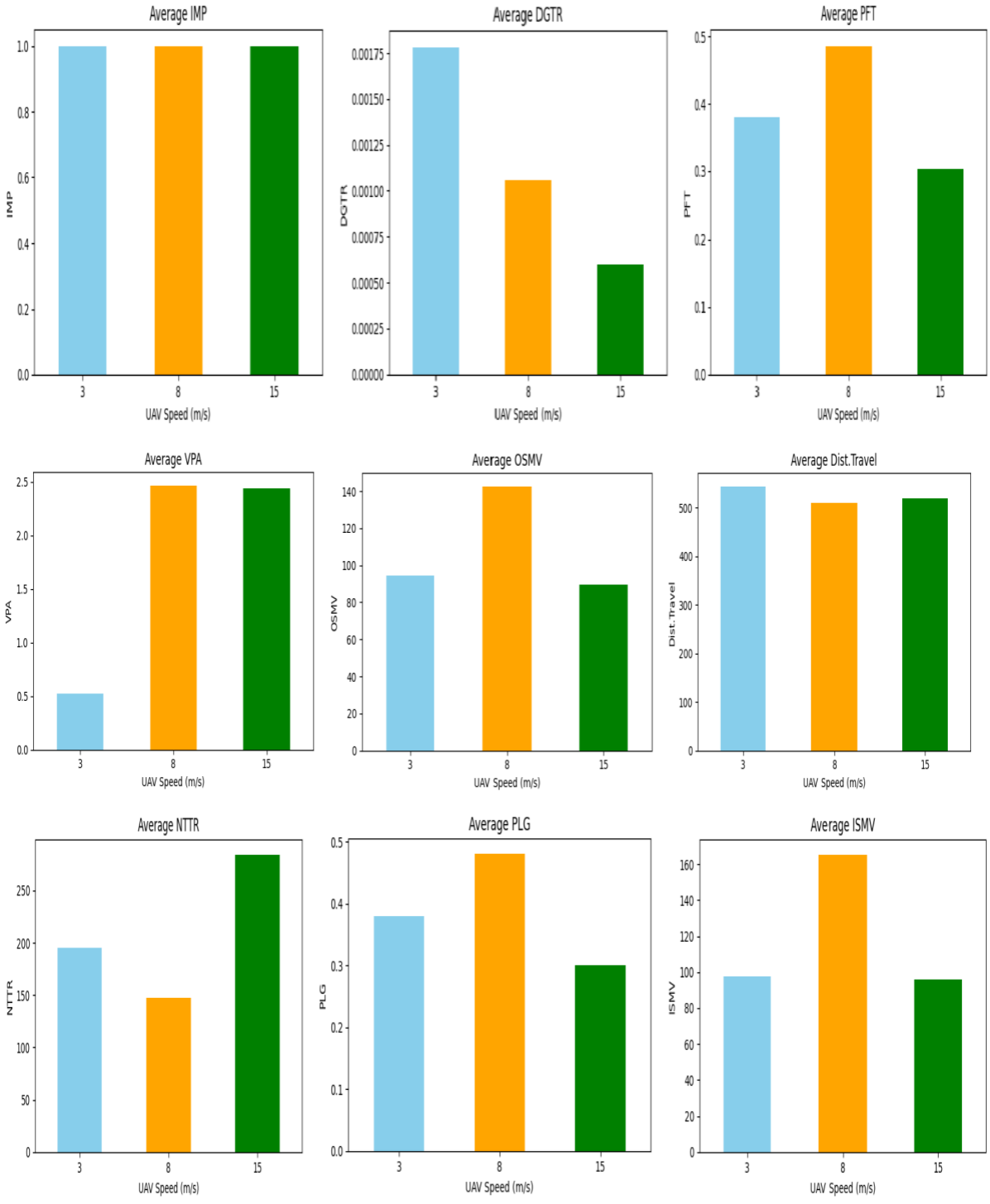


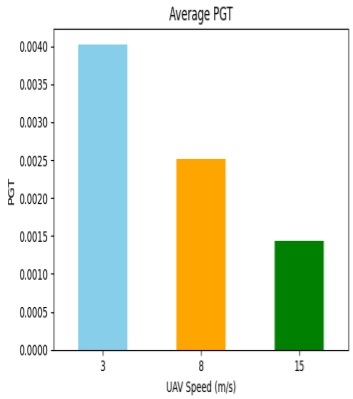

Average ISMV
ISMV
Update Interval (Sec)
Average PGT
PGT
Update Interval (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Update Interval (Sec)
Average Crash %
Crash %
Update Interval (Sec)
Average DFTR
DFTR
Update Interval (Sec)
Average Duration
Duration
Update Interval (Sec)

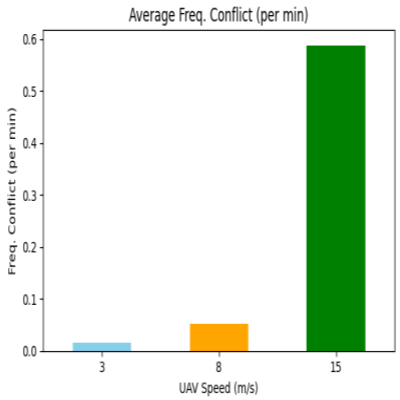

Average Freq. Collision (per min)
Freq. Collision (per min)
0.04
0.02
0.00
−0.02
−0.04
0.4
0.5
1
Update Interval (Sec)
Average PU
PU
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.4
0.5
1
Update Interval (Sec)
Average Battery. Cons%
Battery. Cons%
12
10
8
6
4
2
0
0.4
0.5
1
Update Interval (Sec)
Average Fail-Safe%
Fail-Safe%
1.0
0.8
0.6
0.4
0.2
0.0
0.4
0.5
1
Update Interval (Sec)
Average HPA
HPA
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0.4
0.5
1
Update Interval (Sec)
Average Dist. Dev
Dist. Dev
0.04
0.02
0.00
−0.02
−0.04
1
0.5
0.4
Update Interval (Sec)

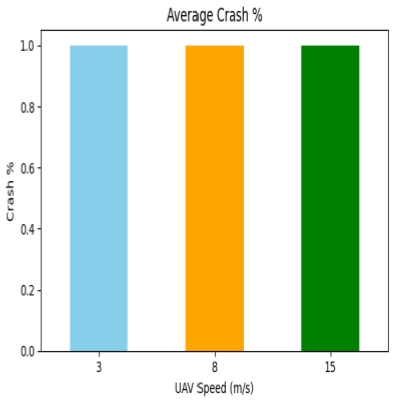
3) Accelerometer faults with near-gale wind:

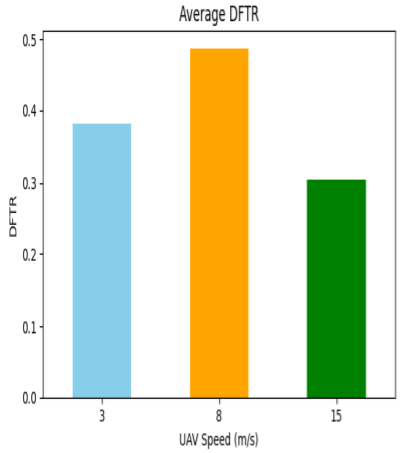
- **Impact of different UAV speeds:**

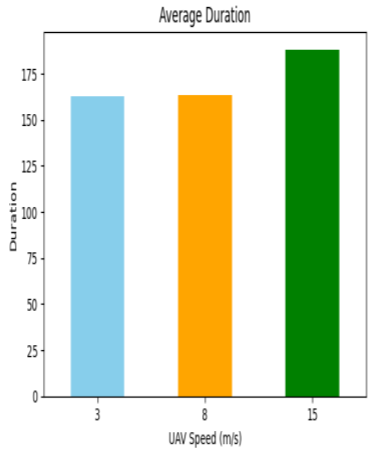


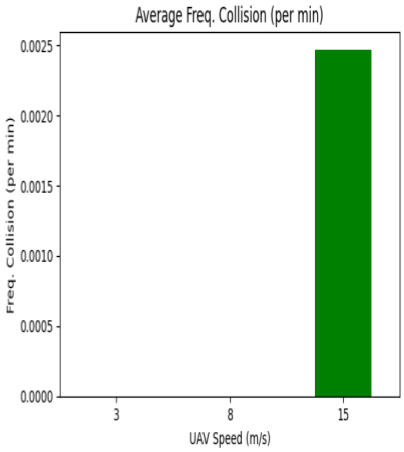

Average PGT
PGT
UAV Speed (m/s)

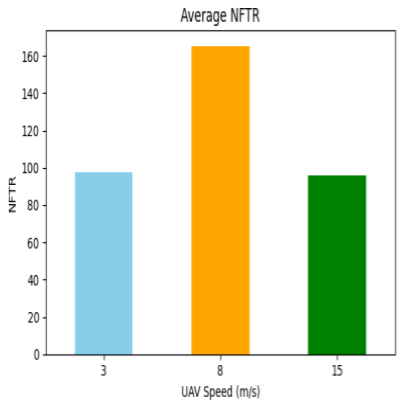

Average Freq. Conflict (per min)
Freq. Conflict (per min)
UAV Speed (m/s)

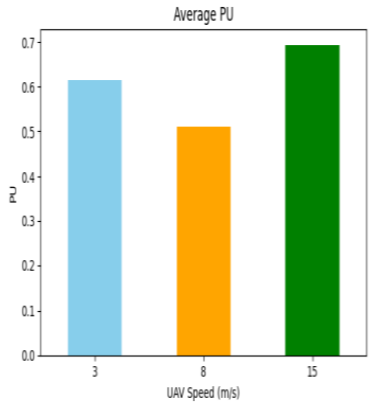

Average Crash %
Crash %
UAV Speed (m/s)

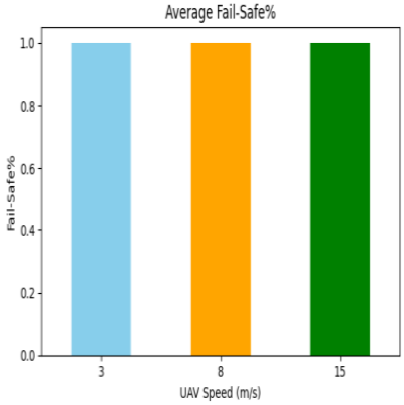

Average DFTR
DFTR
UAV Speed (m/s)

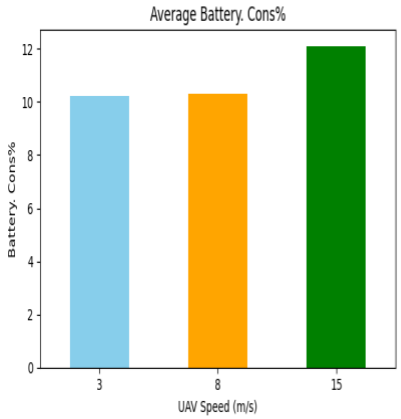

Average Duration
Duration
UAV Speed (m/s)

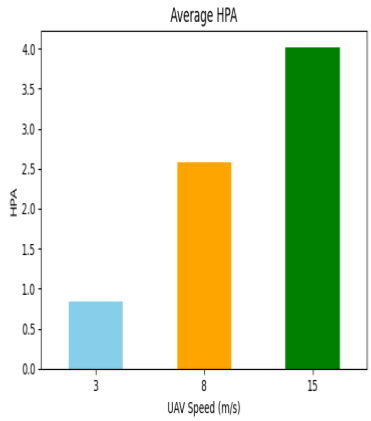

Average Freq. Collision (per min)
Freq. Collision (per min)
UAV Speed (m/s)

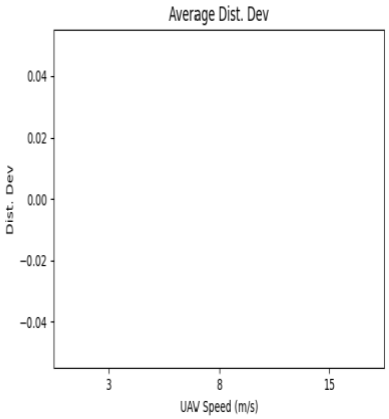

Average NFTR
NFTR
UAV Speed (m/s)


Average PU
PU
UAV Speed (m/s)

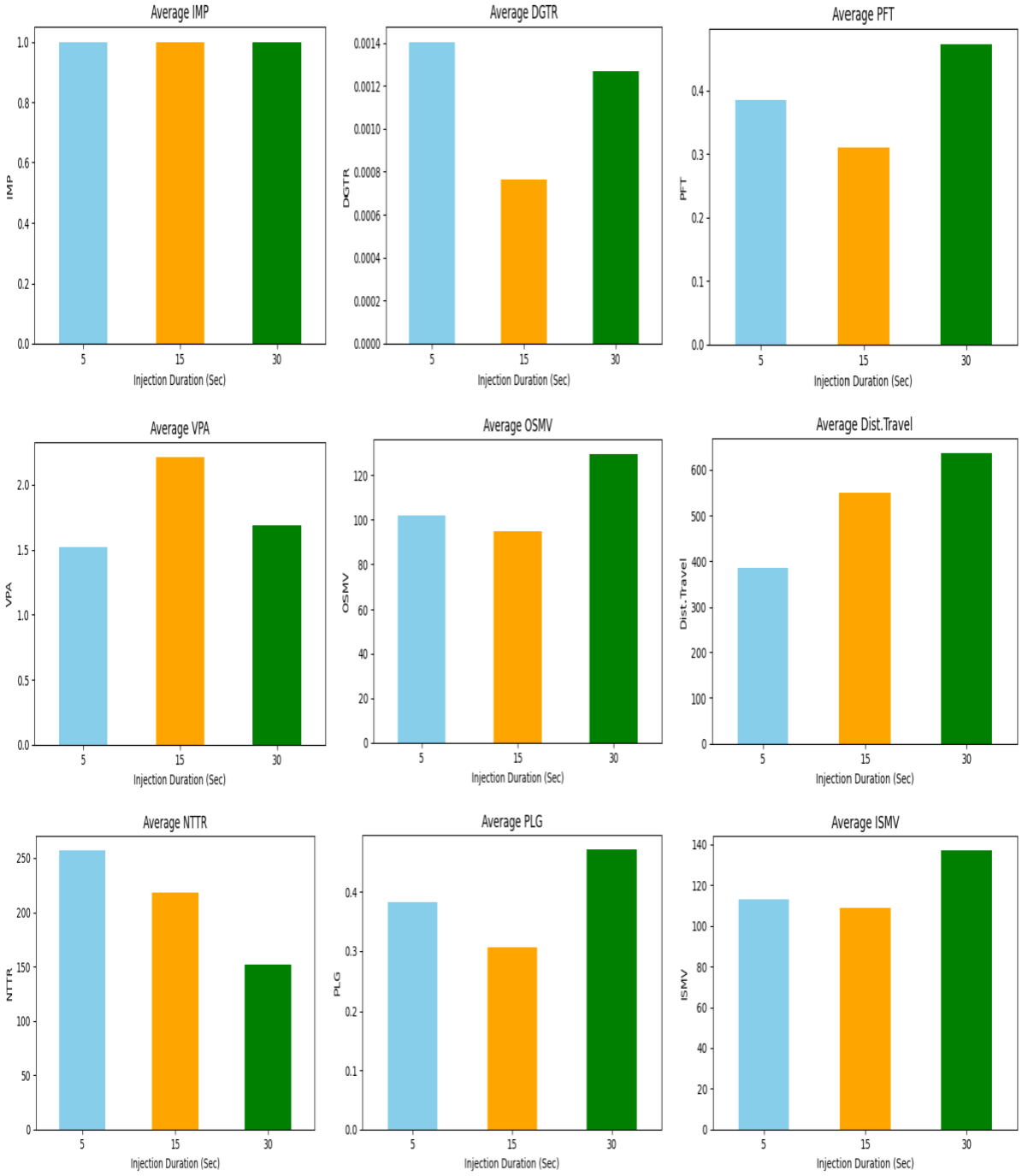

Average Fail-Safe%
Fail-Safe%
UAV Speed (m/s)

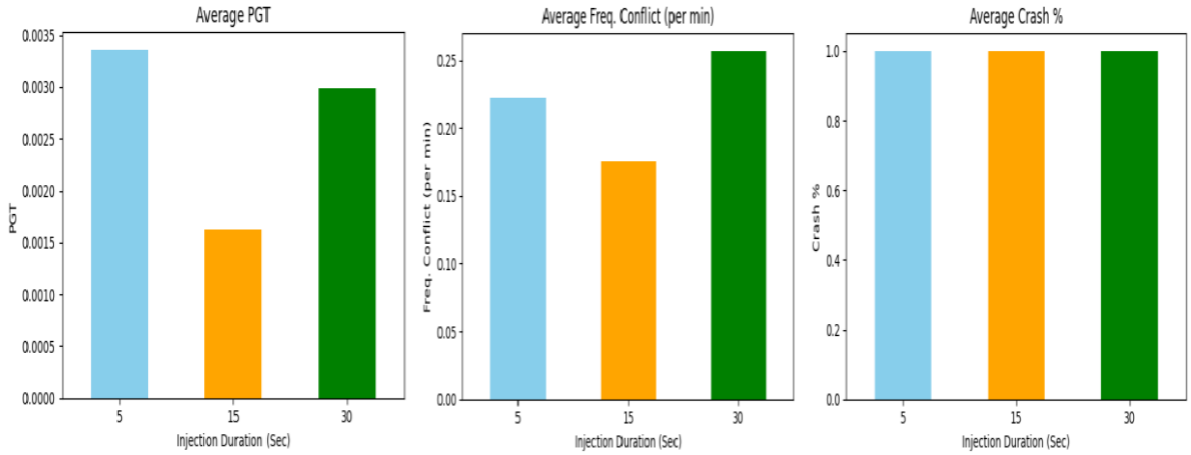

Average Battery. Cons%
Battery. Cons%
UAV Speed (m/s)

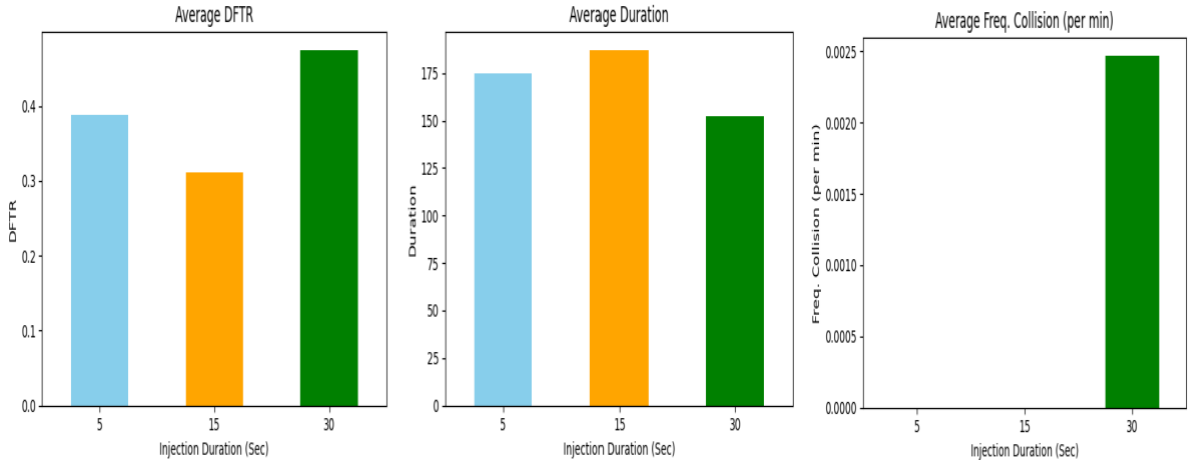

Average HPA
HPA
UAV Speed (m/s)

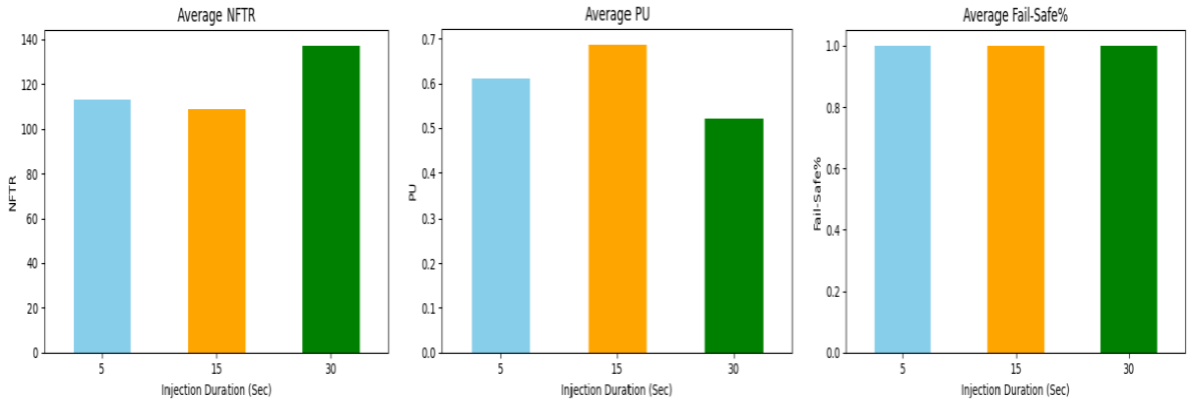

Average Dist. Dev
Dist. Dev
UAV Speed (m/s)

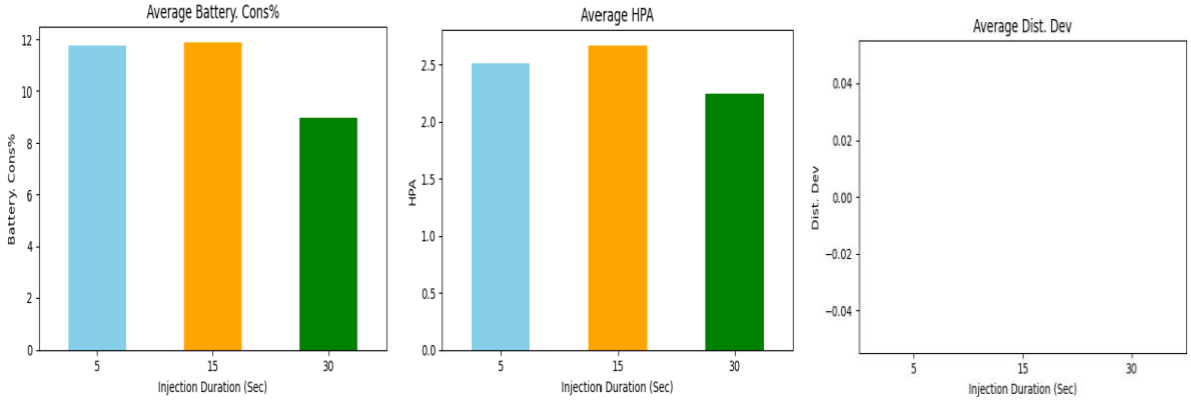
- **Impact of different injection durations:**



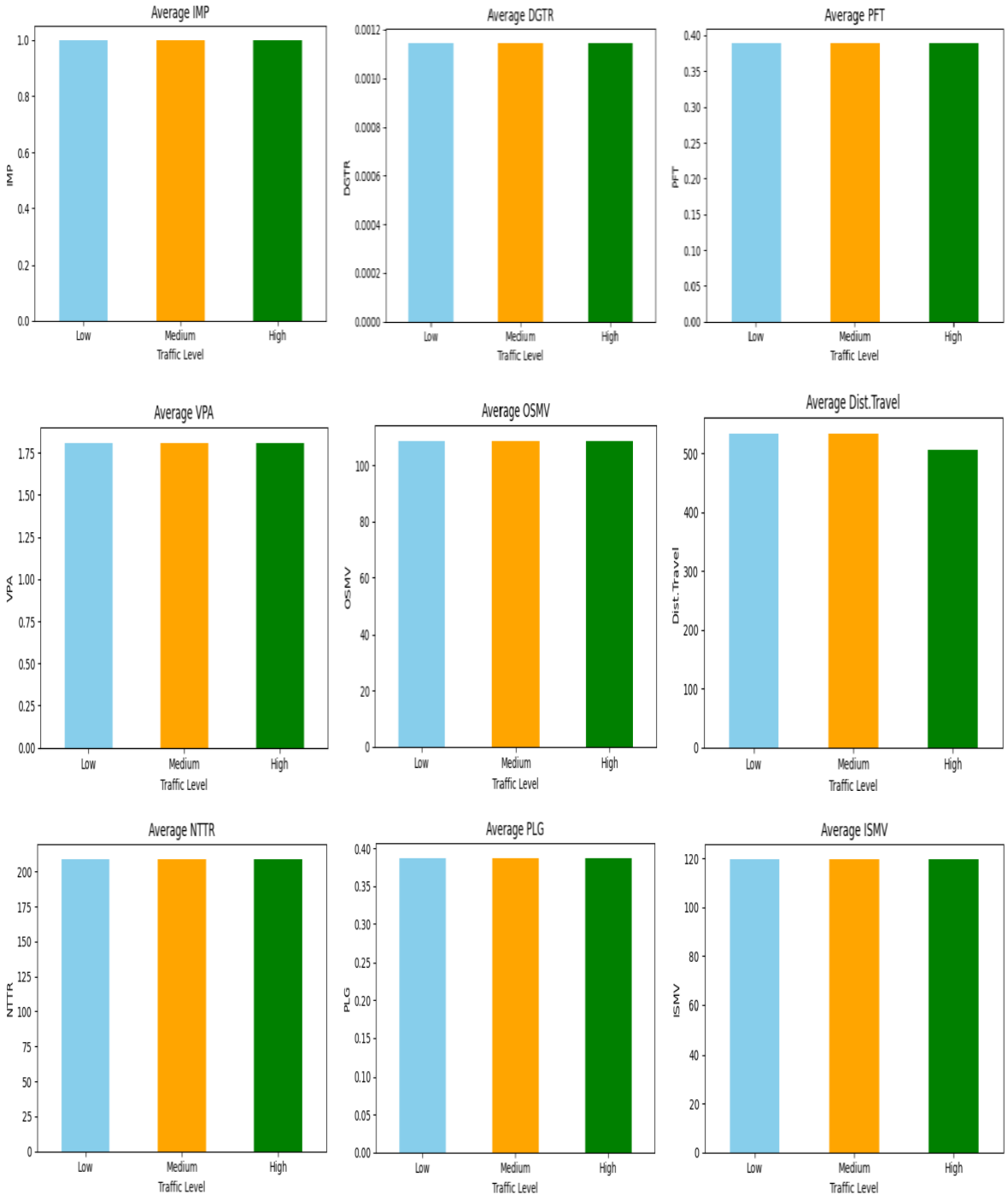

Average PGT
PGT
Injection Duration (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Injection Duration (Sec)
Average Crash %
Crash %
Injection Duration (Sec)

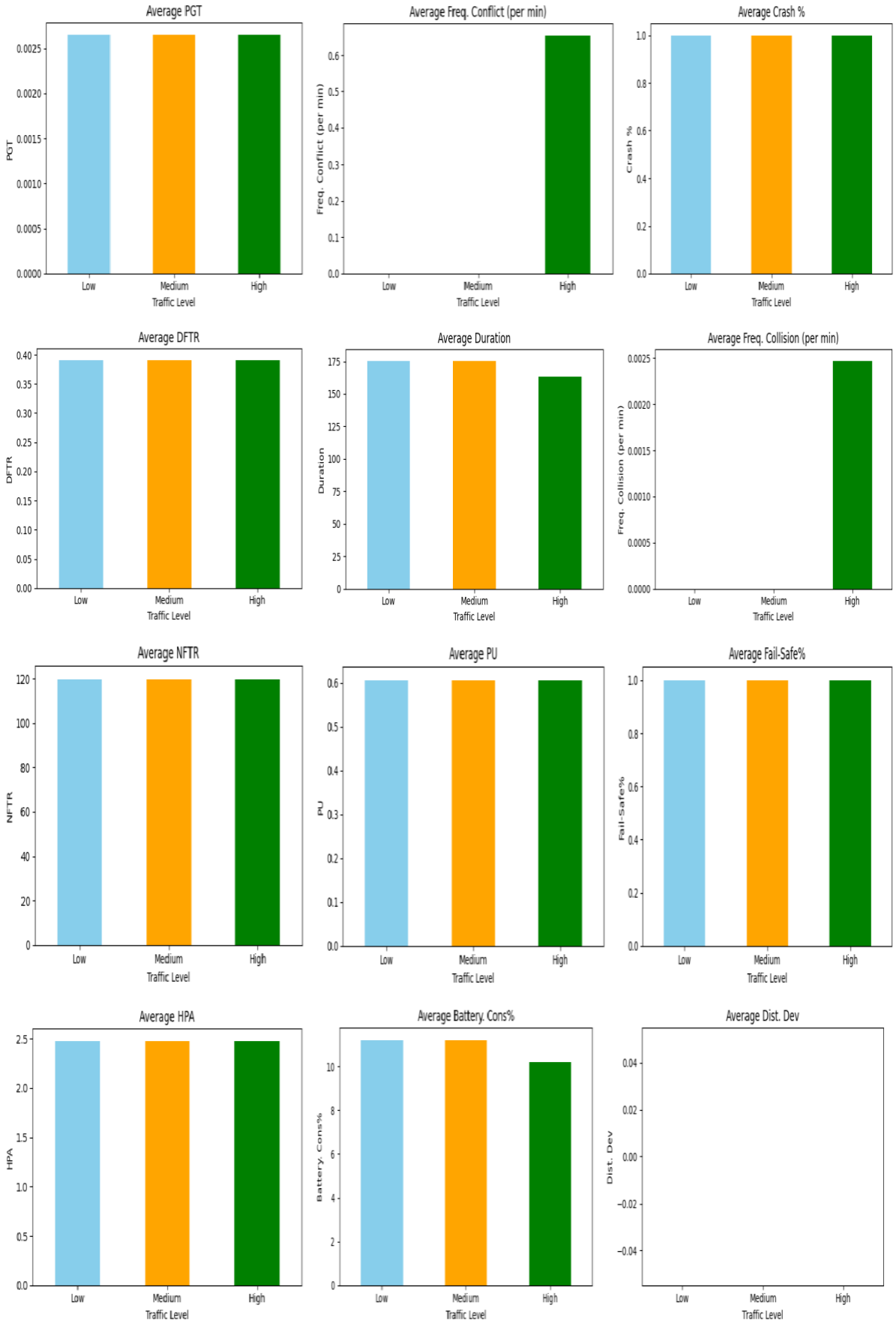

Average DFTR
DFTR
Injection Duration (Sec)
Average Duration
Duration
Injection Duration (Sec)
Average Freq. Collision (per min)
Freq. Collision (per min)
Injection Duration (Sec)


Average NFTR
NFTR
Injection Duration (Sec)
Average PU
PU
Injection Duration (Sec)
Average Fail-Safe%
Fail-Safe%
Injection Duration (Sec)

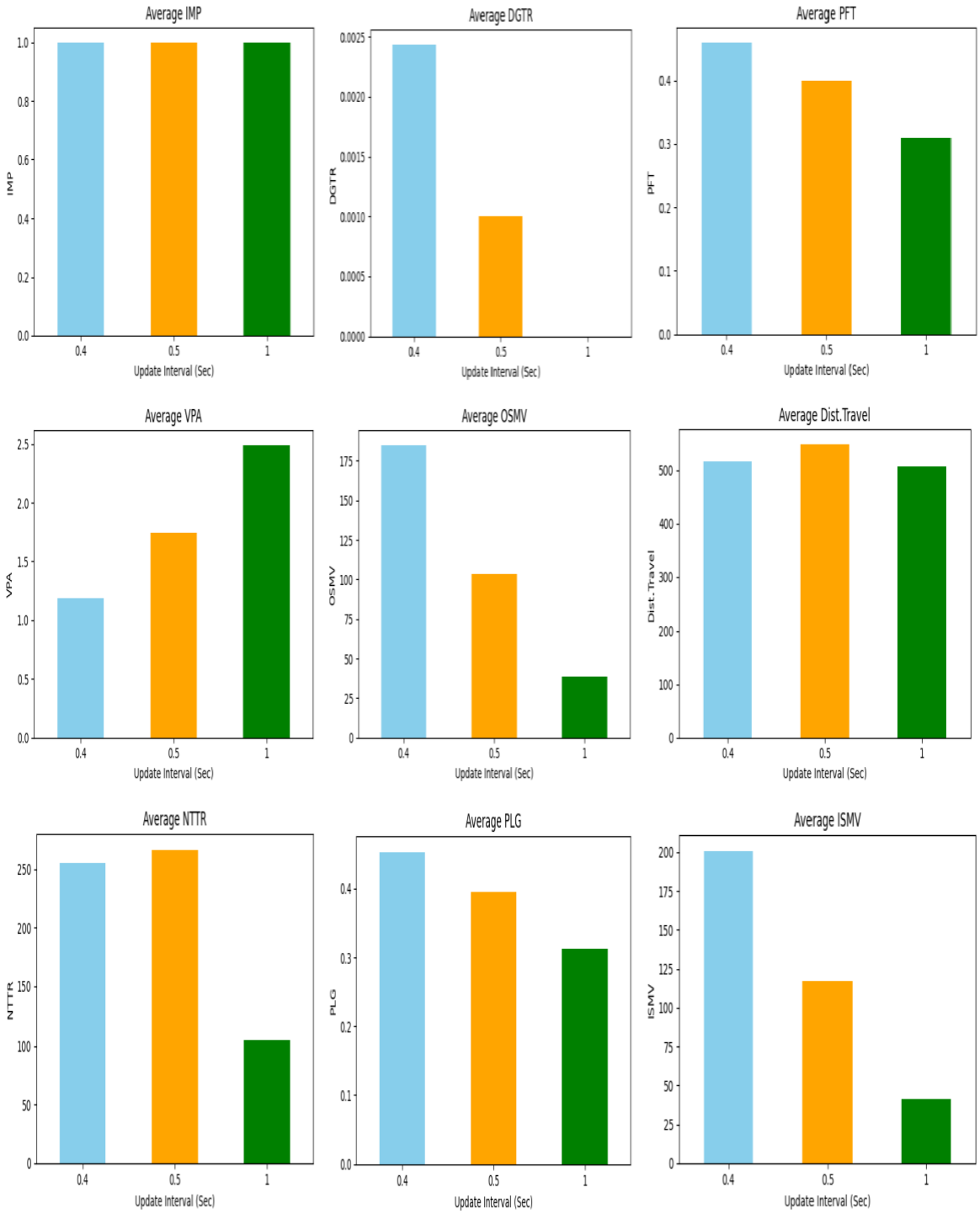

Average Battery. Cons%
Battery. Cons%
Injection Duration (Sec)
Average HPA
HPA
Injection Duration (Sec)
Average Dist. Dev
Dist. Dev
Injection Duration (Sec)

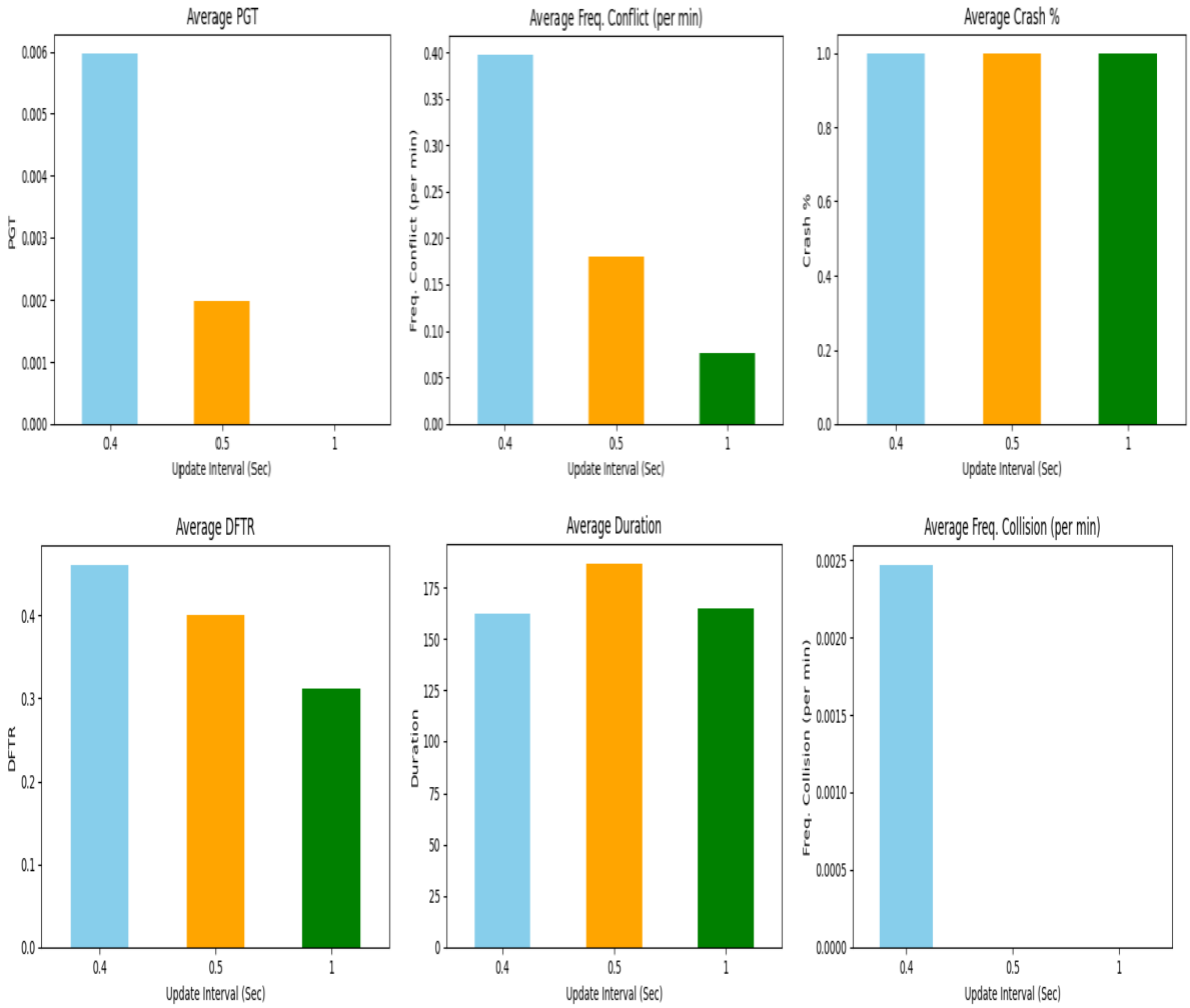
- **Impact of different traffic levels:**

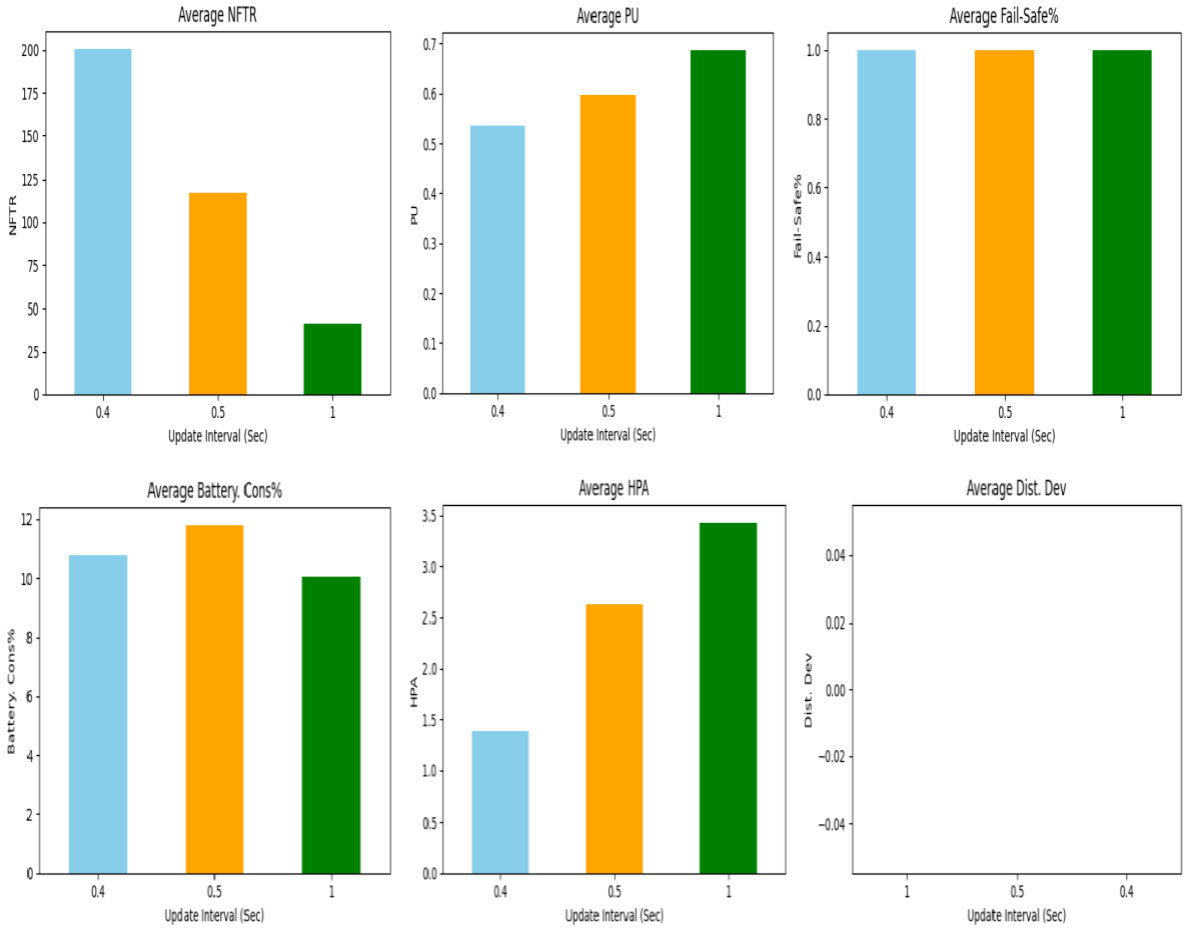



Average PGT
PGT
Traffic Level
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Traffic Level
Average Crash %
Crash %
Traffic Level
Average DFTR
DFTR
Traffic Level
Average Duration
Duration
Traffic Level
Average Freq. Collision (per min)
Freq. Collision (per min)
Traffic Level
Average NFTR
NFTR
Traffic Level
Average PU
PU
Traffic Level
Average Fail-Safe%
Fail-Safe%
Traffic Level
Average HPA
HPA
Traffic Level
Average Battery. Cons%
Battery. Cons%
Traffic Level
Average Dist. Dev
Dist. Dev
Traffic Level
Low
Medium
High

- **Impact of different update intervals:**

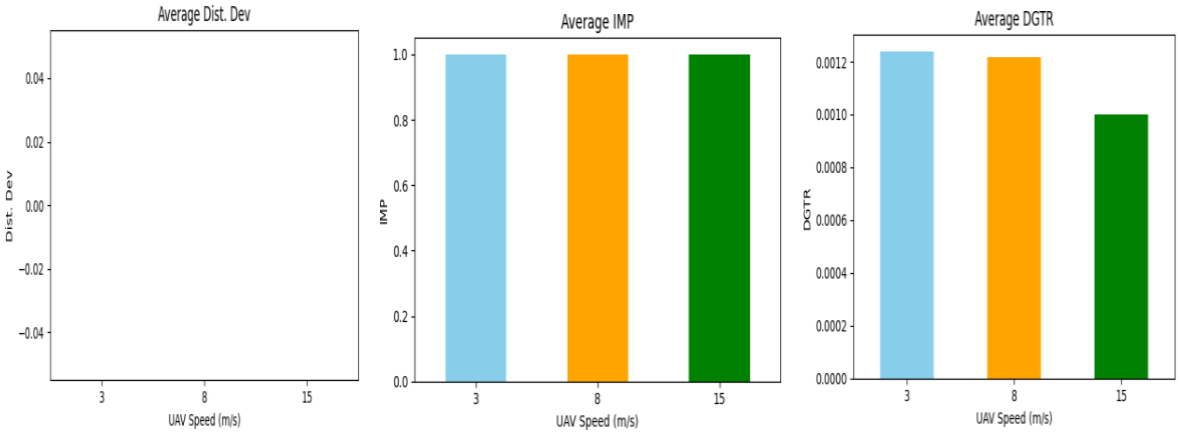


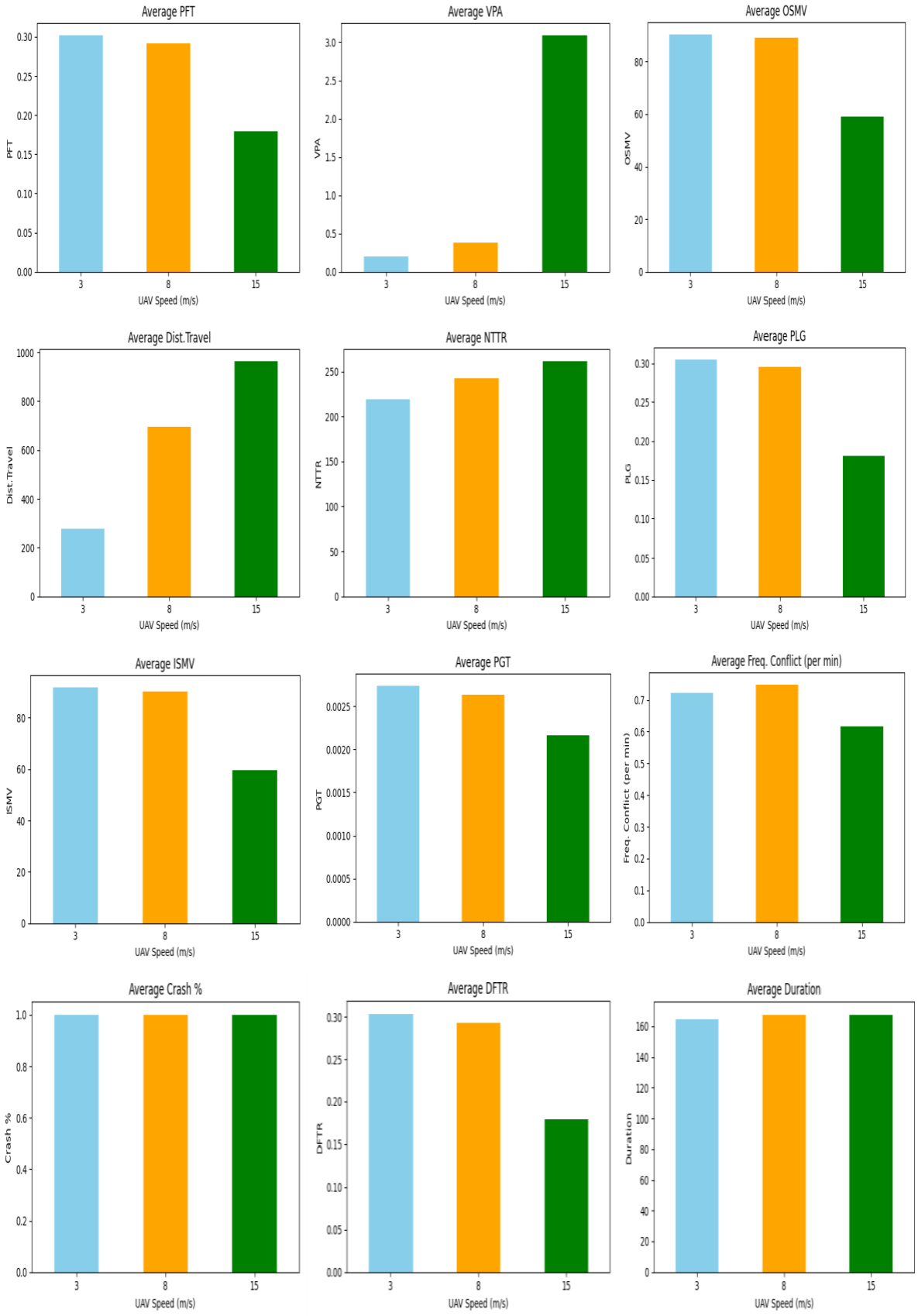

Average PGT
PGT
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0.4
0.5
1
Update Interval (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.4
0.5
1
Update Interval (Sec)
Average Crash %
Crash %
1.0
0.8
0.6
0.4
0.2
0.0
0.4
0.5
1
Update Interval (Sec)
Average DFTR
DFTR
0.4
0.3
0.2
0.1
0.0
0.4
0.5
1
Update Interval (Sec)
Average Duration
Duration
175
150
125
100
75
50
25
0
0.4
0.5
1
Update Interval (Sec)
Average Freq. Collision (per min)
Freq. Collision (per min)
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0.4
0.5
1
Update Interval (Sec)

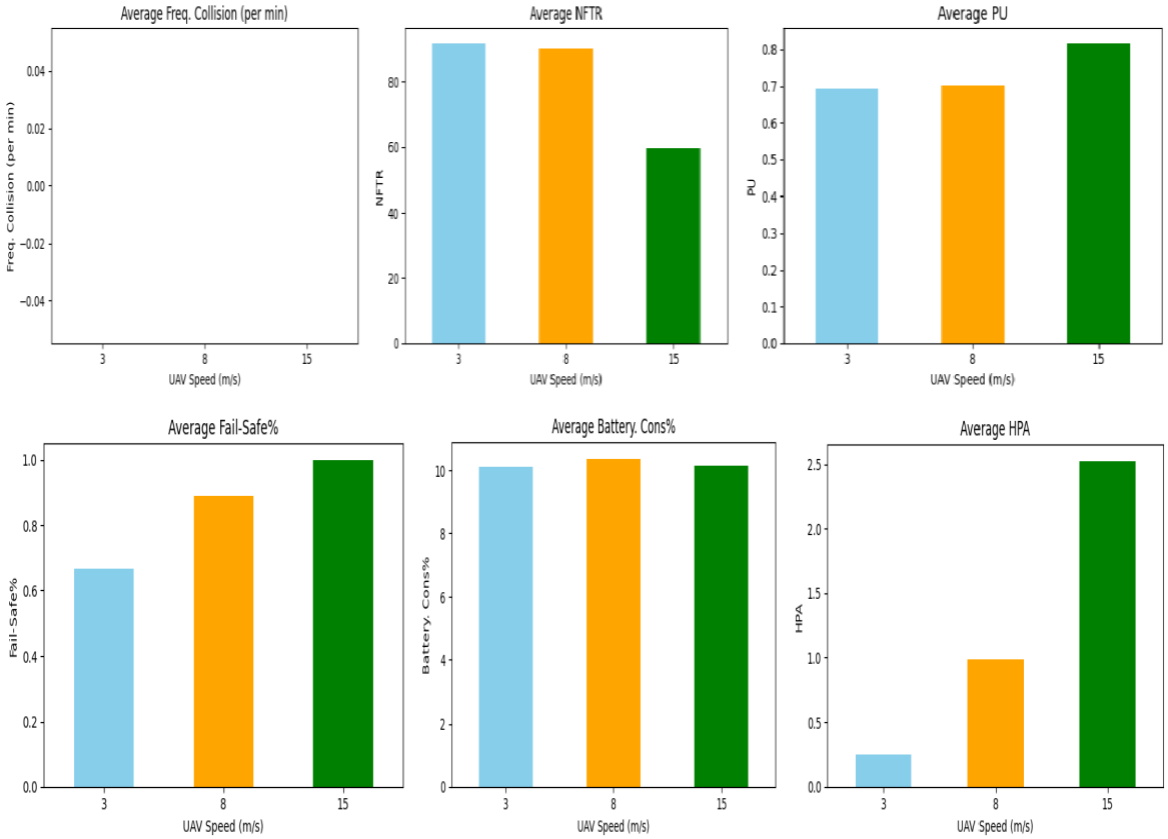


4. Gyroscope with light breeze wind:

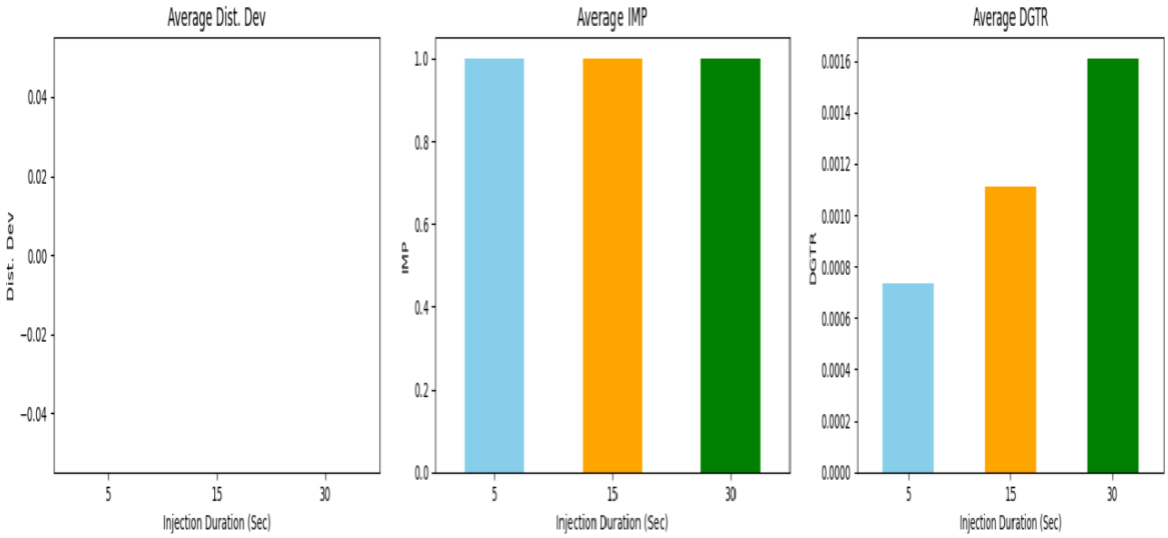
- **Impact of the different UAV speeds:**

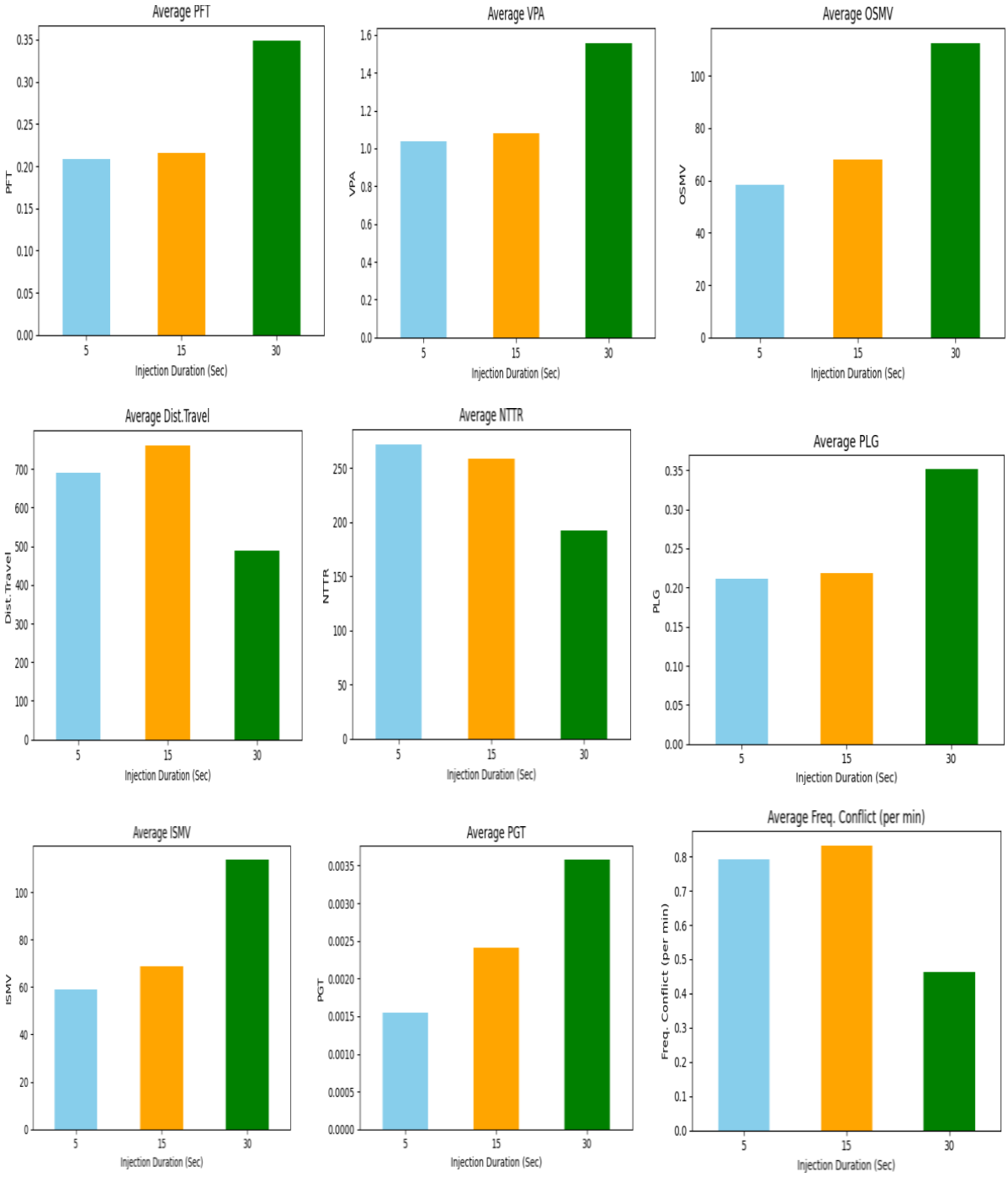


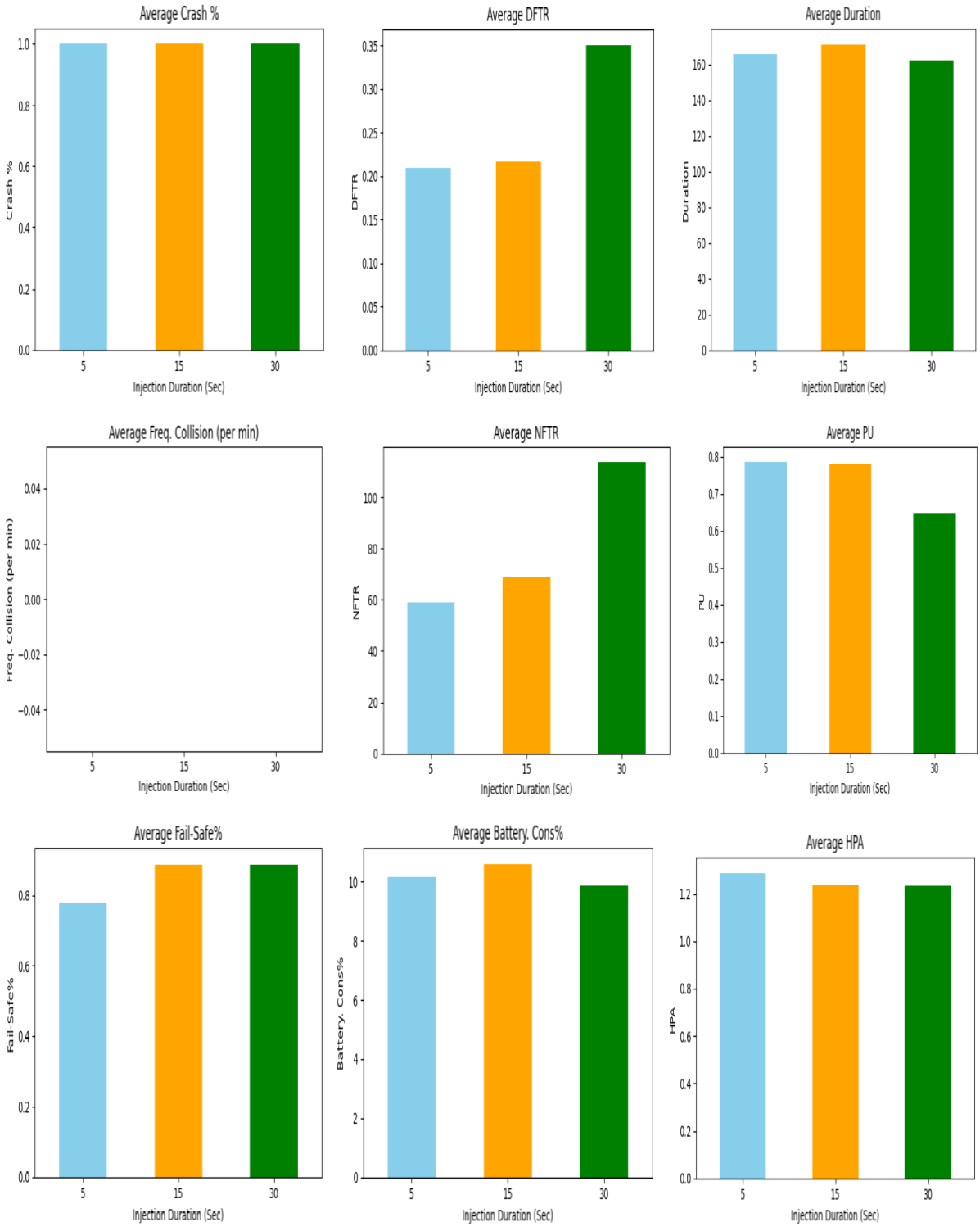

Average PFT
PFT
UAV Speed (m/s)
Average VPA
VPA
UAV Speed (m/s)
Average OSMV
OSMV
UAV Speed (m/s)
Average Dist.Travel
Dist.Travel
UAV Speed (m/s)
Average NTTR
NTTR
UAV Speed (m/s)
Average PLG
PLG
UAV Speed (m/s)
Average ISMV
ISMV
UAV Speed (m/s)
Average PGT
PGT
UAV Speed (m/s)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
UAV Speed (m/s)
Average Crash %
Crash %
UAV Speed (m/s)
Average DFTR
DFTR
UAV Speed (m/s)
Average Duration
Duration
UAV Speed (m/s)



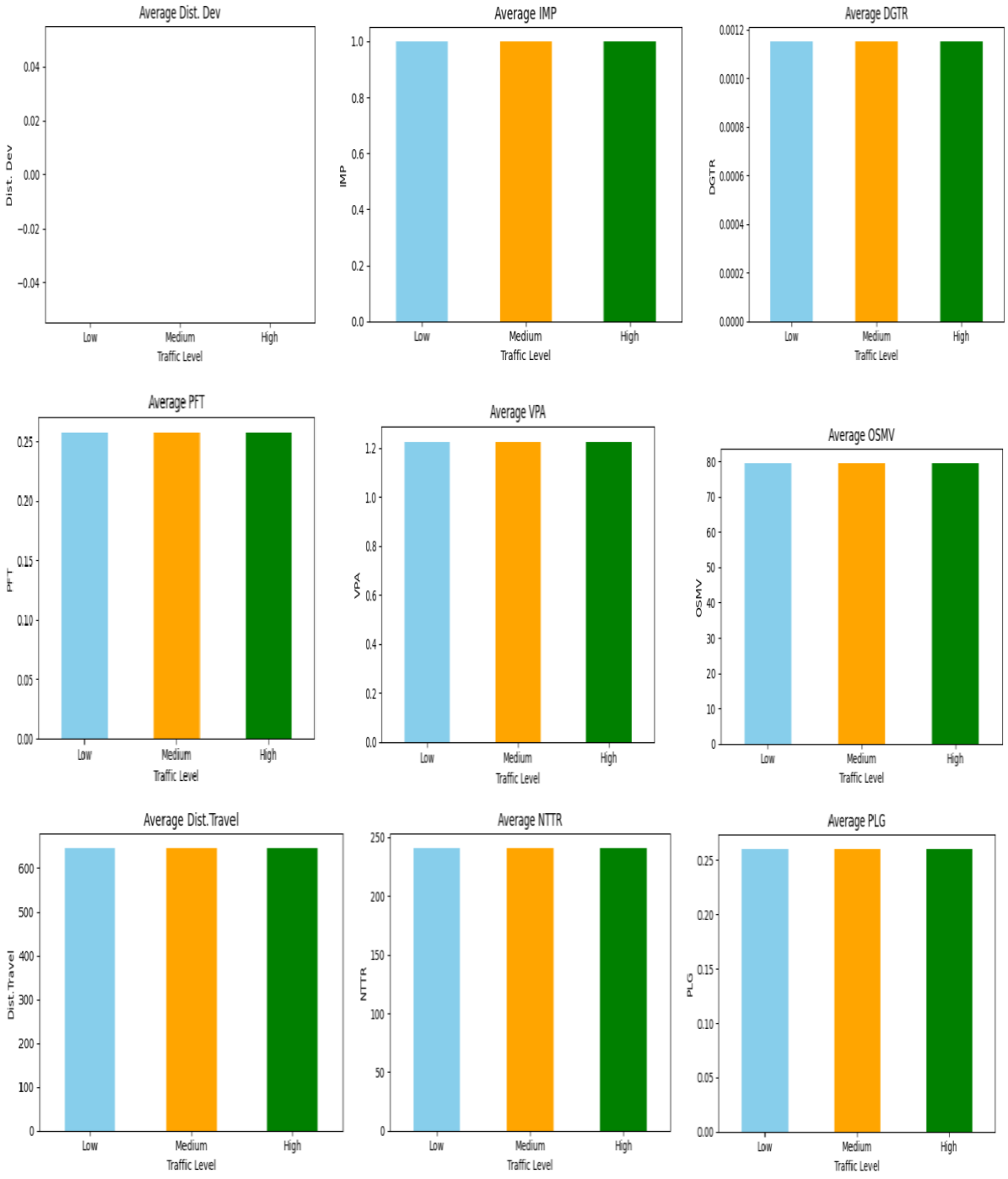
- **Impact of the different injection durations:**

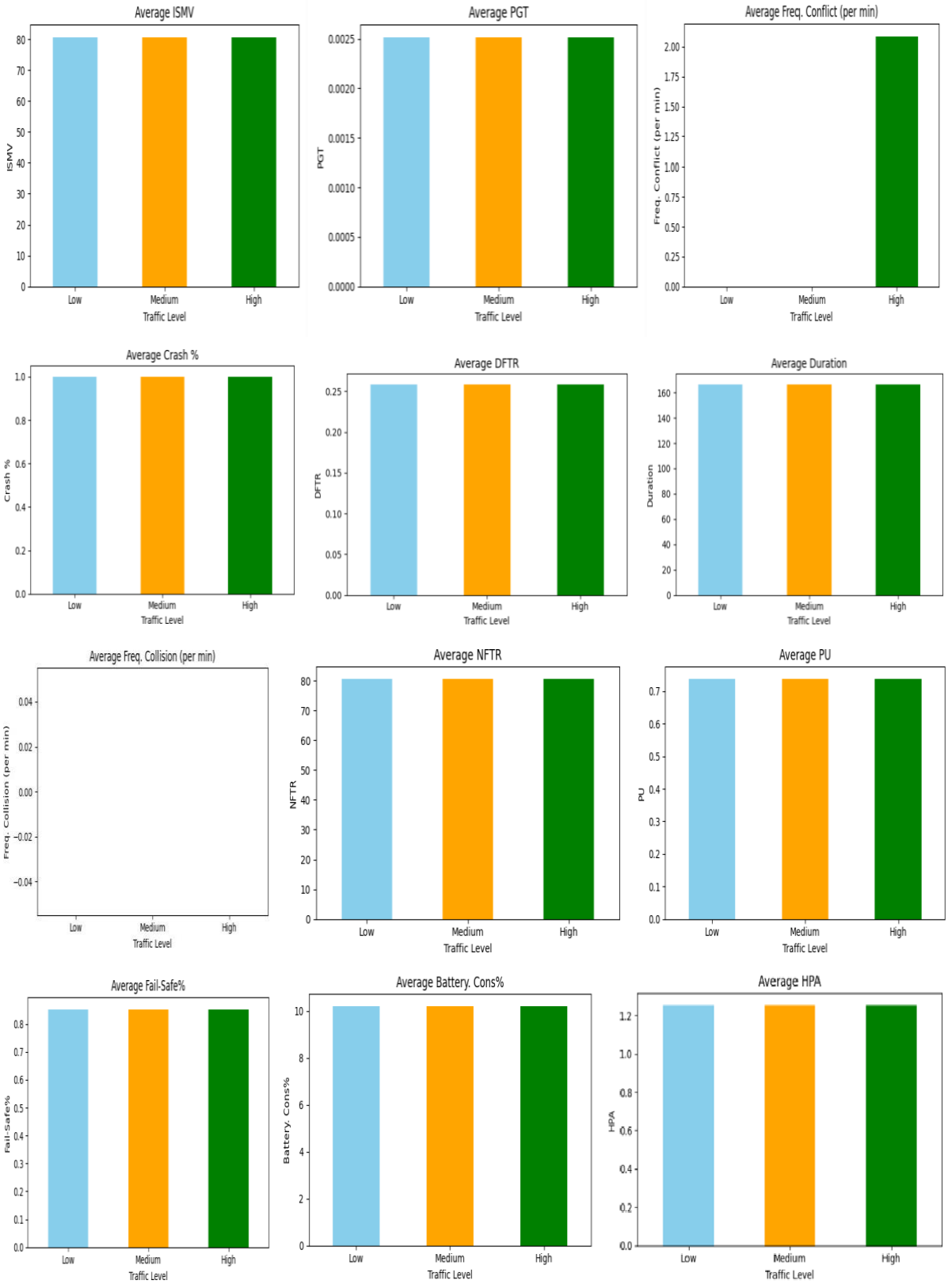



Average PFT
PFT
Injection Duration (Sec)
Average VPA
VPA
Injection Duration (Sec)
Average OSMV
OSMV
Injection Duration (Sec)
Average Dist.Travel
Dist.Travel
Injection Duration (Sec)
Average NTTR
NTTR
Injection Duration (Sec)
Average PLG
PLG
Injection Duration (Sec)
Average ISMV
ISMV
Injection Duration (Sec)
Average PGT
PGT
Injection Duration (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Injection Duration (Sec)

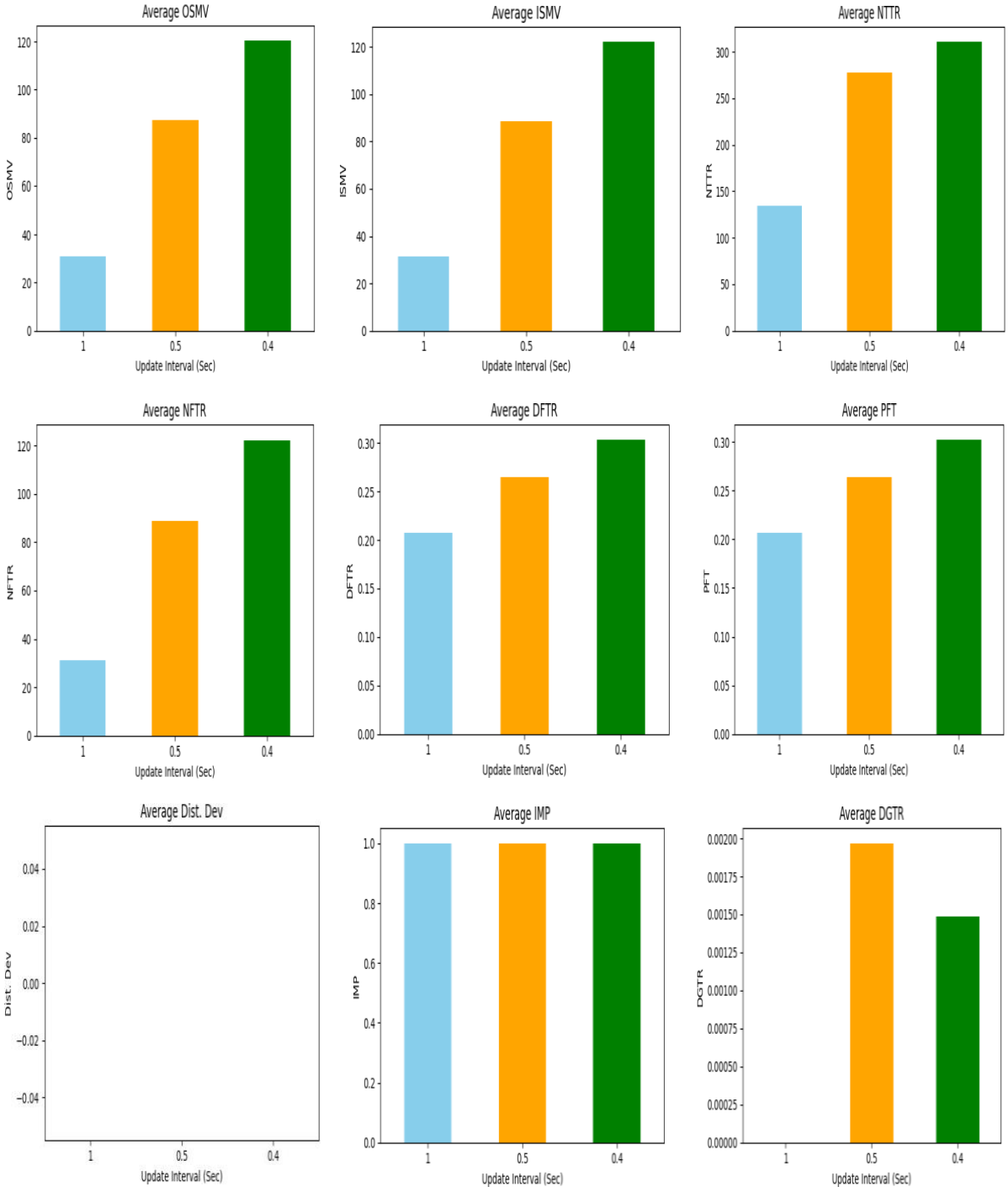

Average Crash %
Crash %
Injection Duration (Sec)
Average DFTR
DFTR
Injection Duration (Sec)
Average Duration
Duration
Injection Duration (Sec)
Average Freq. Collision (per min)
Freq. Collision (per min)
Injection Duration (Sec)
Average NFTR
NFTR
Injection Duration (Sec)
Average PU
PU
Injection Duration (Sec)
Average Fail-Safe%
Fail-Safe%
Injection Duration (Sec)
Average Battery. Cons%
Battery. Cons%
Injection Duration (Sec)
Average HPA
HPA
Injection Duration (Sec)

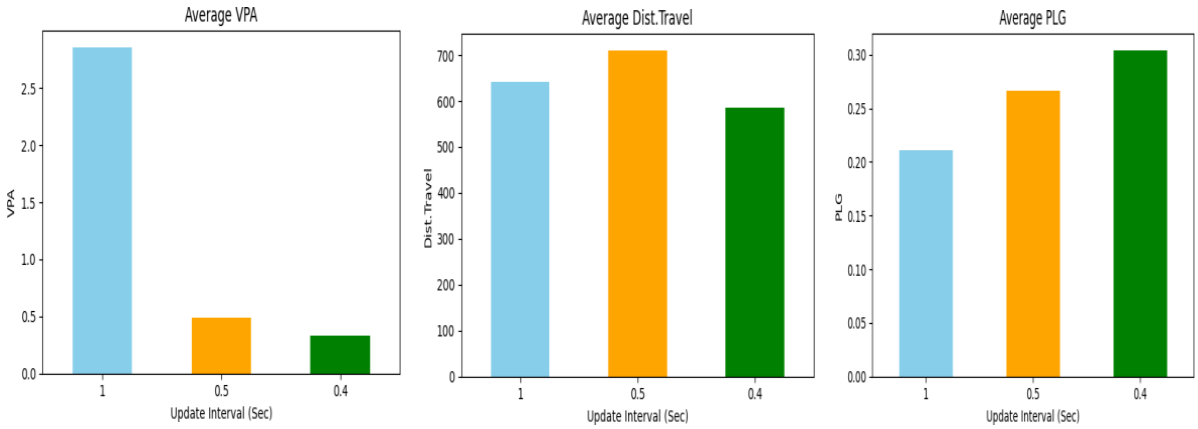
- **Impact of different traffic levels:**




Average ISMV
ISMV
Traffic Level
Low
Medium
High
Average PGT
PGT
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Average Crash %
Crash %
Average DFTR
DFTR
Average Duration
Duration
Average Freq. Collision (per min)
Freq. Collision (per min)
Average NFTR
NFTR
Average PU
PU
Average Fail-Safe%
Fail-Safe%
Average Battery. Cons%
Battery. Cons%
Average HPA
HPA

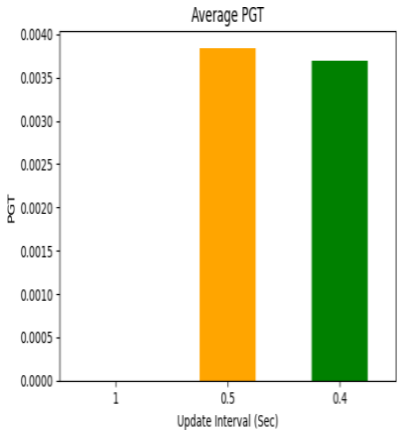
- **Impact of different update intervals:**

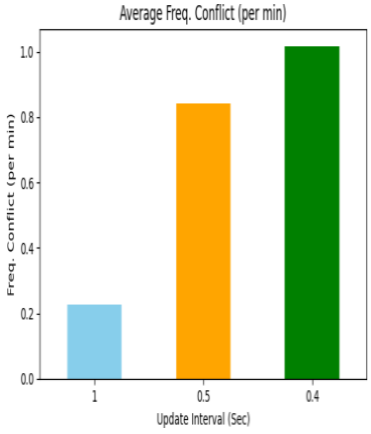


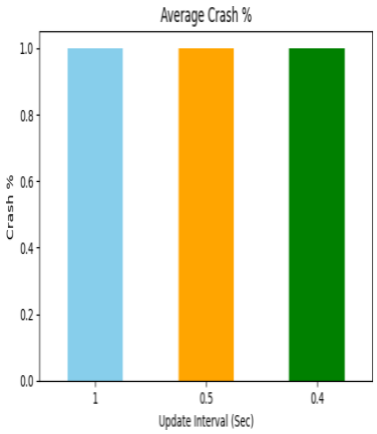

Average VPA
VPA
Update Interval (Sec)
1
0.5
0.4

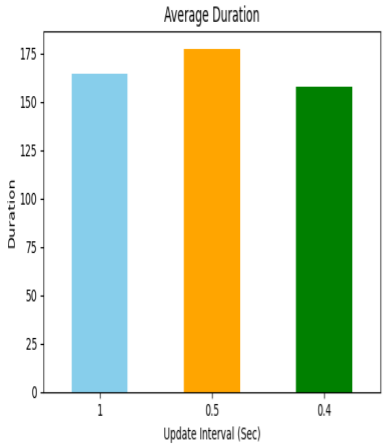
Average Dist.Travel
Dist.Travel
Update Interval (Sec)
1
0.5
0.4

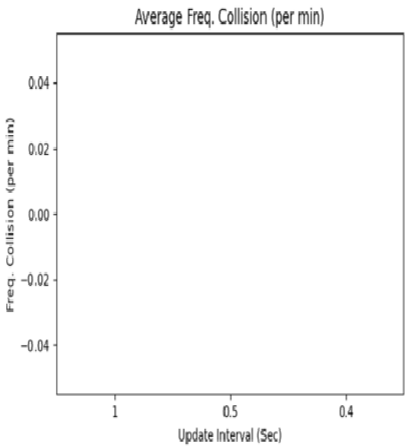
Average PLG
PLG
Update Interval (Sec)
1
0.5
0.4

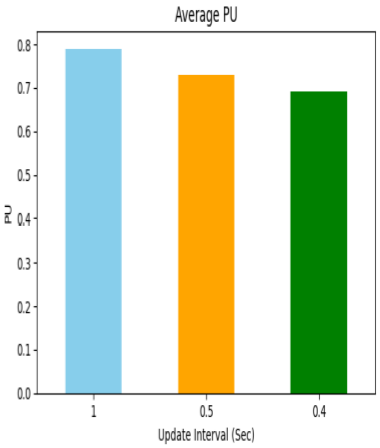

Average PGT
PGT
Update Interval (Sec)
1
0.5
0.4

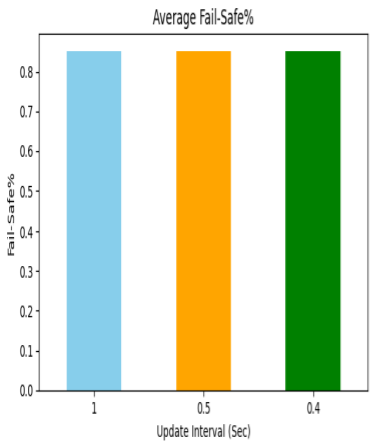

Average Freq. Conflict (per min)
Freq. Conflict (per min)
Update Interval (Sec)
1
0.5
0.4

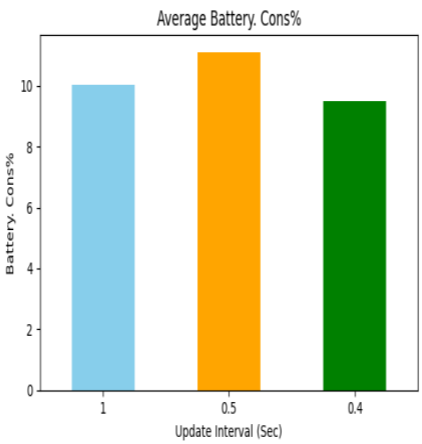

Average Crash %
Crash %
Update Interval (Sec)
1
0.5
0.4

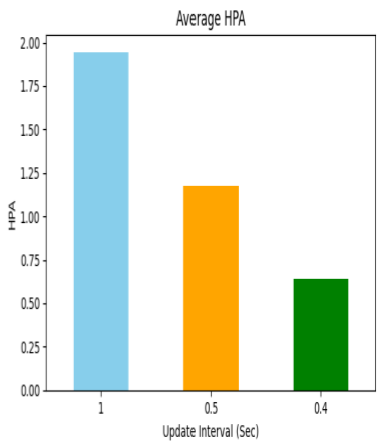

Average Duration
Duration
Update Interval (Sec)
1
0.5
0.4


Average Freq. Collision (per min)
Freq. Collision (per min)
Update Interval (Sec)
1
0.5
0.4


Average PU
PU
Update Interval (Sec)
1
0.5
0.4

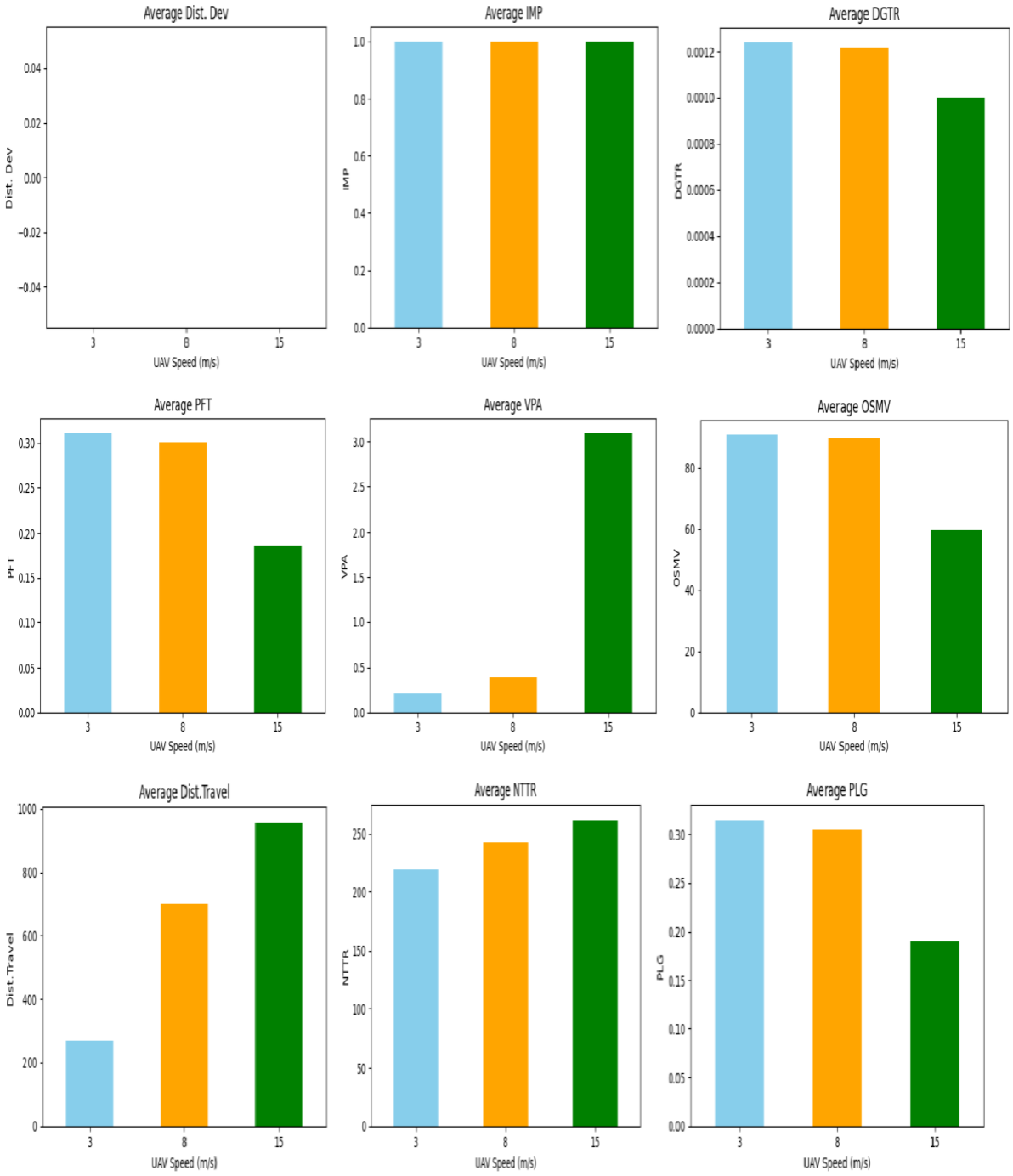

Average Fail-Safe%
Fail-Safe%
Update Interval (Sec)
1
0.5
0.4

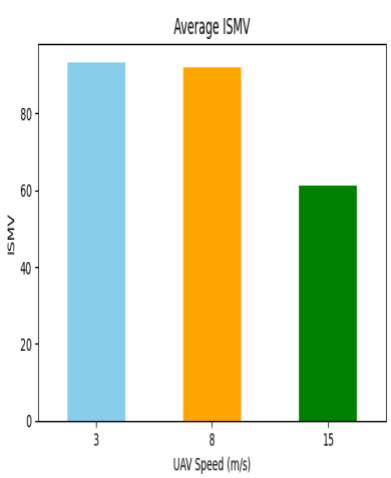

Average Battery. Cons%
Battery. Cons%
Update Interval (Sec)
1
0.5
0.4

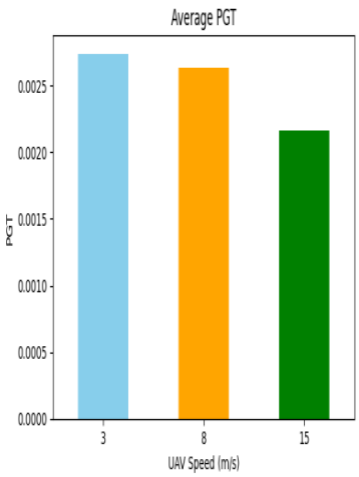

Average HPA
HPA
Update Interval (Sec)
1
0.5
0.4

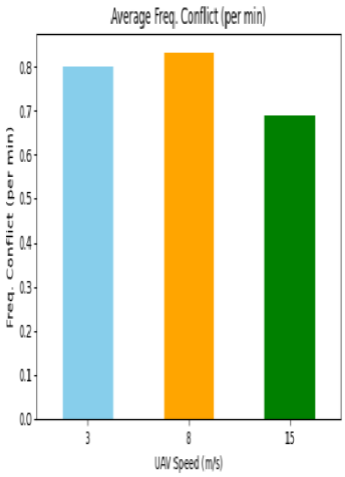
5. Gyroscope with Moderate breeze wind:

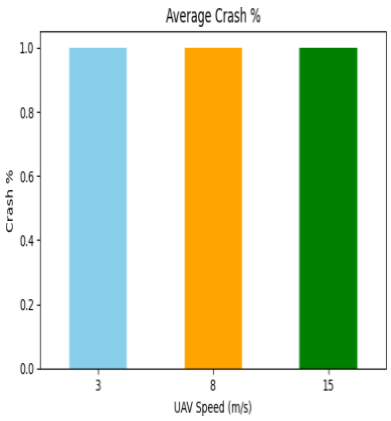
- **Impact pf different UAV speeds:**

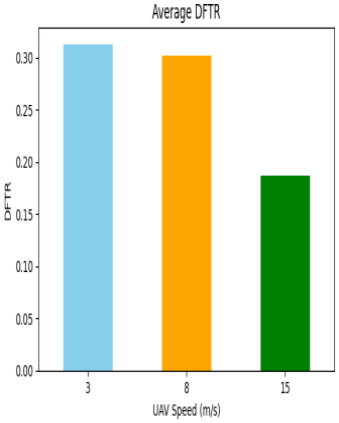


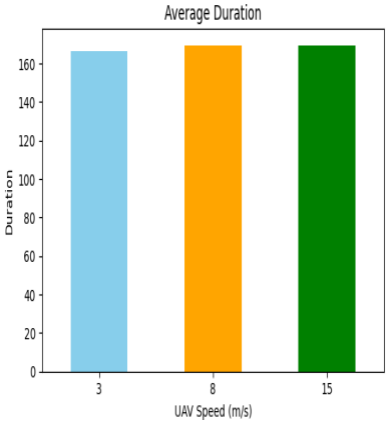

Average ISMV
ISMV
UAV Speed (m/s)

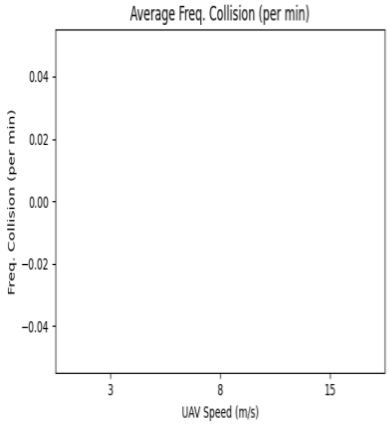

Average PGT
PGT
UAV Speed (m/s)

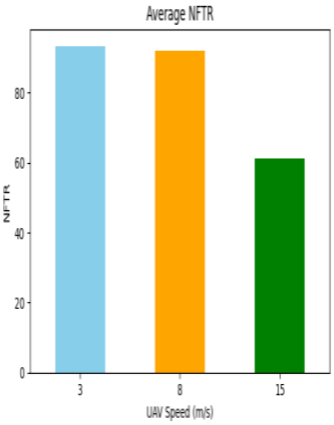

Average Freq. Conflict (per min)
Freq. Conflict (per min)
UAV Speed (m/s)

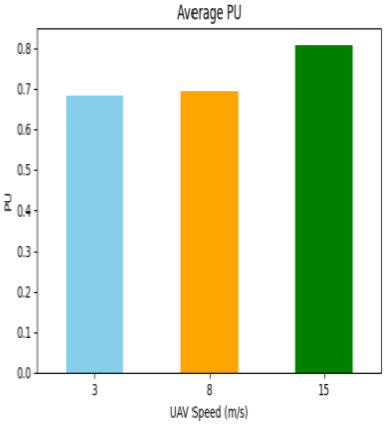

Average Crash %
Crash %
UAV Speed (m/s)

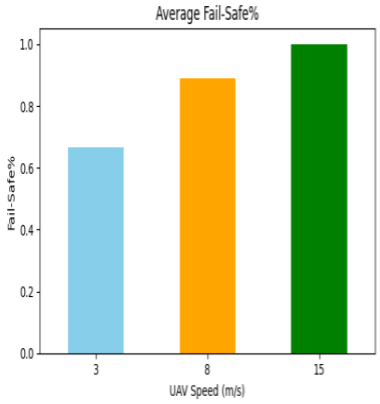

Average DFTR
DFTR
UAV Speed (m/s)

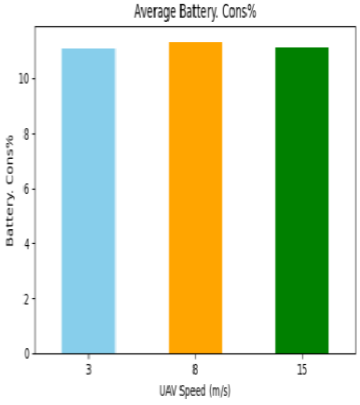

Average Duration
Duration
UAV Speed (m/s)

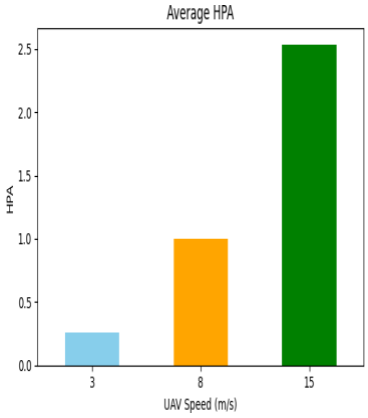

Average Freq. Collision (per min)
Freq. Collision (per min)
UAV Speed (m/s)


Average NFTR
NFTR
UAV Speed (m/s)

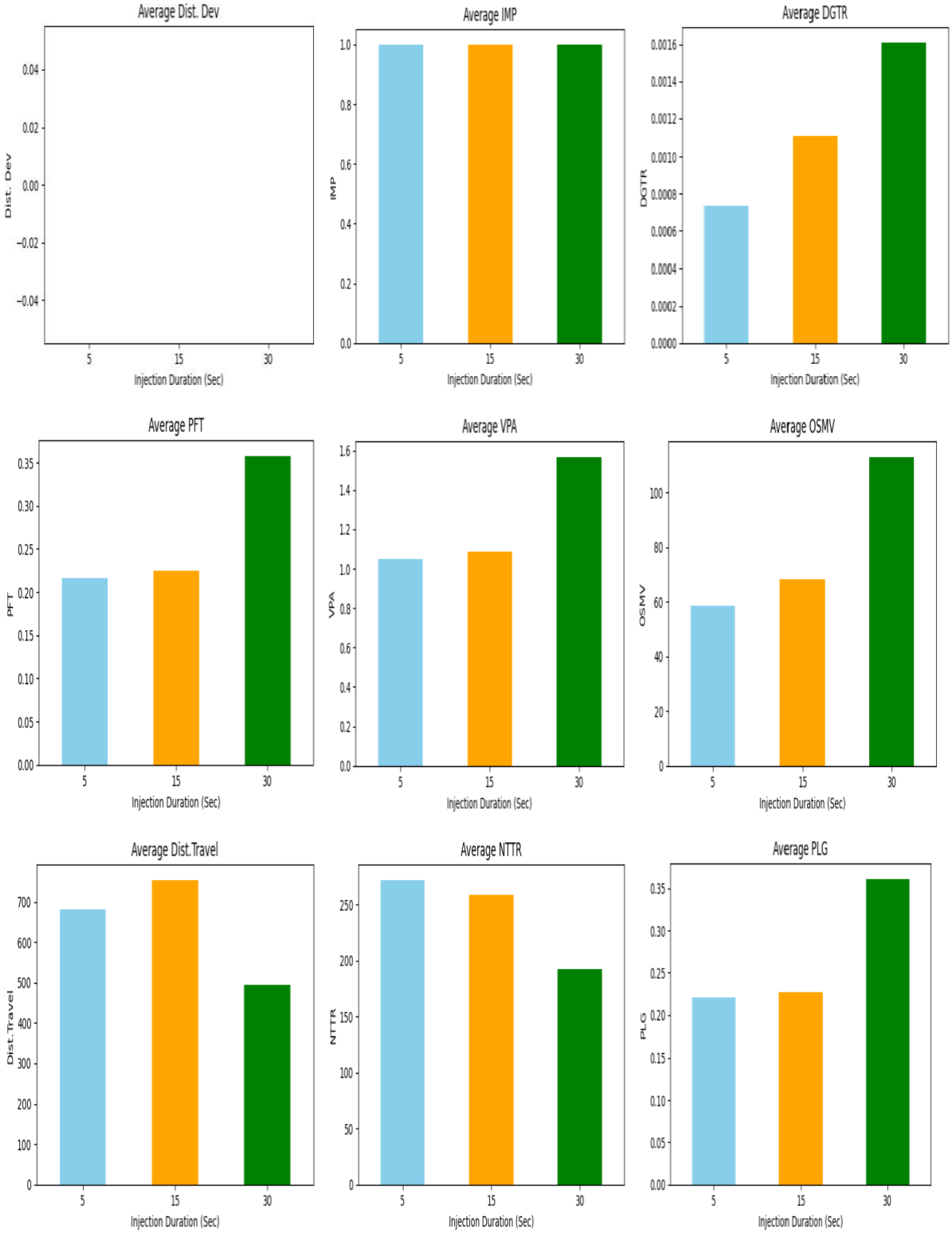

Average PU
PU
UAV Speed (m/s)

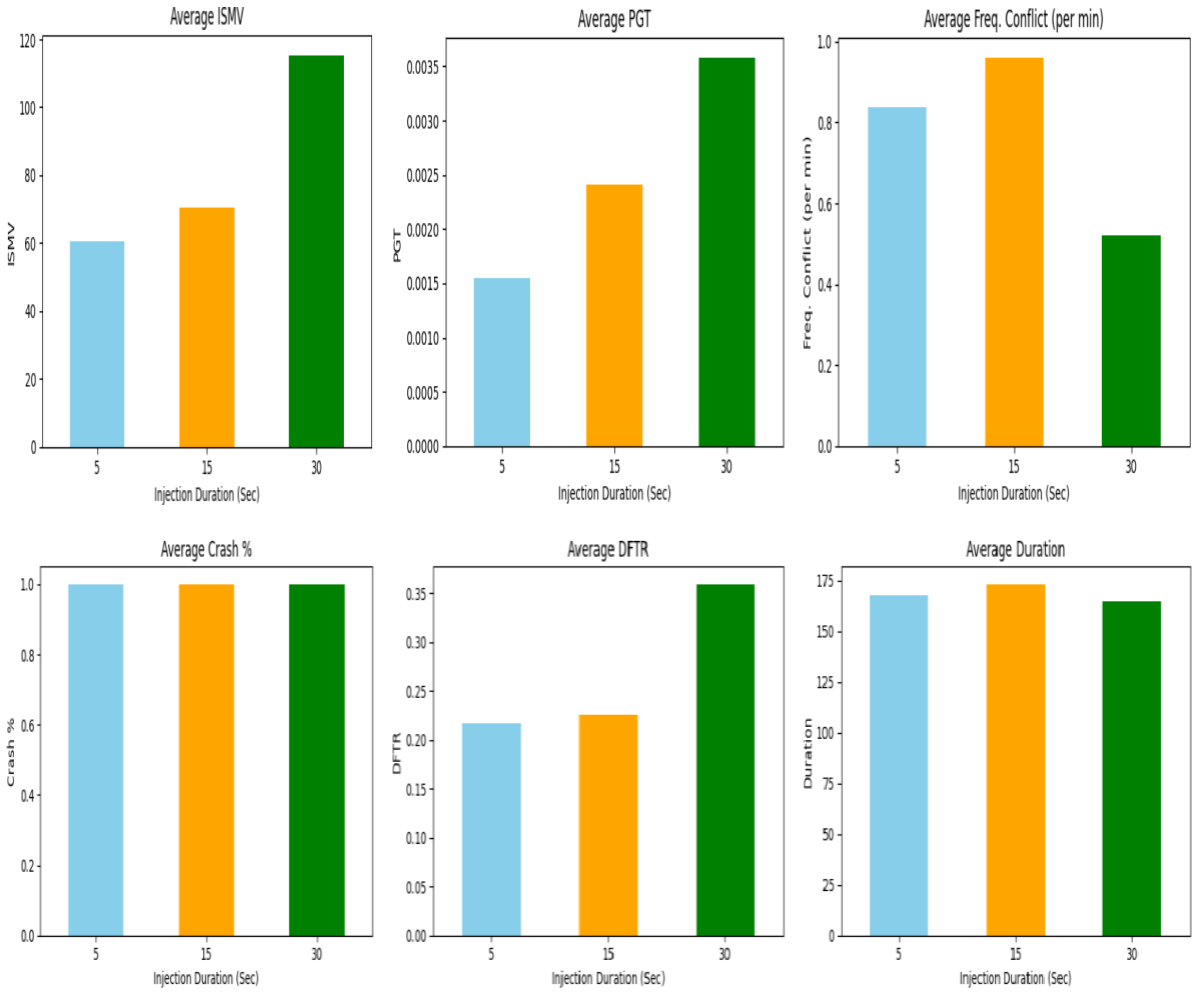

Average Fail-Safe%
Fail-Safe%
UAV Speed (m/s)

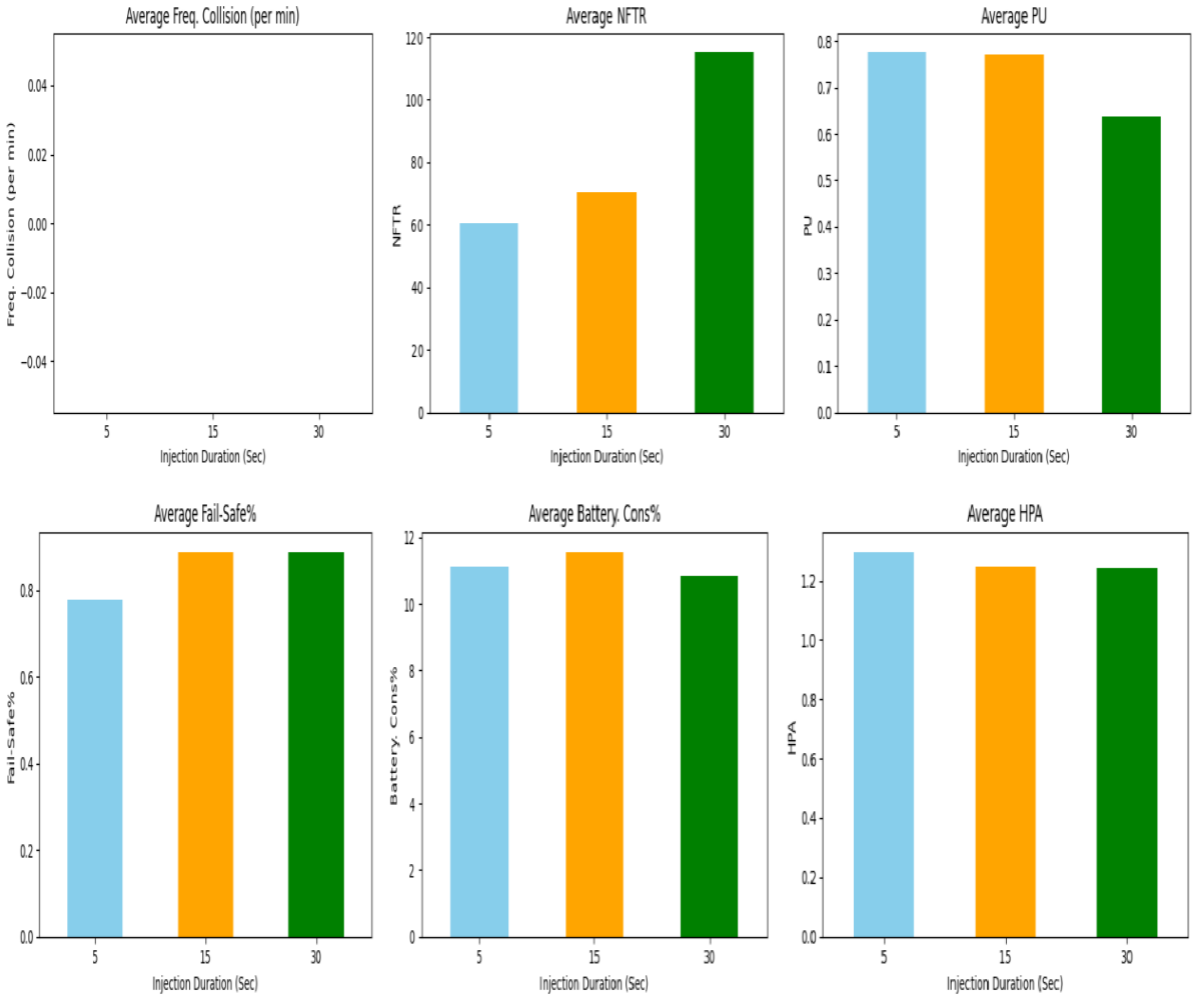

Average Battery. Cons%
Battery. Cons%
UAV Speed (m/s)


Average HPA
HPA
UAV Speed (m/s)

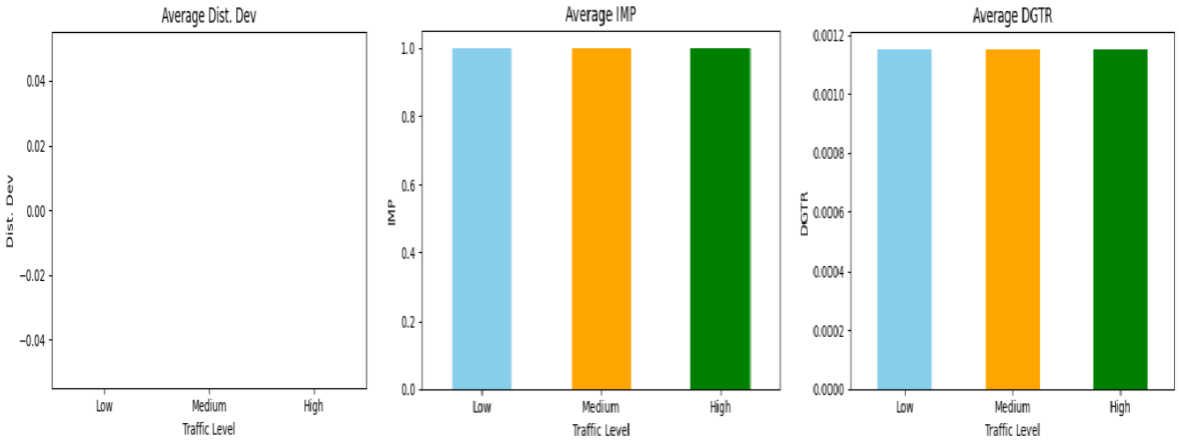
- **Impact of the different Injection durations:**

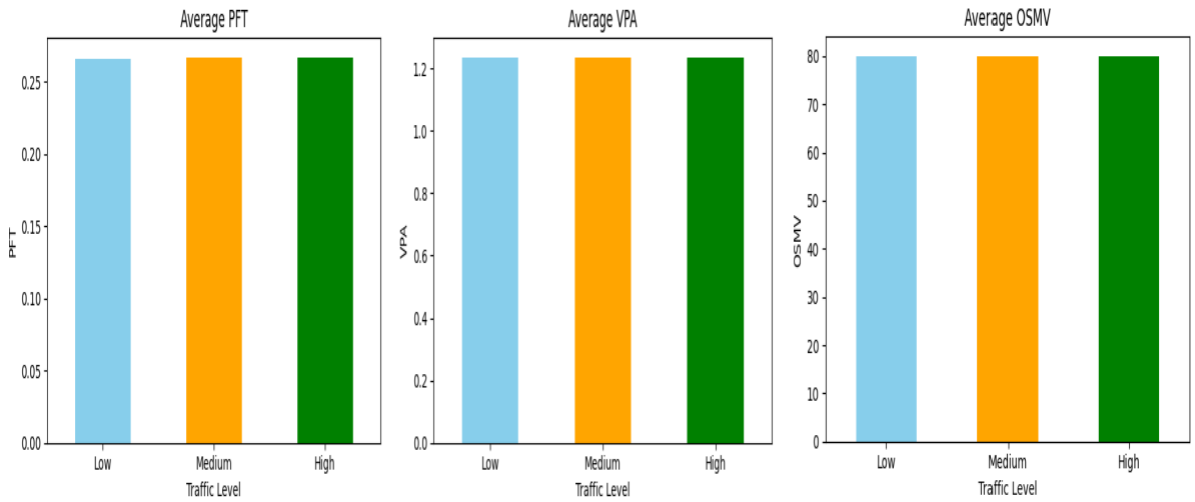



Average ISMV
ISMV
Injection Duration (Sec)
Average PGT
PGT
Injection Duration (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Injection Duration (Sec)
Average Crash %
Crash %
Injection Duration (Sec)
Average DFTR
DFTR
Injection Duration (Sec)
Average Duration
Duration
Injection Duration (Sec)



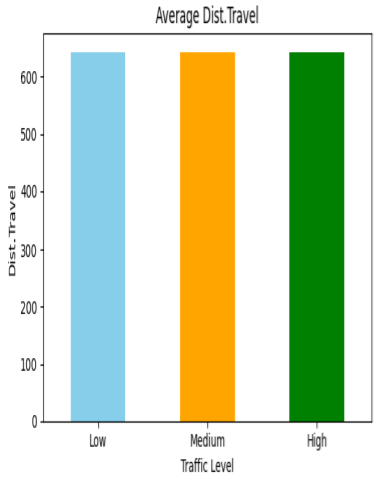
- **Impact of different Traffic Levels:**

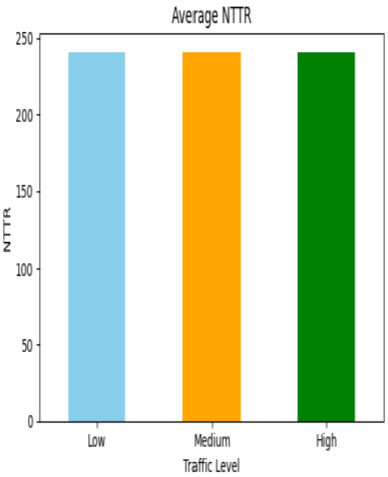


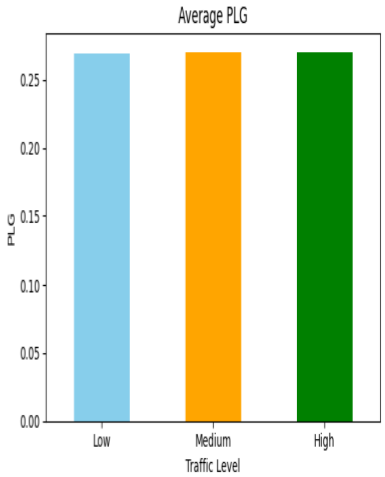

Average PFT
PFT
0.00
0.05
0.10
0.15
0.20
0.25
Low
Medium
High
Traffic Level

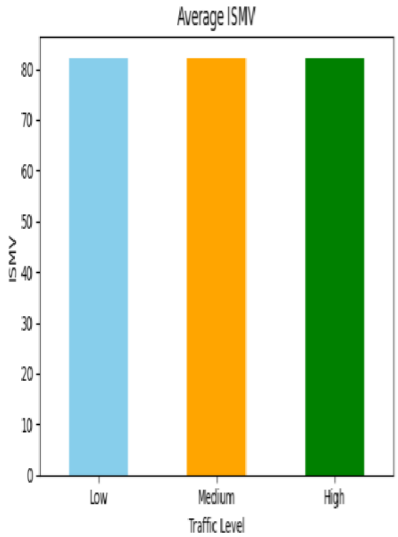
Average VPA
VPA
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Low
Medium
High
Traffic Level

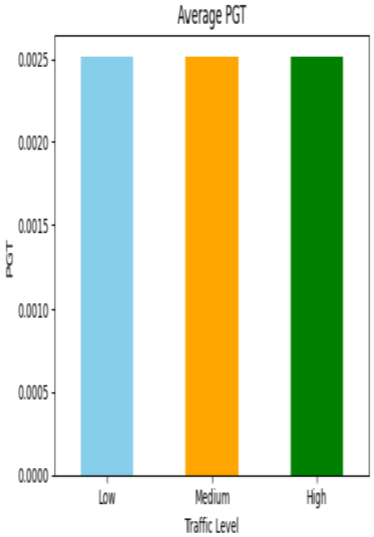
Average OSMV
OSMV
0
10
20
30
40
50
60
70
80
Low
Medium
High
Traffic Level

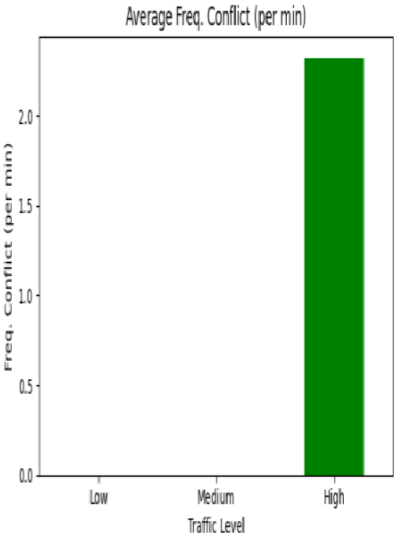

Average Dist.Travel
Dist.Travel
0
100
200
300
400
500
600
Low
Medium
High
Traffic Level

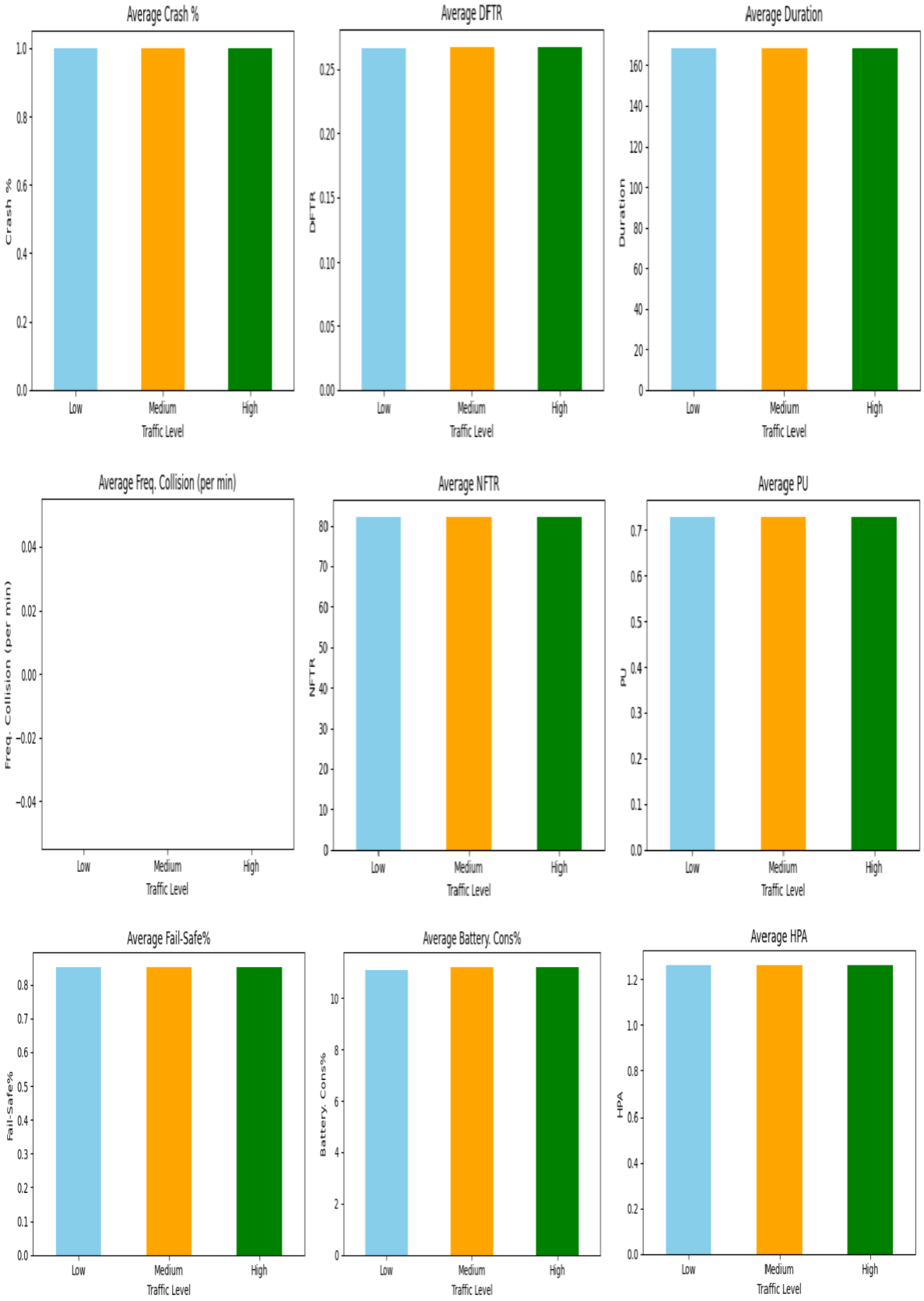

Average NTTR
NTTR
0
50
100
150
200
250
Low
Medium
High
Traffic Level


Average PLG
PLG
0.00
0.05
0.10
0.15
0.20
0.25
Low
Medium
High
Traffic Level

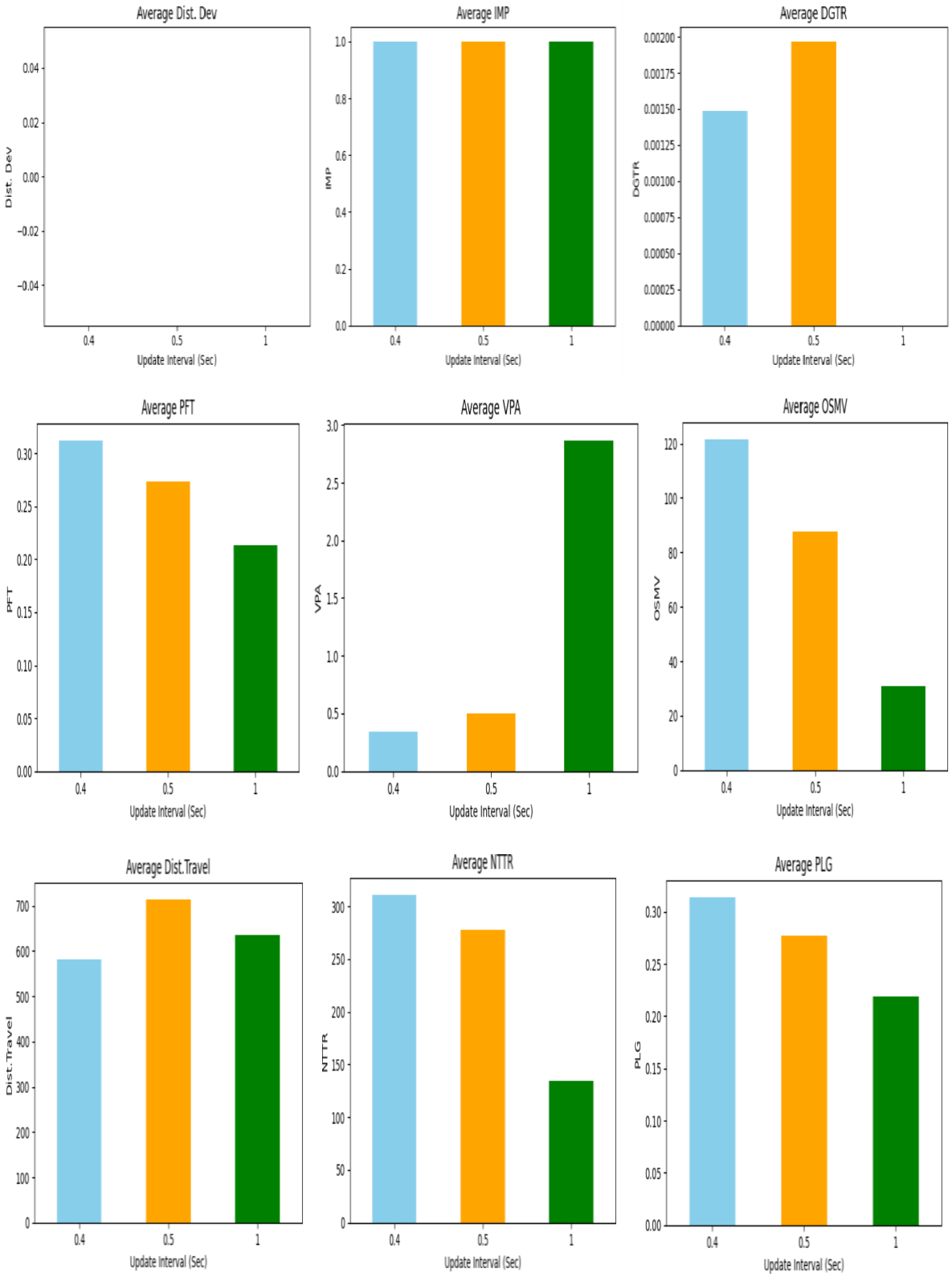

Average ISMV
ISMV
0
10
20
30
40
50
60
70
80
Low
Medium
High
Traffic Level

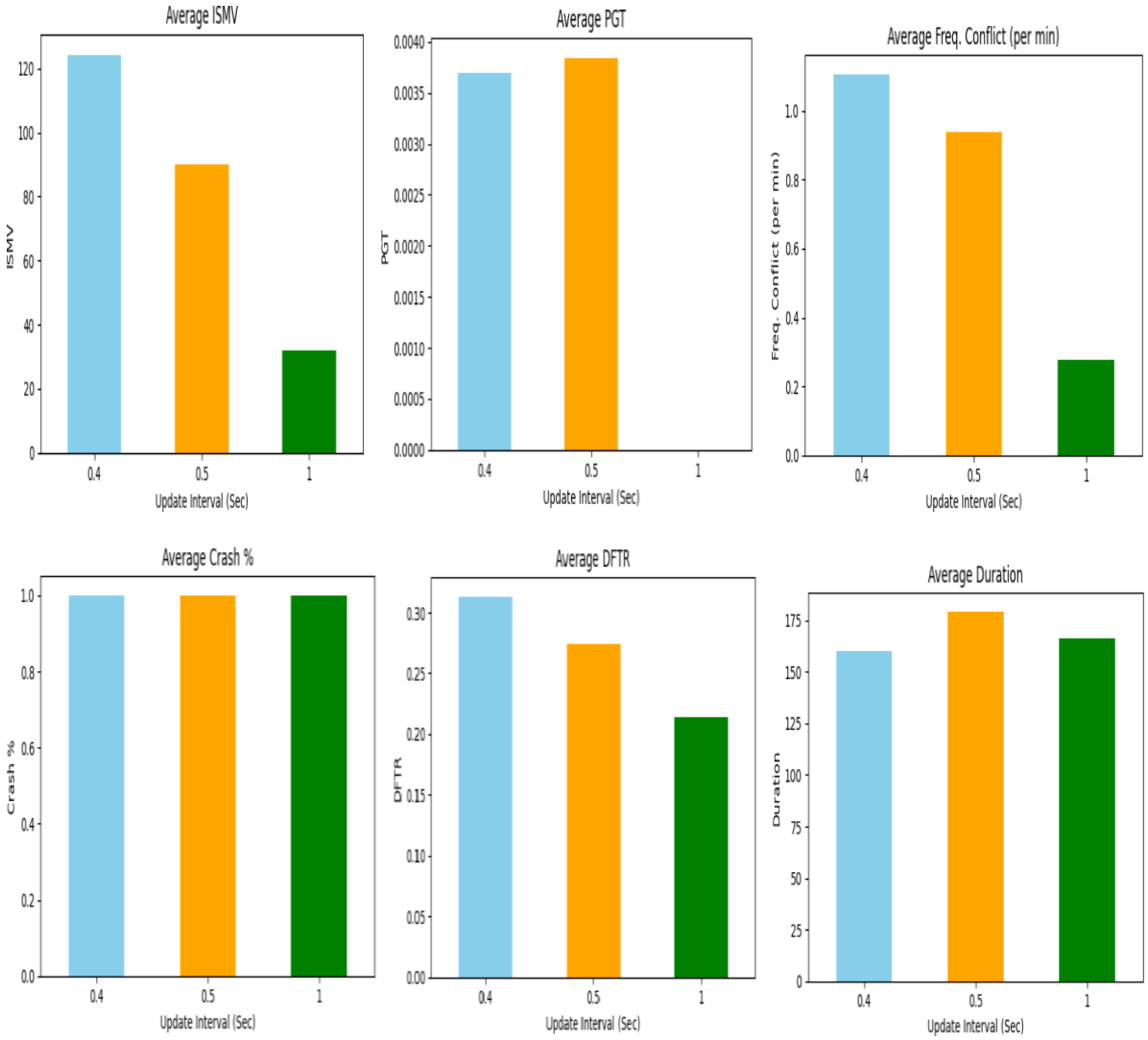

Average PGT
PGT
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
Low
Medium
High
Traffic Level

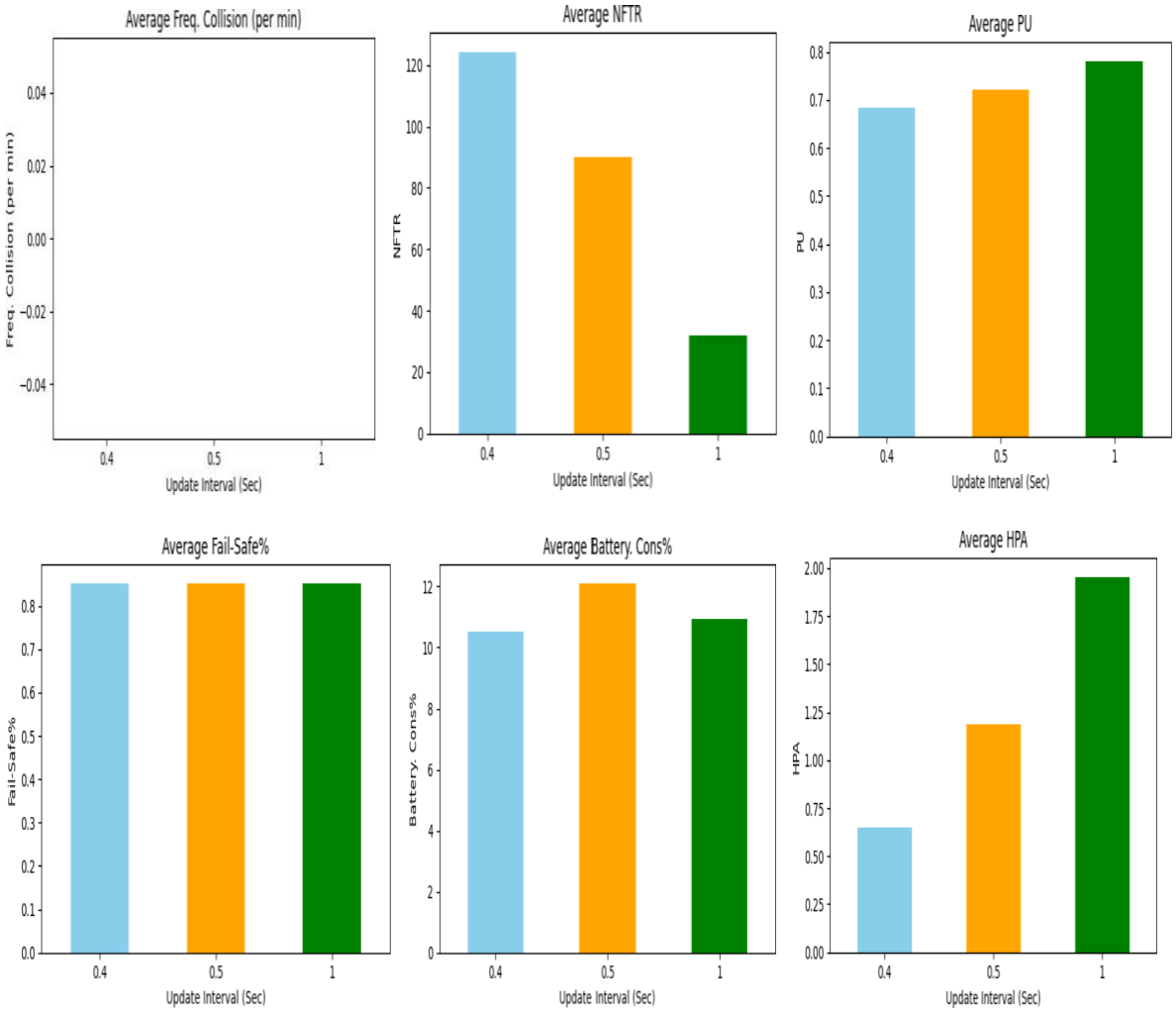

Average Freq. Conflict (per min)
Freq. Conflict (per min)
0.0
0.5
1.0
1.5
2.0
Low
Medium
High
Traffic Level


Average Crash %
Crash %
Low
Medium
High
Traffic Level
Average DFTR
DFTR
Average Duration
Duration
Average Freq. Collision (per min)
Freq. Collision (per min)
Average NFTR
NFTR
Average PU
PU
Average Fail-Safe%
Fail-Safe%
Average Battery. Cons%
Battery. Cons%
Average HPA
HPA

- **Impact of Different update Intervals:**

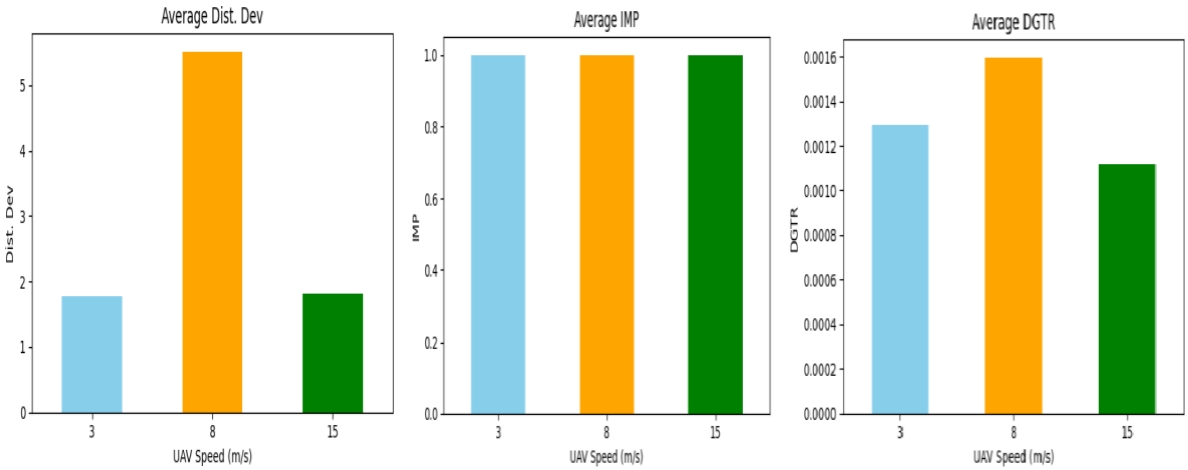


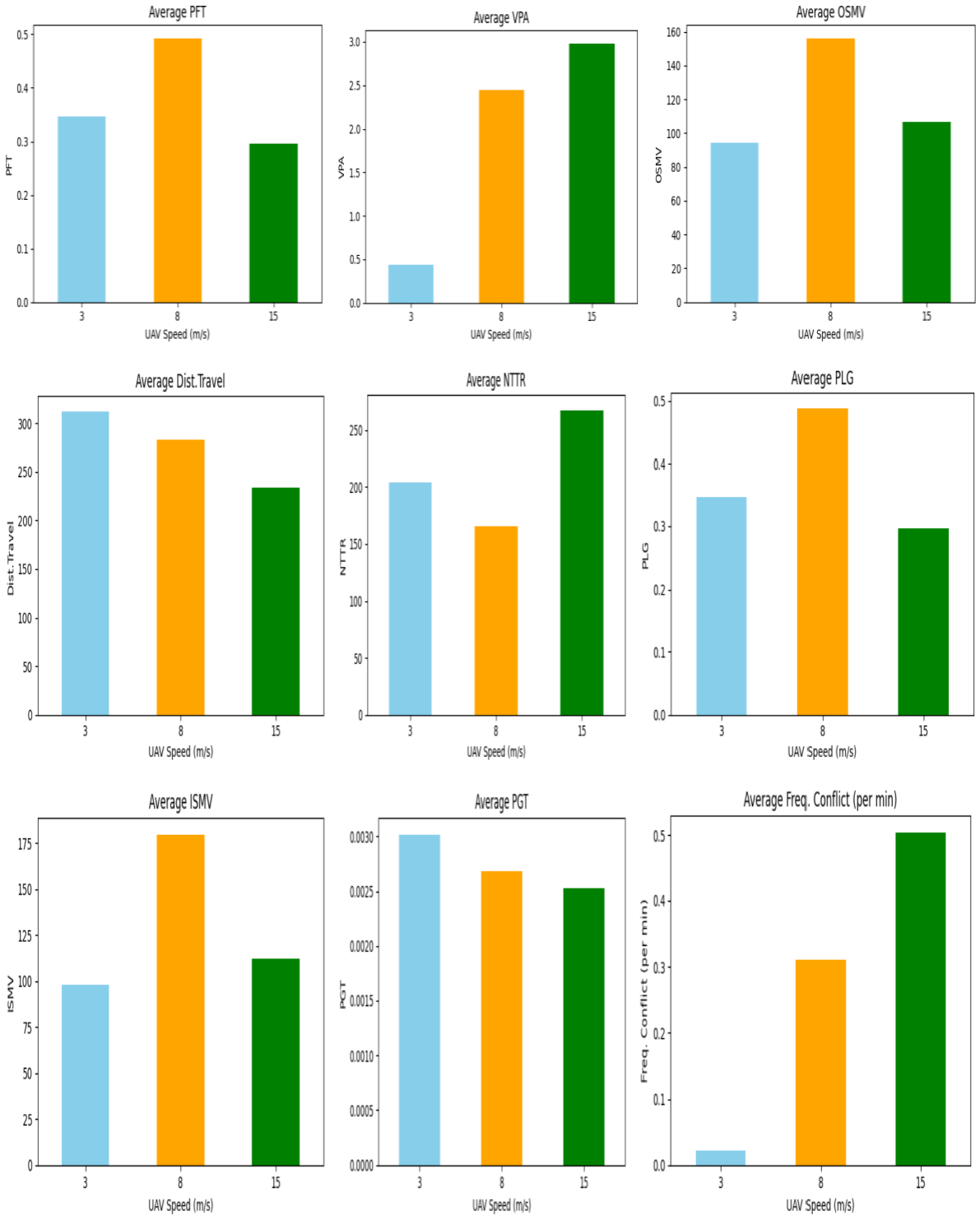

Average ISMV
ISMV
Update Interval (Sec)
Average PGT
PGT
Update Interval (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Update Interval (Sec)
Average Crash %
Crash %
Update Interval (Sec)
Average DFTR
DFTR
Update Interval (Sec)
Average Duration
Duration
Update Interval (Sec)

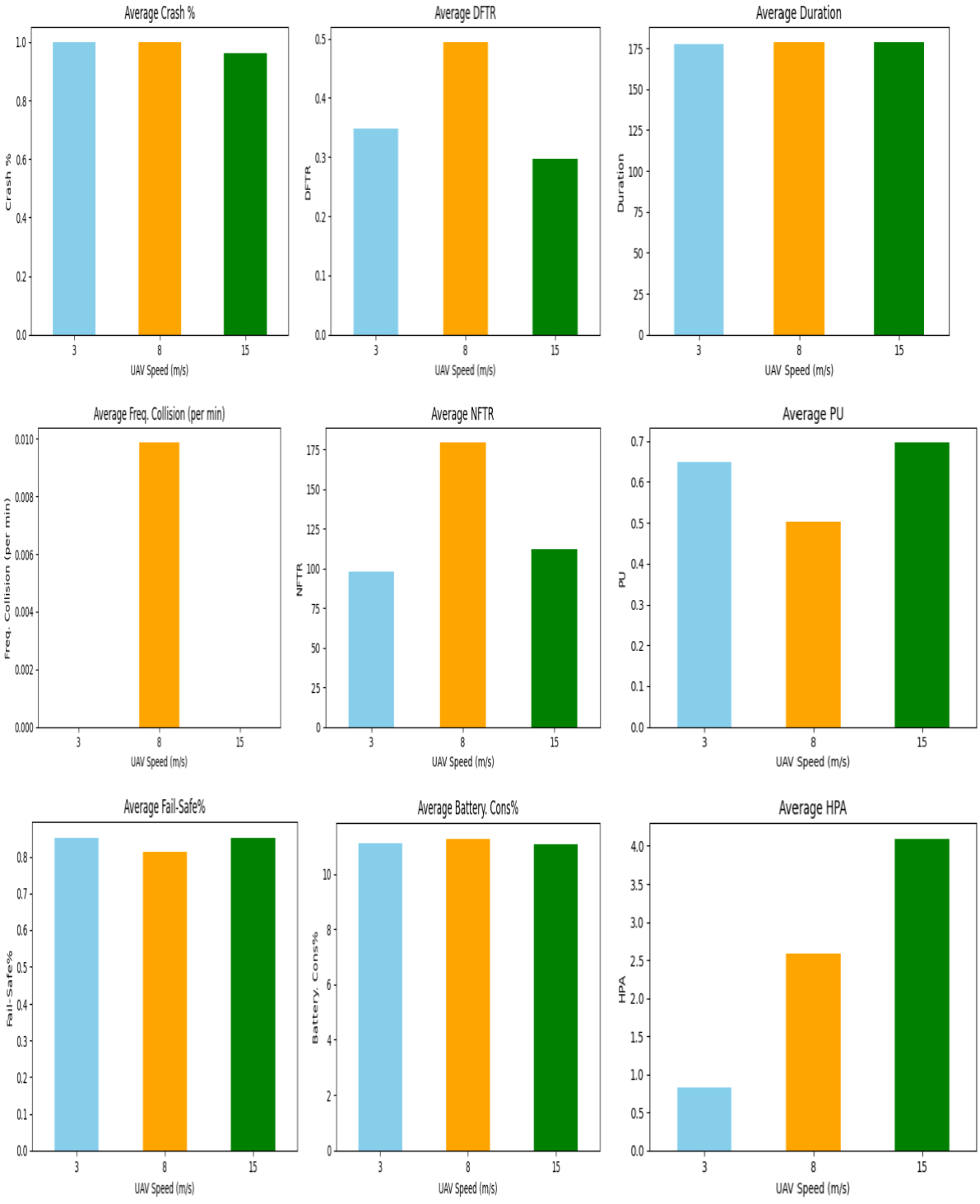


6. Gyroscope with near-gale wind:

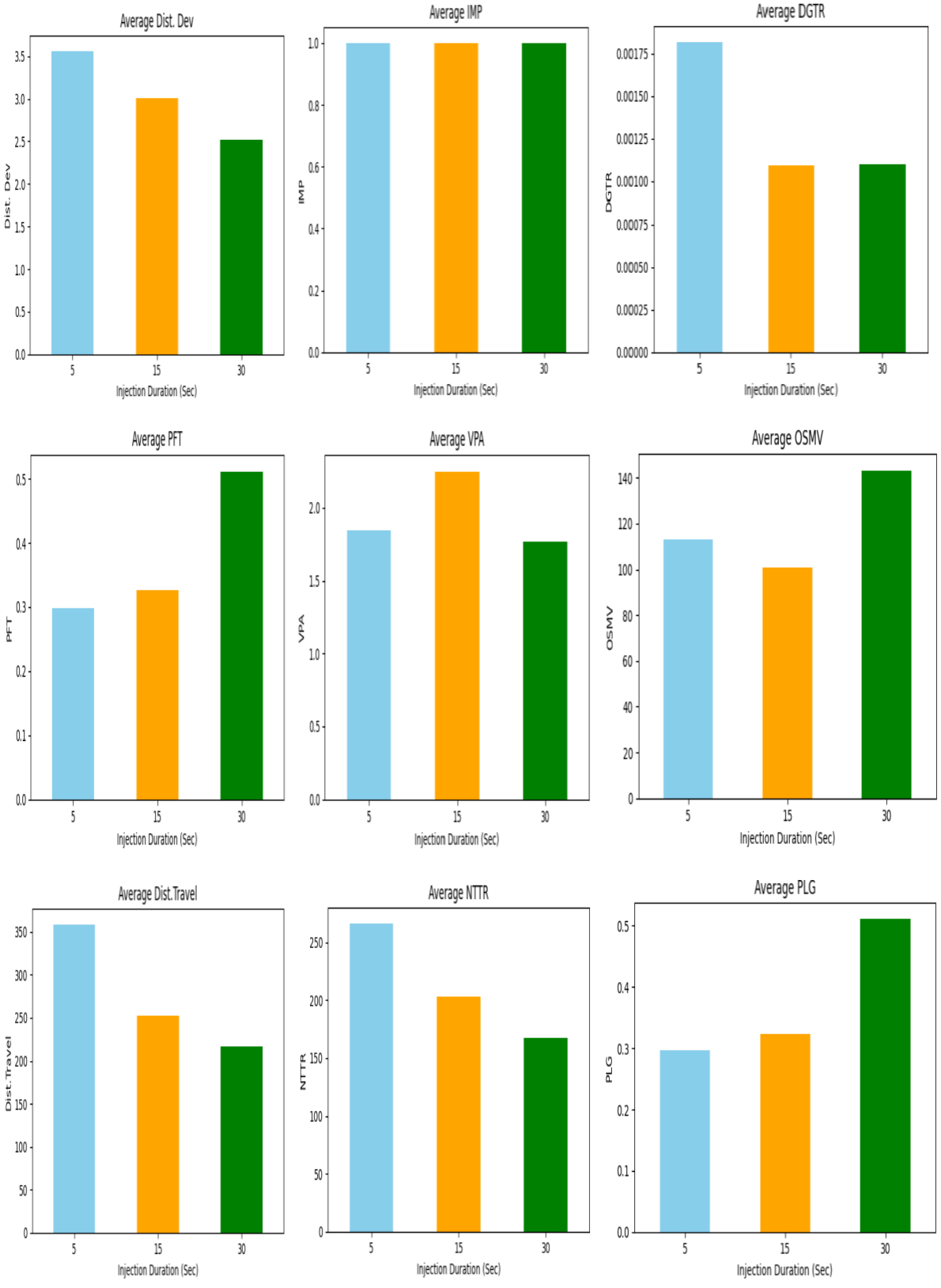
- **Impact of different UAV speeds:**

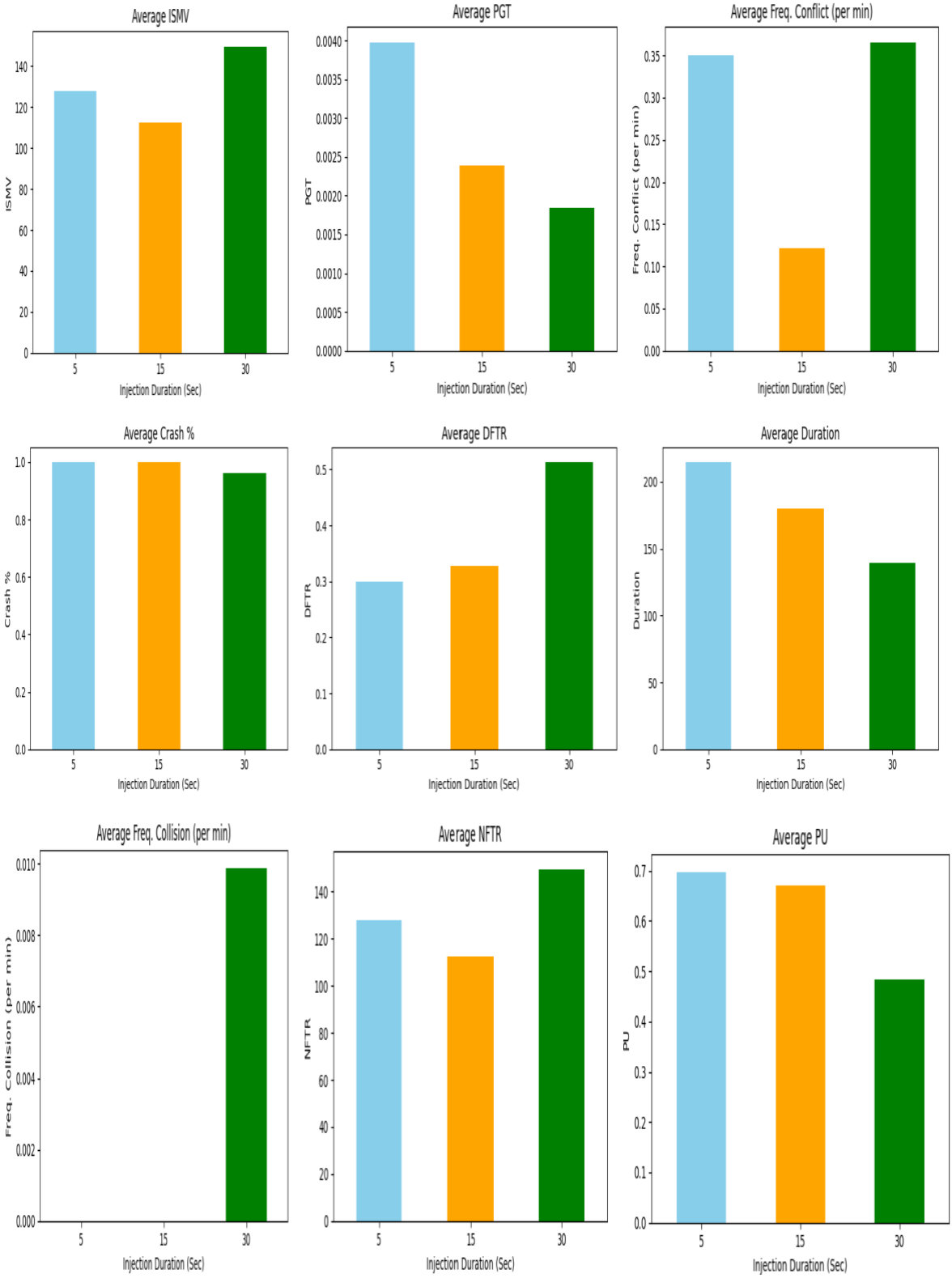


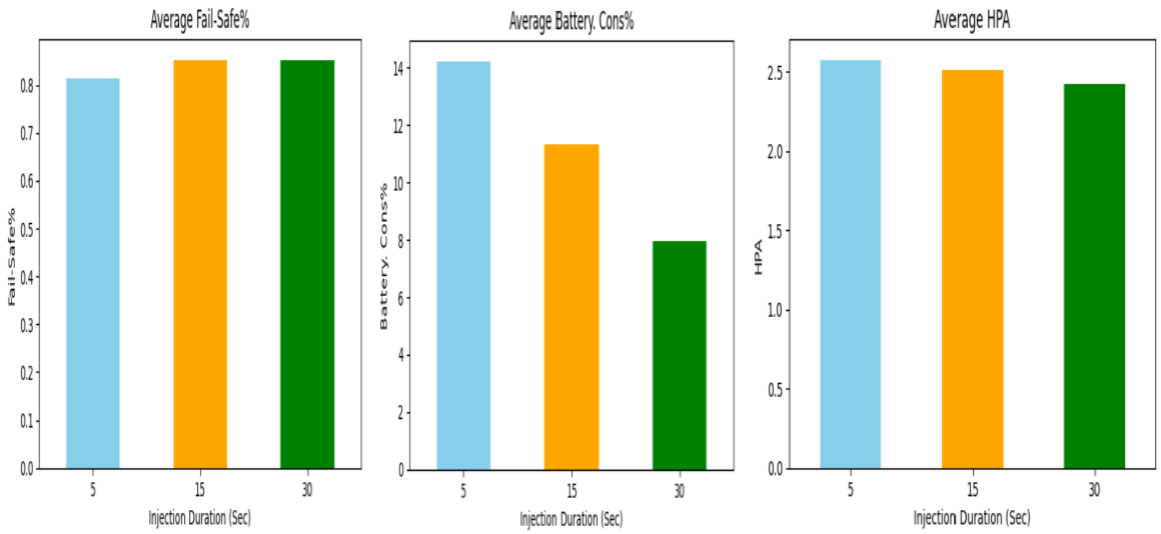

Average PFT
PFT
UAV Speed (m/s)
Average VPA
VPA
UAV Speed (m/s)
Average OSMV
OSMV
UAV Speed (m/s)
Average Dist.Travel
Dist.Travel
UAV Speed (m/s)
Average NTTR
NTTR
UAV Speed (m/s)
Average PLG
PLG
UAV Speed (m/s)
Average ISMV
ISMV
UAV Speed (m/s)
Average PGT
PGT
UAV Speed (m/s)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
UAV Speed (m/s)


Average Crash %
Crash %
UAV Speed (m/s)
Average DFTR
DFTR
UAV Speed (m/s)
Average Duration
Duration
UAV Speed (m/s)
Average Freq. Collision (per min)
Freq. Collision (per min)
UAV Speed (m/s)
Average NFTR
NFTR
UAV Speed (m/s)
Average PU
PU
UAV Speed (m/s)
Average Fail-Safe%
Fail-Safe%
UAV Speed (m/s)
Average Battery. Cons%
Battery. Cons%
UAV Speed (m/s)
Average HPA
HPA
UAV Speed (m/s)

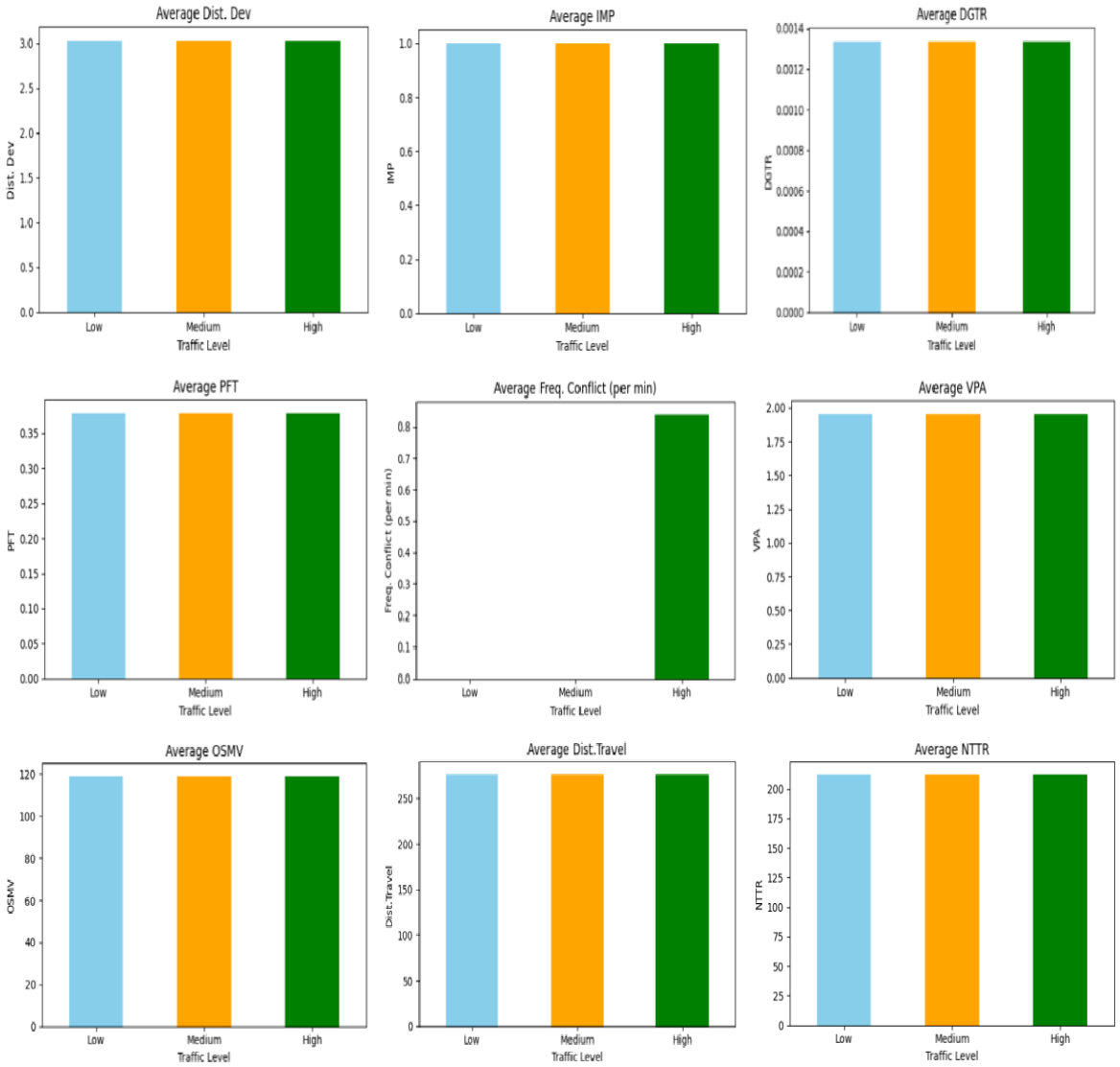
- **Impact of different Injection durations:**

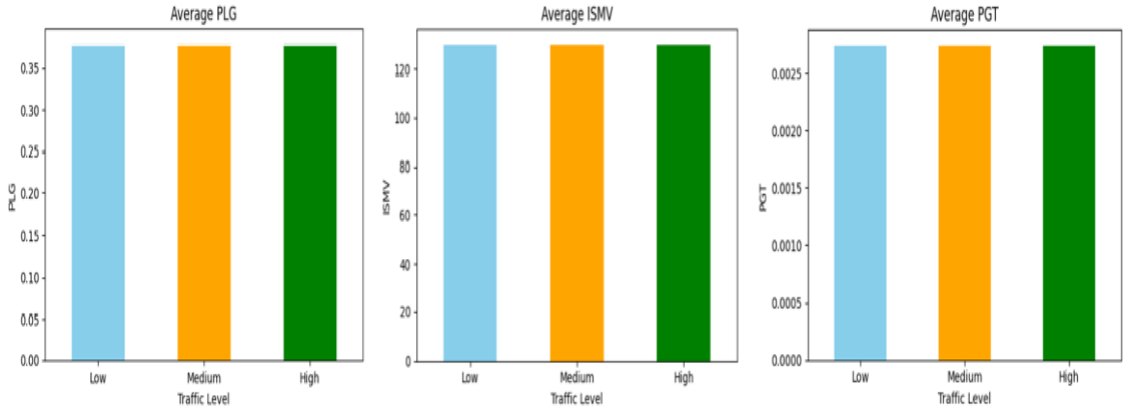



Average ISMV
ISMV
Injection Duration (Sec)
Average PGT
PGT
Injection Duration (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Injection Duration (Sec)
Average Crash %
Crash %
Injection Duration (Sec)
Average DFTR
DFTR
Injection Duration (Sec)
Average Duration
Duration
Injection Duration (Sec)
Average Freq. Collision (per min)
Freq. Collision (per min)
Injection Duration (Sec)
Average NFTR
NFTR
Injection Duration (Sec)
Average PU
PU
Injection Duration (Sec)



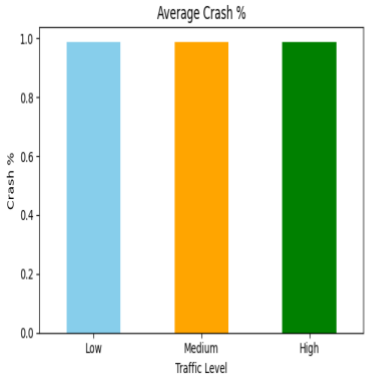
- **Impact of different traffic levels:**

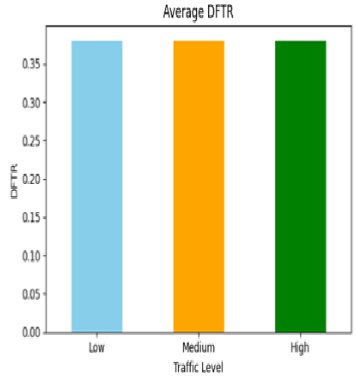


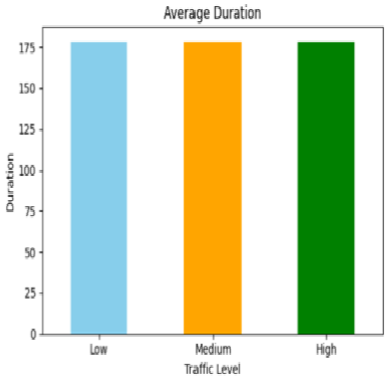

Average PLG
PLG
Traffic Level
Low
Medium
High

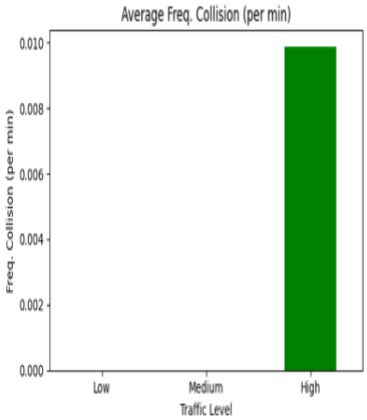
Average ISMV
ISMV
Traffic Level
Low
Medium
High

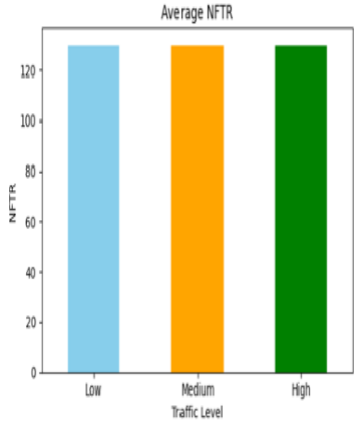
Average PGT
PGT
Traffic Level
Low
Medium
High

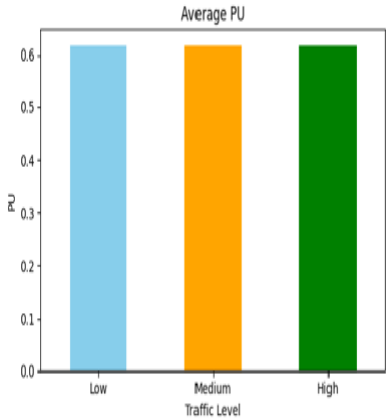

Average Crash %
Crash %
Traffic Level
Low
Medium
High

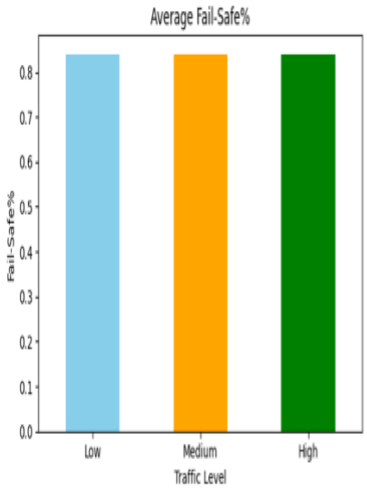

Average DFTR
DFTR
Traffic Level
Low
Medium
High

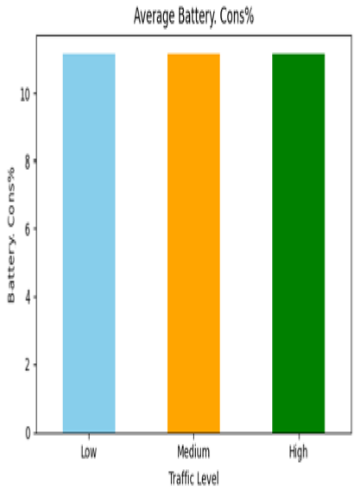

Average Duration
Duration
Traffic Level
Low
Medium
High

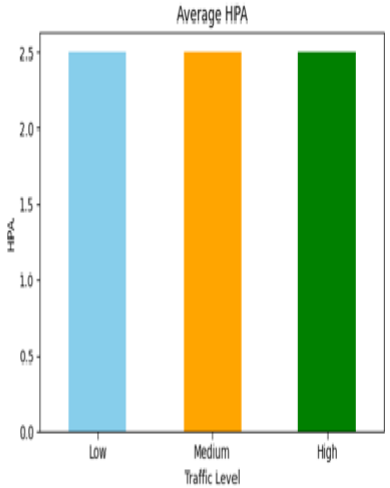

Average Freq. Collision (per min)
Freq. Collision (per min)
Traffic Level
Low
Medium
High


Average NFTR
NFTR
Traffic Level
Low
Medium
High

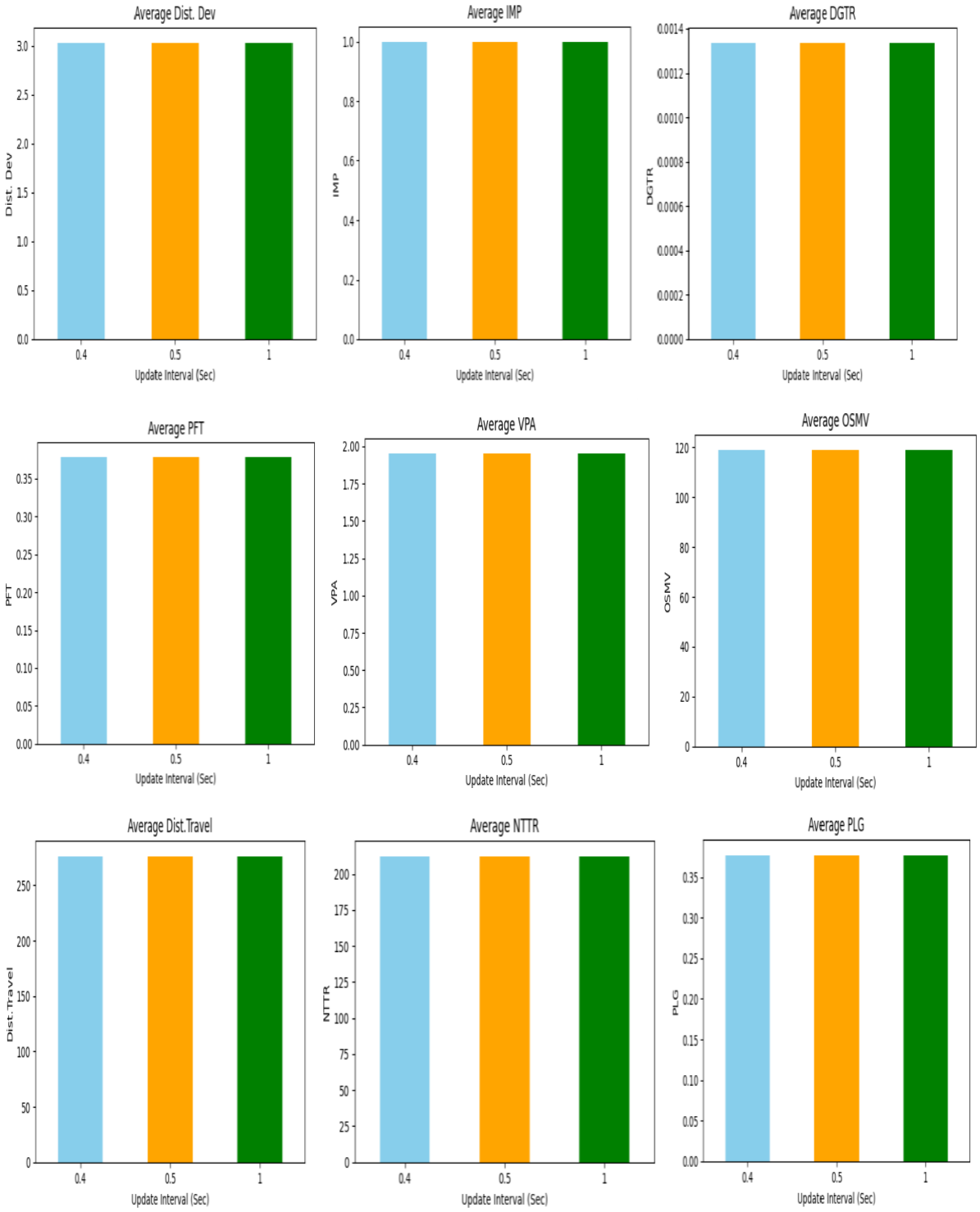

Average PU
PU
Traffic Level
Low
Medium
High

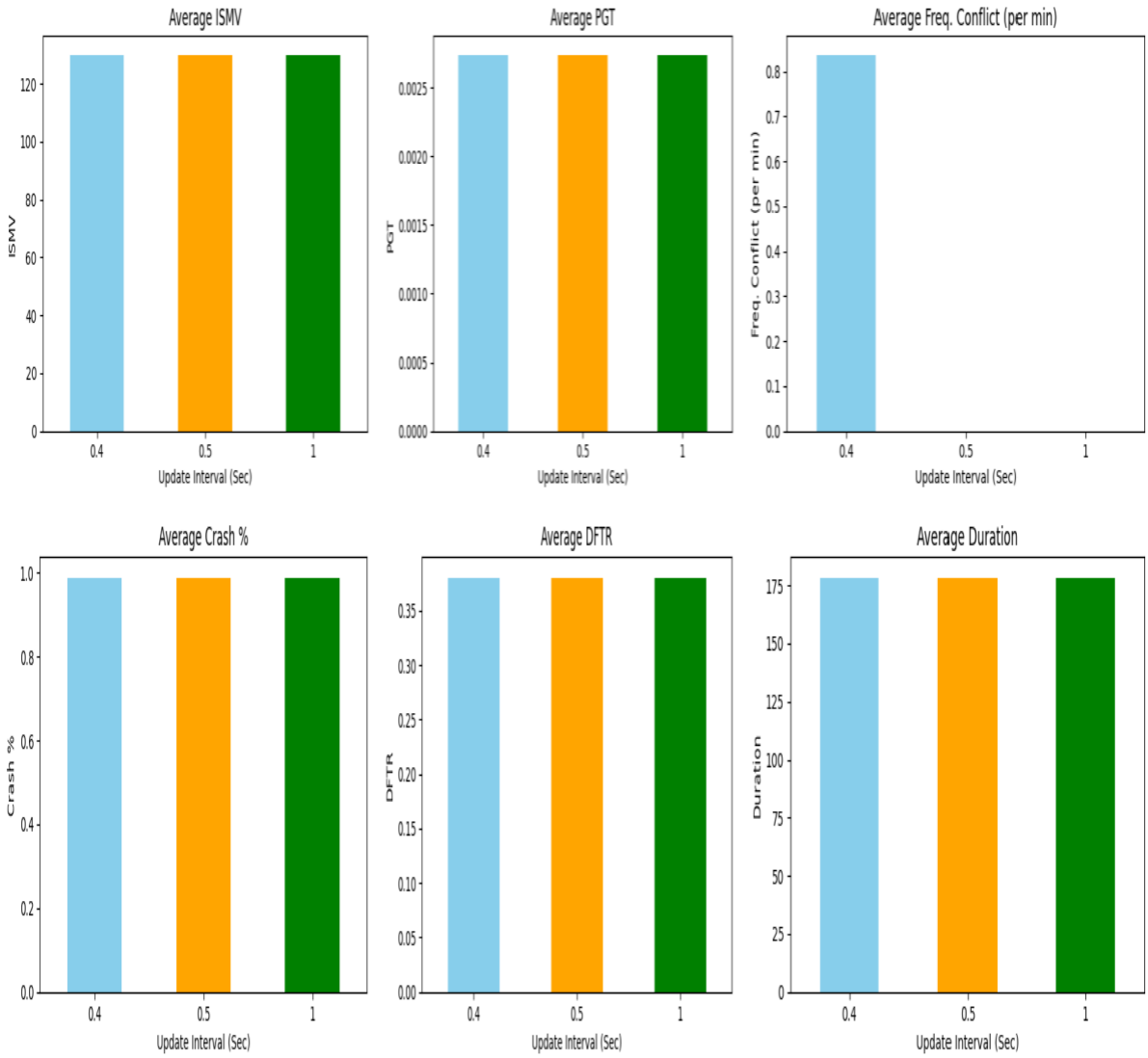

Average Fail-Safe%
Fail-Safe%
Traffic Level
Low
Medium
High

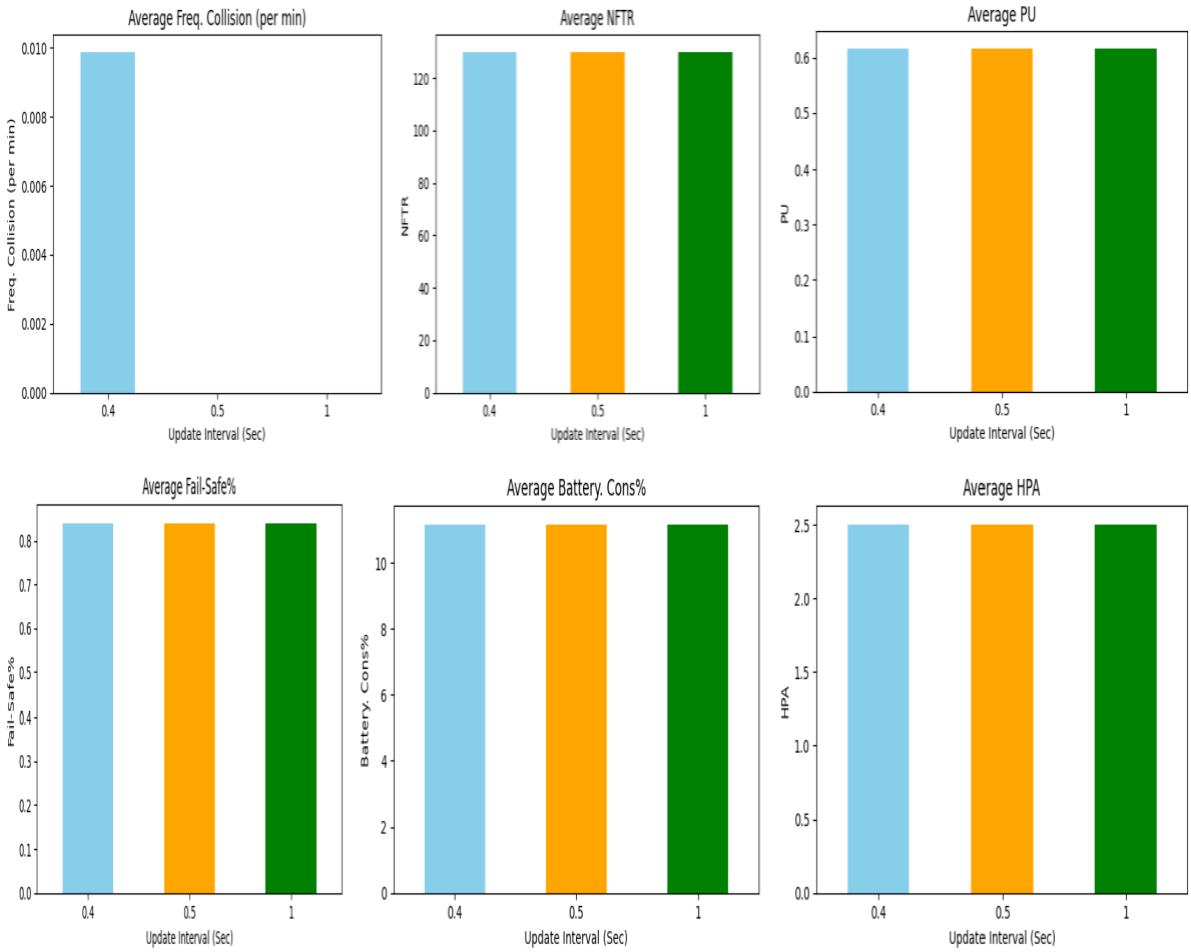

Average Battery. Cons%
Battery. Cons%
Traffic Level
Low
Medium
High


Average HPA
HPA.
Traffic Level
Low
Medium
High

- **Impact of different update intervals:**

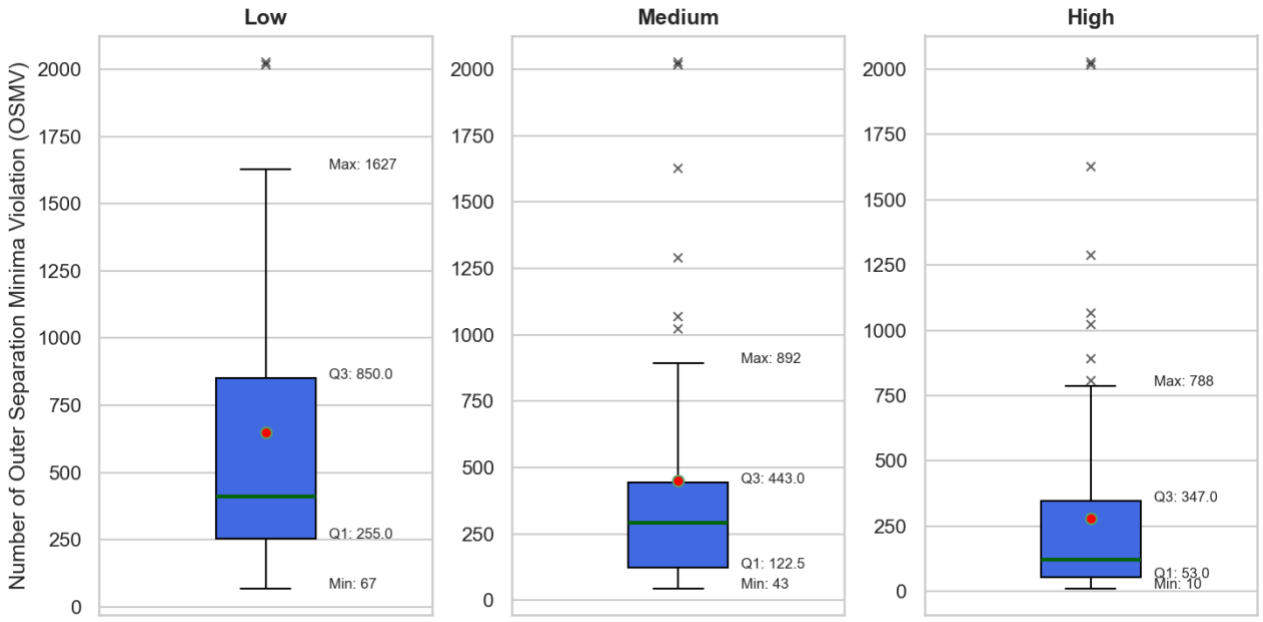


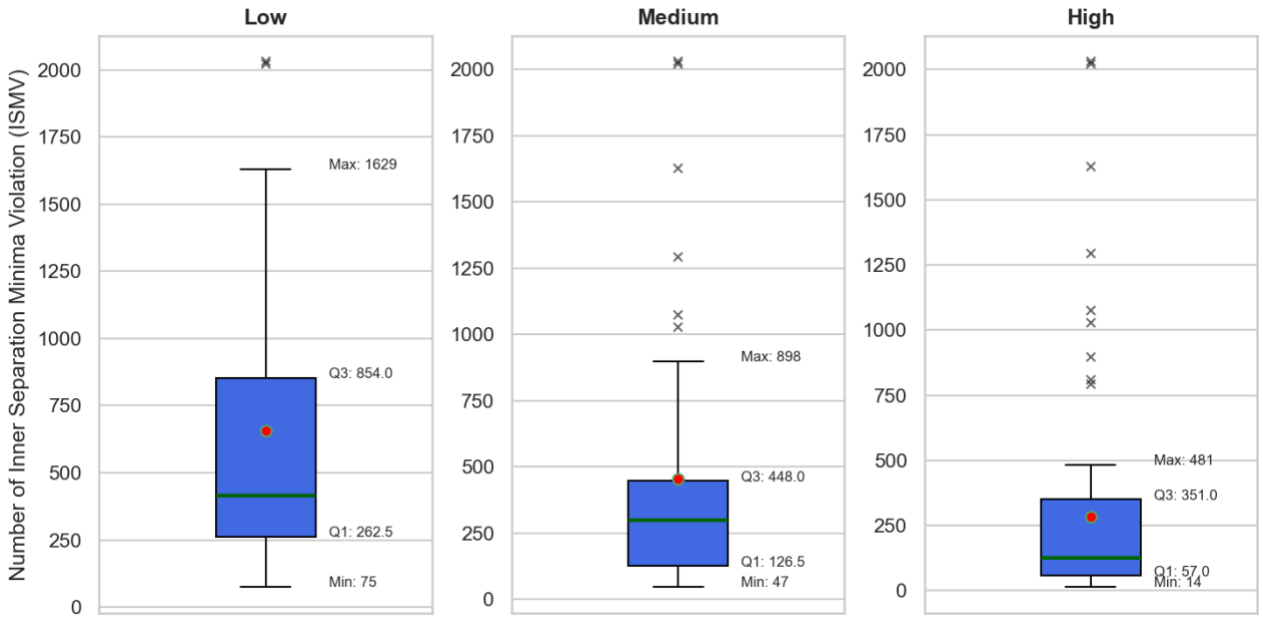

Average ISMV
ISMV
Update Interval (Sec)
Average PGT
PGT
Update Interval (Sec)
Average Freq. Conflict (per min)
Freq. Conflict (per min)
Update Interval (Sec)
Average Crash %
Crash %
Update Interval (Sec)
Average DFTR
DFTR
Update Interval (Sec)
Average Duration
Duration
Update Interval (Sec)

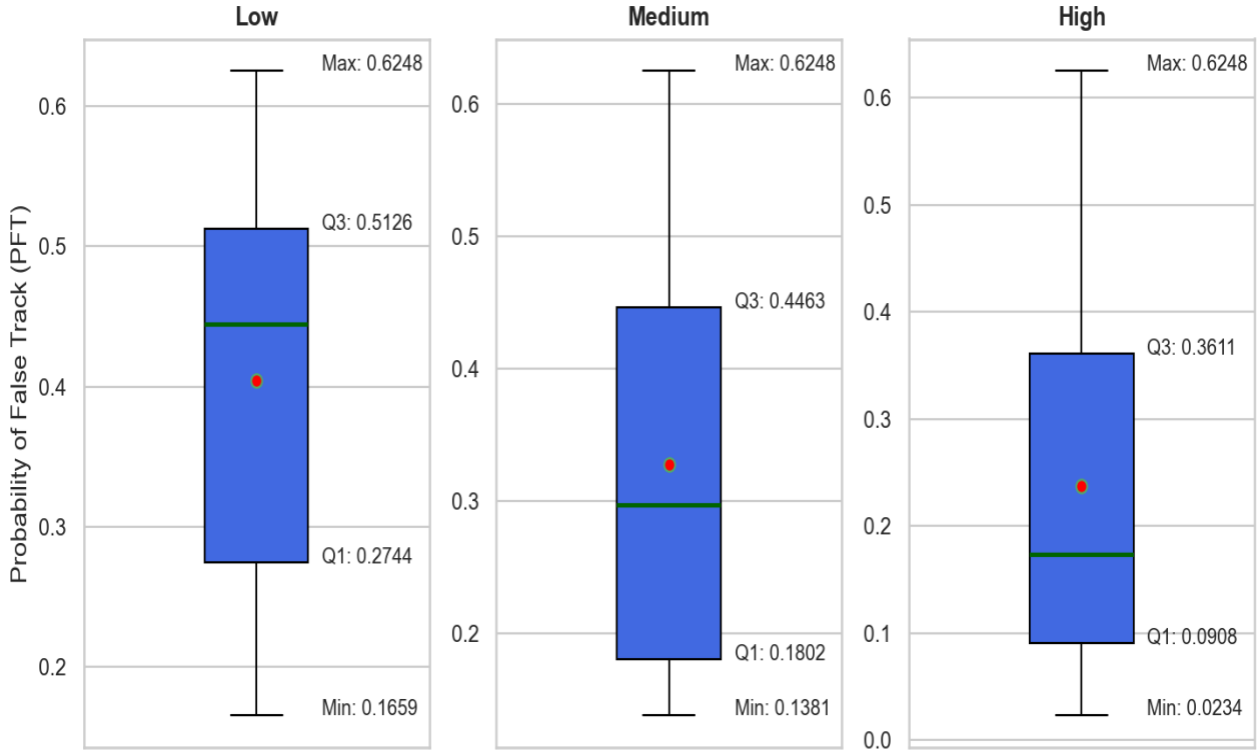

Average Freq. Collision (per min)
Freq. Collision (per min)
0.010
0.008
0.006
0.004
0.002
0.000
0.4
0.5
1
Update Interval (Sec)
Average NFTR
NFTR
120
100
80
60
40
20
0
0.4
0.5
1
Update Interval (Sec)
Average PU
PU
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.4
0.5
1
Update Interval (Sec)
Average Fail-Safe%
Fail-Safe%
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.4
0.5
1
Update Interval (Sec)
Average Battery. Cons%
Battery. Cons%
10
8
6
4
2
0
0.4
0.5
1
Update Interval (Sec)
Average HPA
HPA
2.5
2.0
1.5
1.0
0.5
0.0
0.4
0.5
1
Update Interval (Sec)

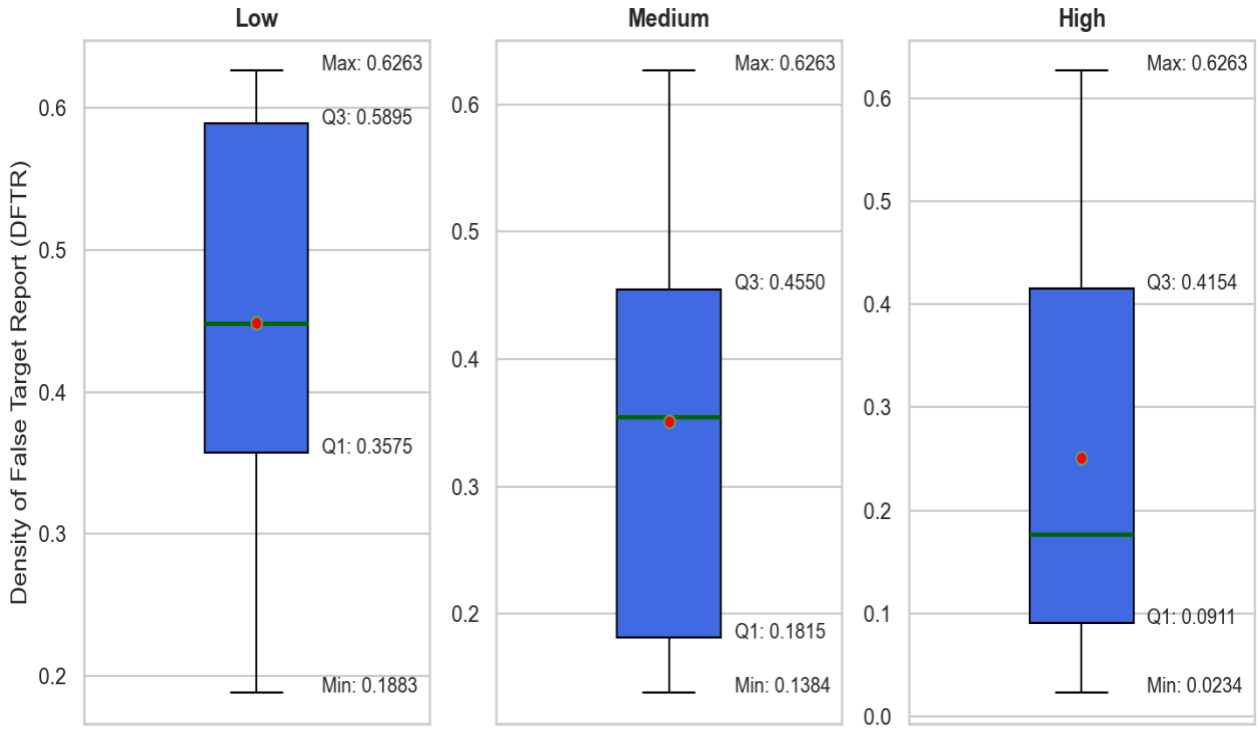
Results Risk Thresholds for Critical Metrics Across Traffic Levels Under GPS Faults and Varying Wind Conditions.

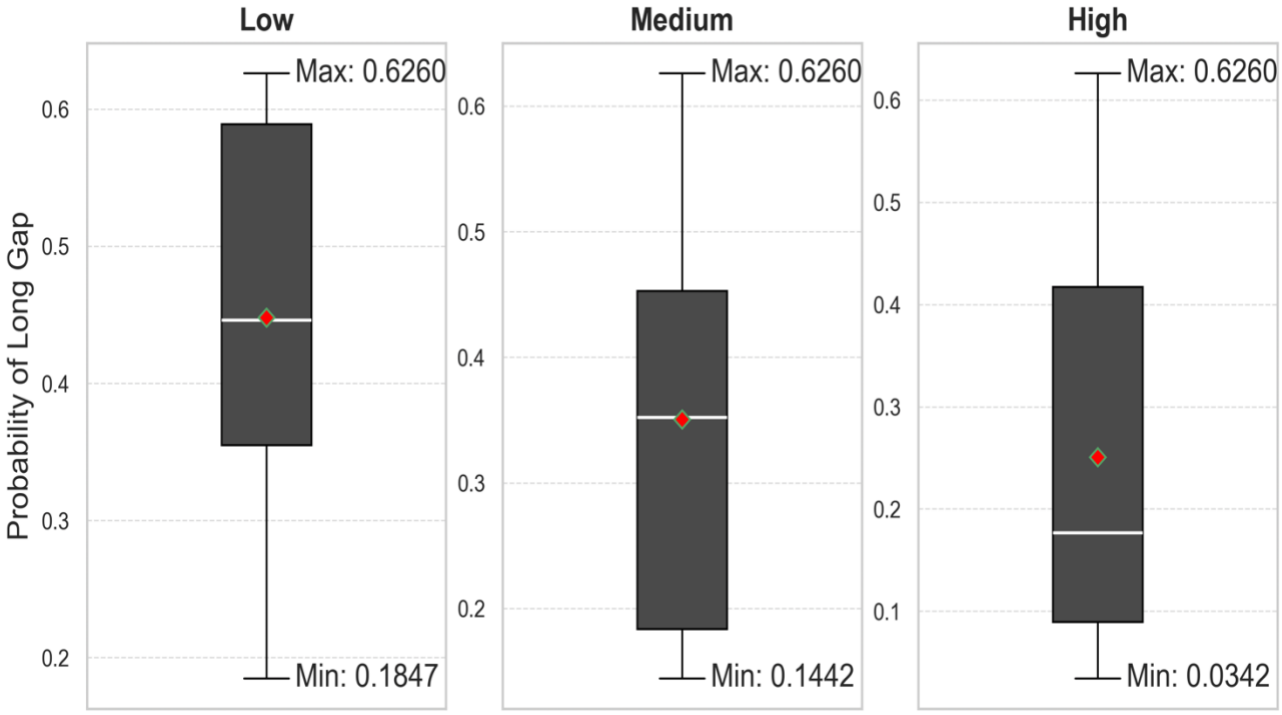
1. GPS and Light Breeze wind Condition:

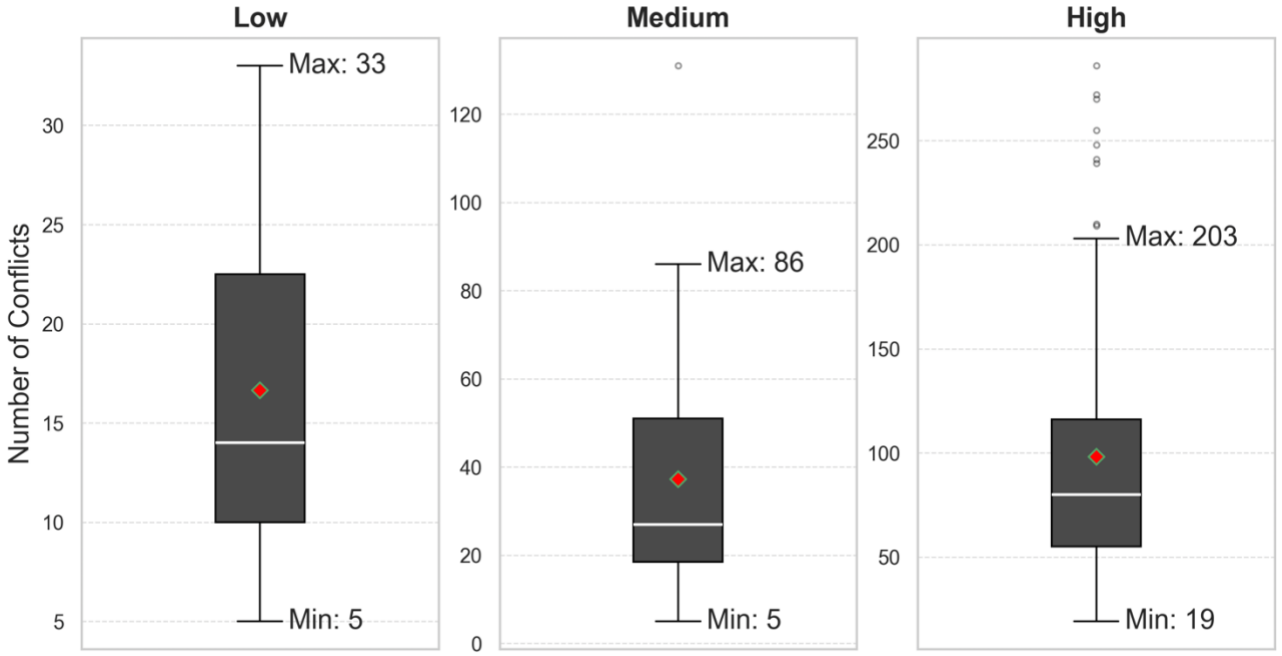


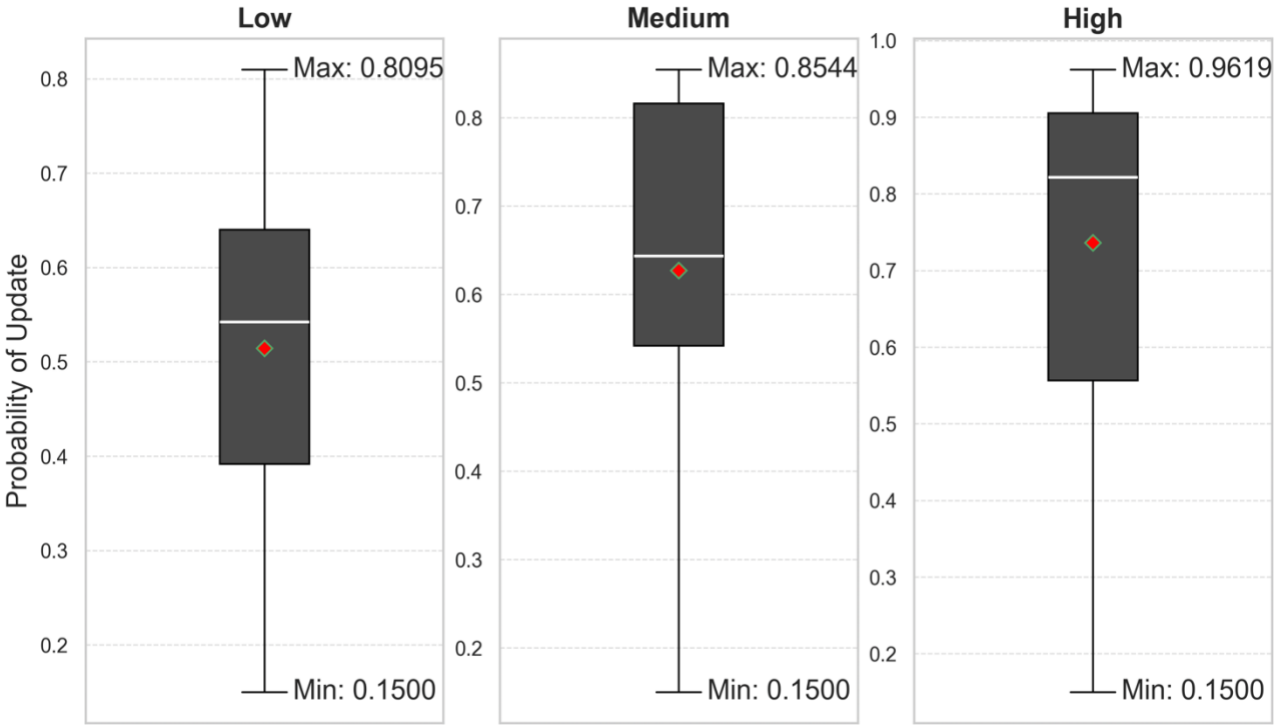



Low
Medium
High
Probability of False Track (PFT)
Max: 0.6248
Q3: 0.5126
Q1: 0.2744
Min: 0.1659
Max: 0.6248
Q3: 0.4463
Q1: 0.1802
Min: 0.1381
Max: 0.6248
Q3: 0.3611
Q1: 0.0908
Min: 0.0234
0.6
0.5
0.4
0.3
0.2
0.1
0.0

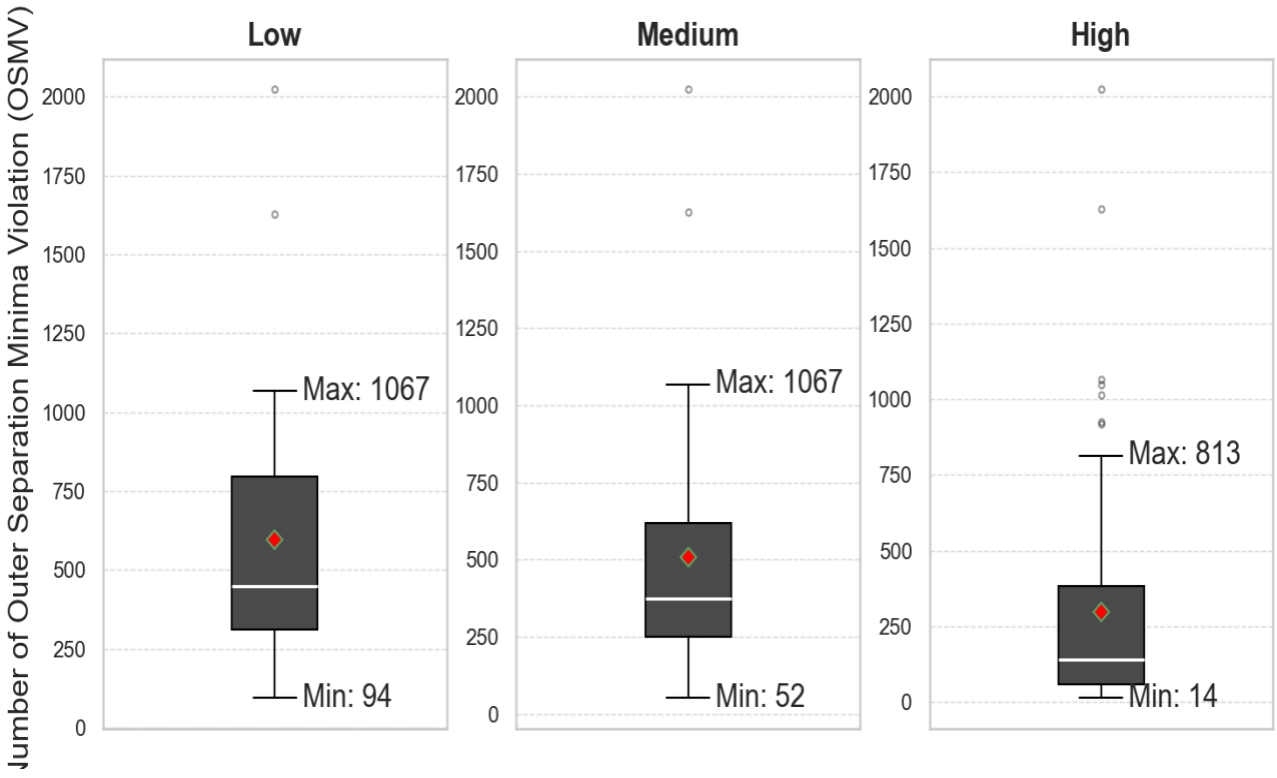

Low
Medium
High
Density of False Target Report (DFTR)
Max: 0.6263
Q3: 0.5895
Q1: 0.3575
Min: 0.1883
Max: 0.6263
Q3: 0.4550
Q1: 0.1815
Min: 0.1384
Max: 0.6263
Q3: 0.4154
Q1: 0.0911
Min: 0.0234
0.6
0.5
0.4
0.3
0.2
0.1
0.0

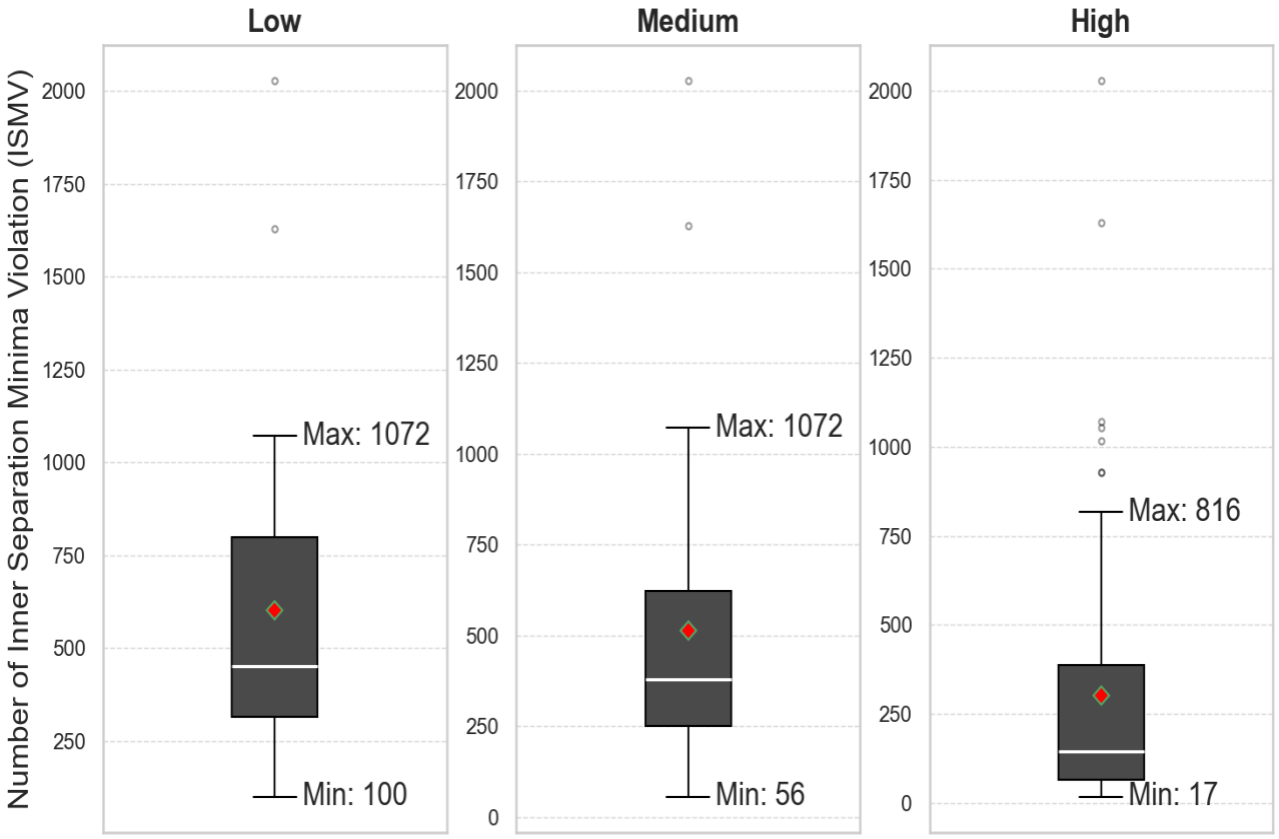

Low
Medium
High
Probability of Long Gap
Max: 0.6260
Min: 0.1847
Max: 0.6260
Min: 0.1442
Max: 0.6260
Min: 0.0342

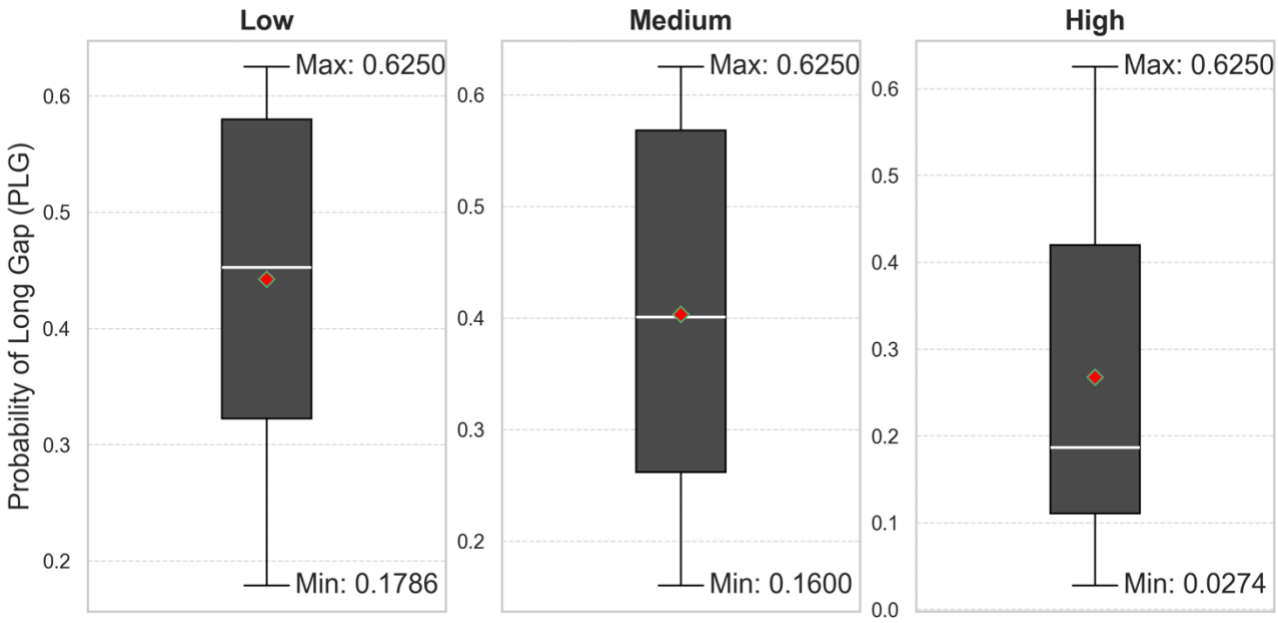

Low
Medium
High
Number of Conflicts
Max: 33
Min: 5
Max: 86
Min: 5
Max: 203
Min: 19

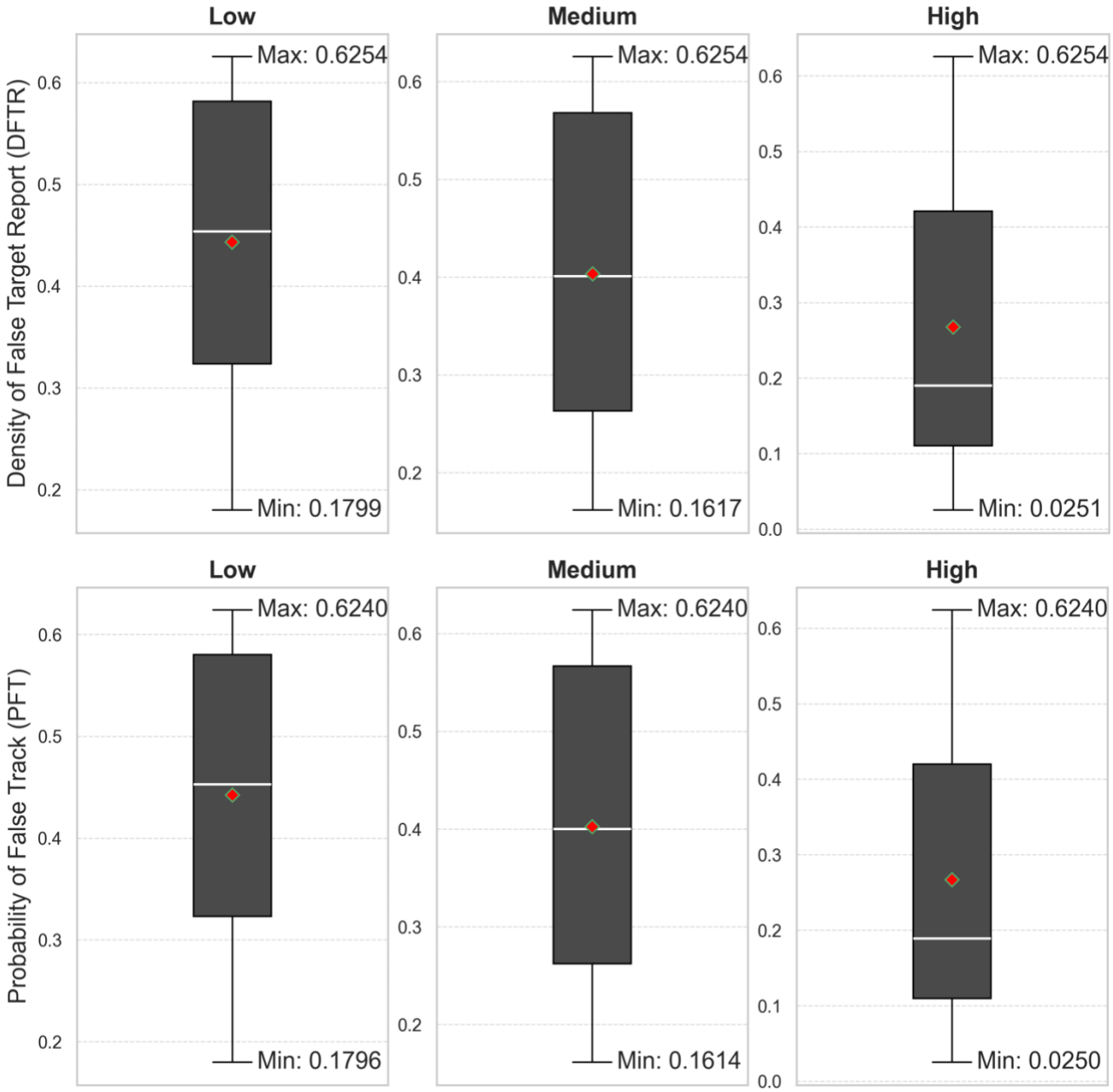


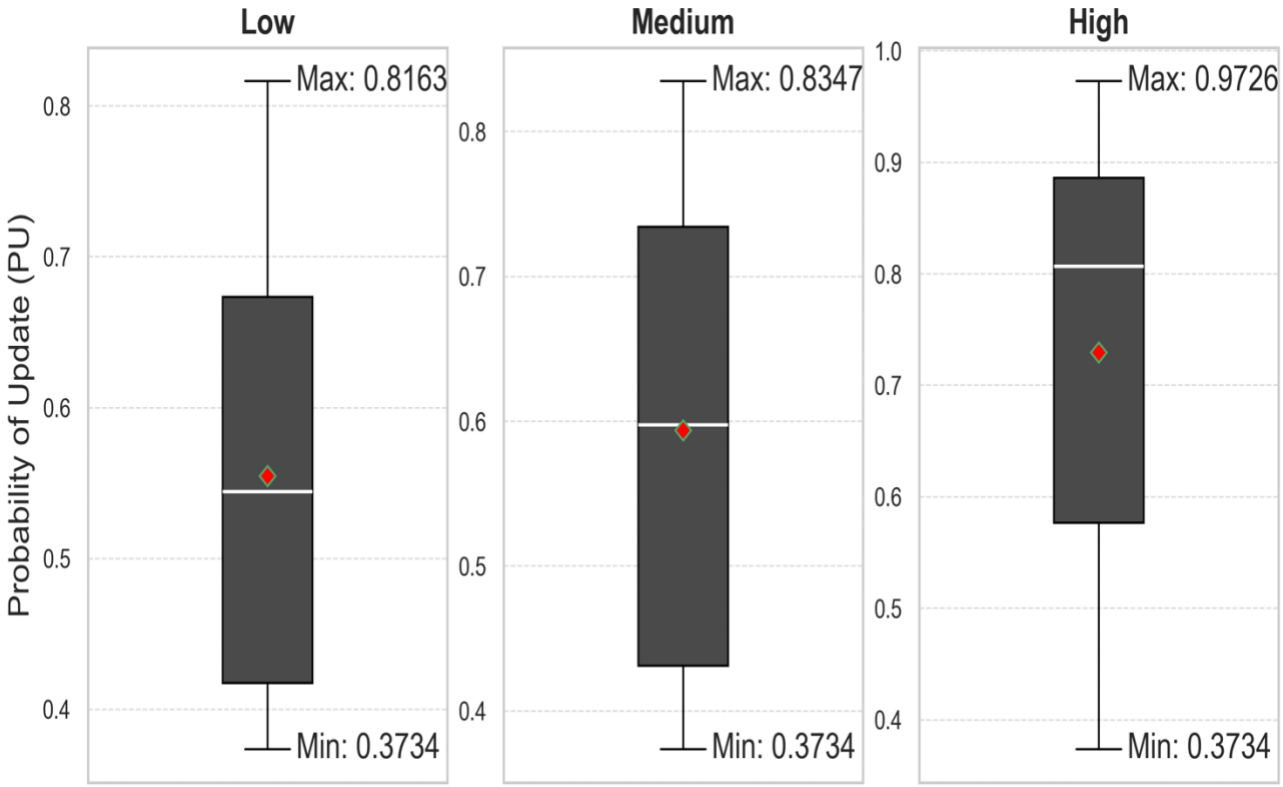
2. GPS and Moderate Breeze wind Condition:

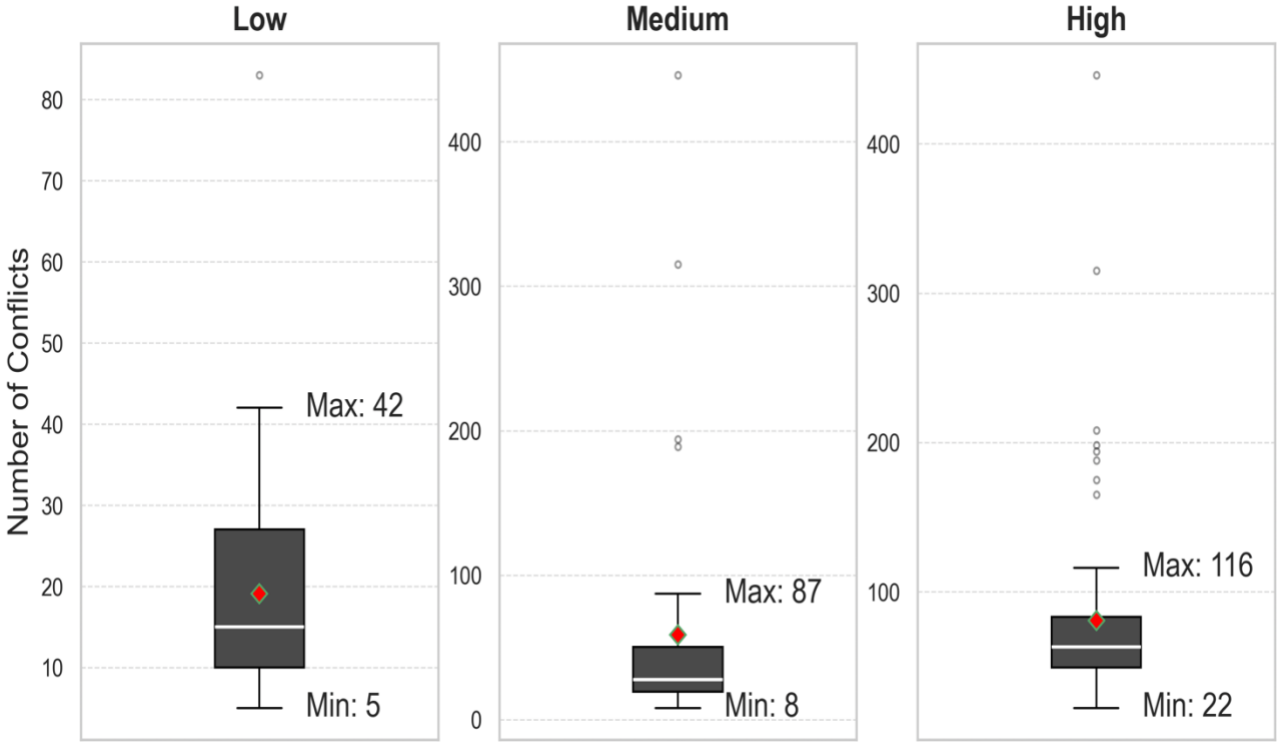



Low
Medium
High
Number of Inner Separation Minima Violation (ISMV)
2000
1750
1500
1250
1000
750
500
250
0
Max: 1072
Min: 100
Max: 1072
Min: 56
Max: 816
Min: 17

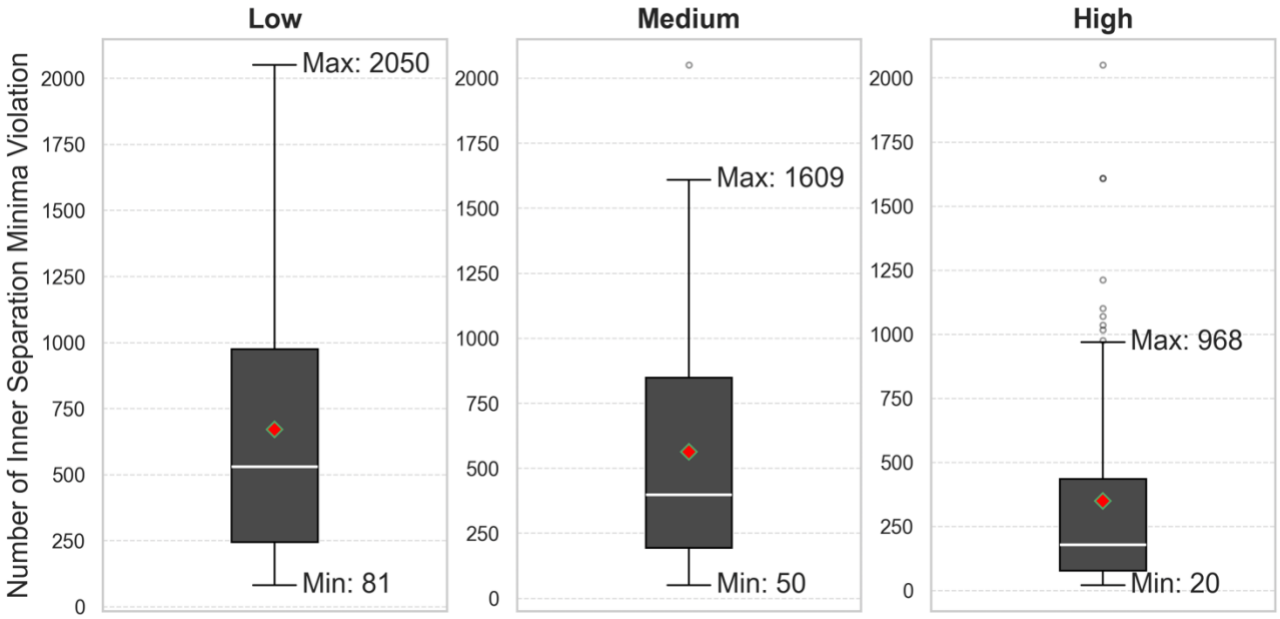

Low
Medium
High
Probability of Long Gap (PLG)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Max: 0.6250
Min: 0.1786
Max: 0.6250
Min: 0.1600
Max: 0.6250
Min: 0.0274

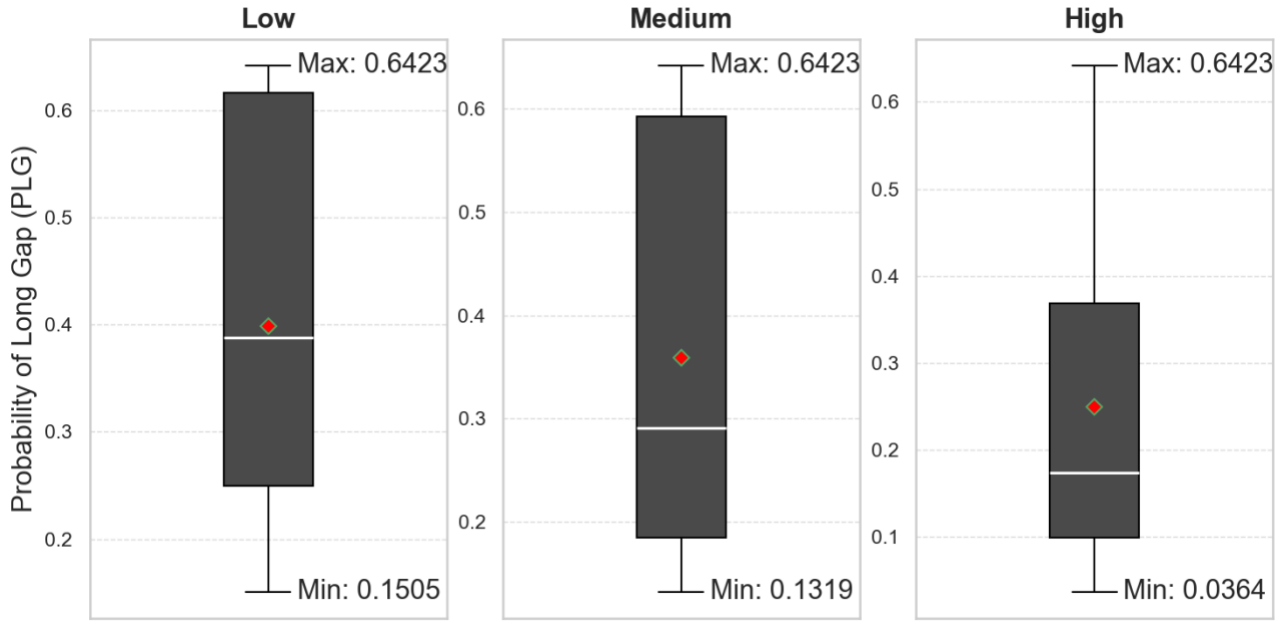

Low
Medium
High
Density of False Target Report (DFTR)
Max: 0.6254
Min: 0.1799
Max: 0.6254
Min: 0.1617
Max: 0.6254
Min: 0.0251
Low
Medium
High
Probability of False Track (PFT)
Max: 0.6240
Min: 0.1796
Max: 0.6240
Min: 0.1614
Max: 0.6240
Min: 0.0250

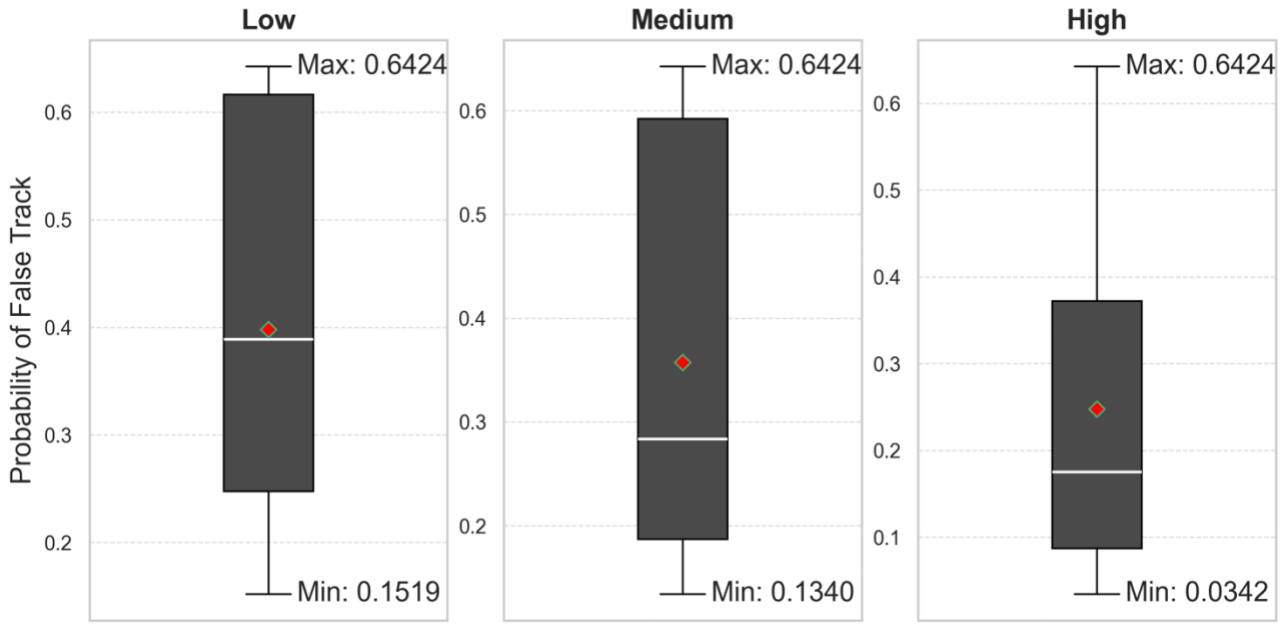

Low
Medium
High
Probability of Update (PU)
Max: 0.8163
Min: 0.3734
Max: 0.8347
Min: 0.3734
Max: 0.9726
Min: 0.3734

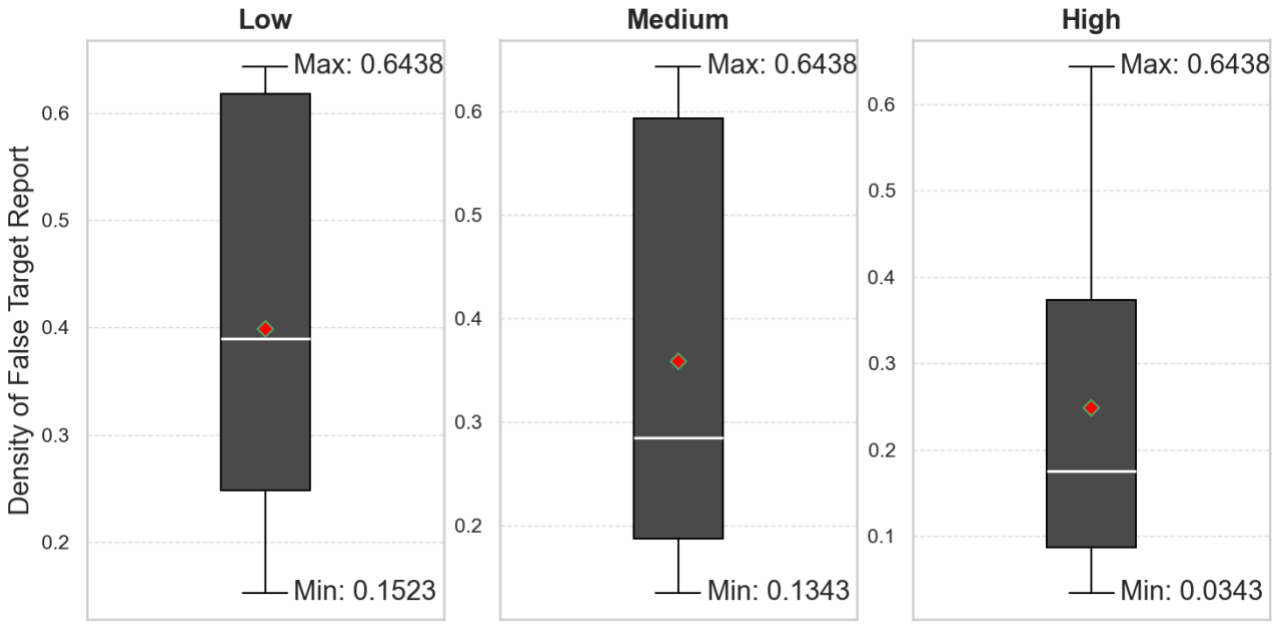

Low
Medium
High
Number of Conflicts
Max: 42
Min: 5
Max: 87
Min: 8
Max: 116
Min: 22

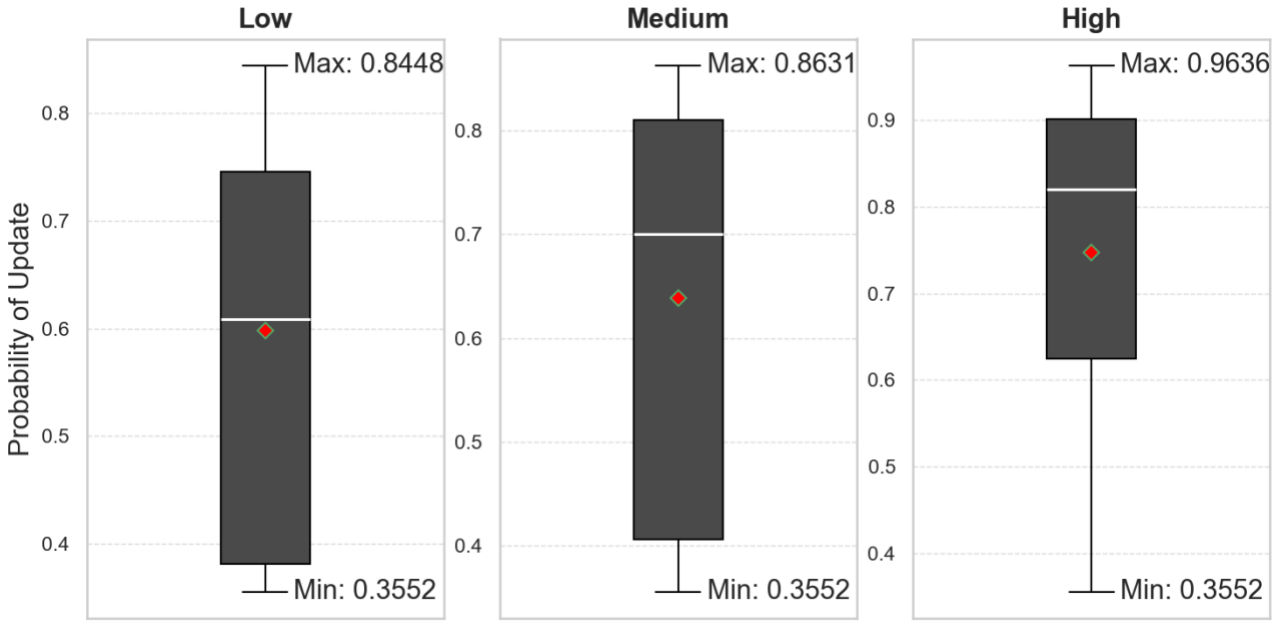
1. GPS and Near-Gale wind Condition:

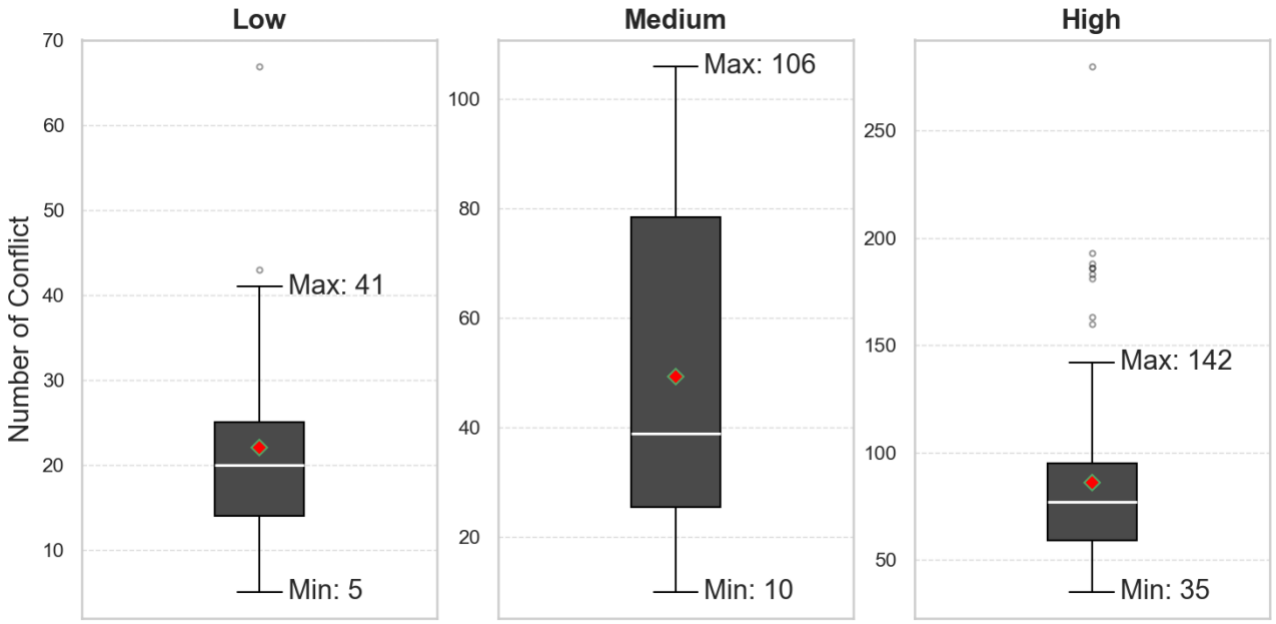


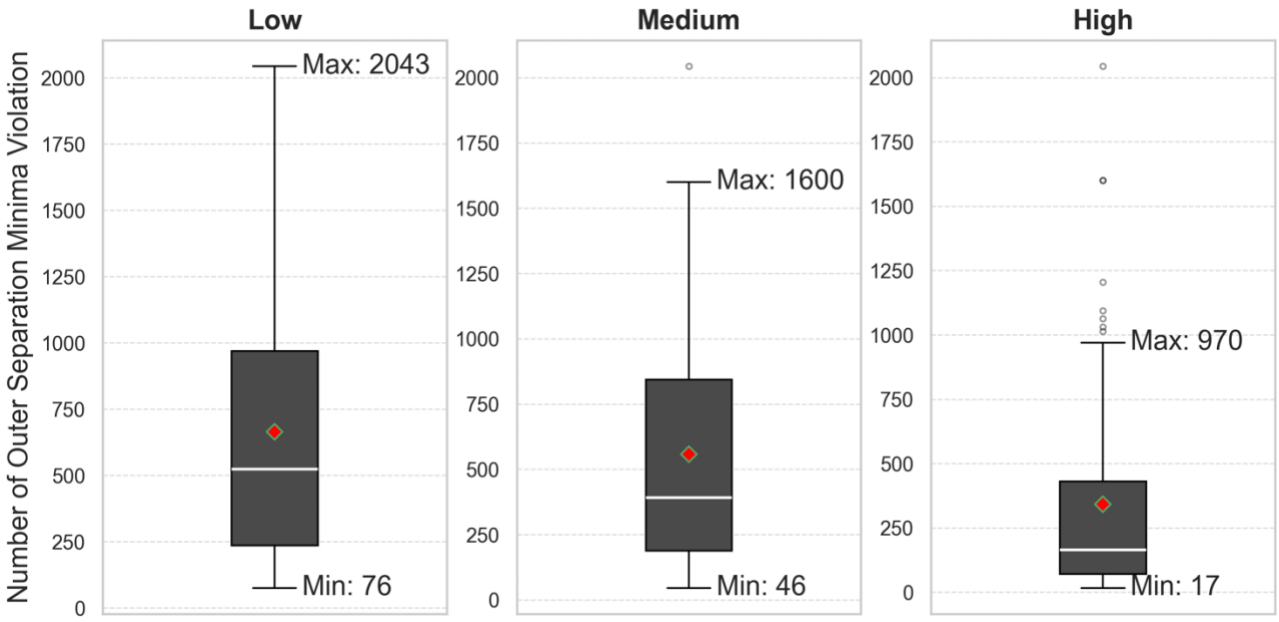




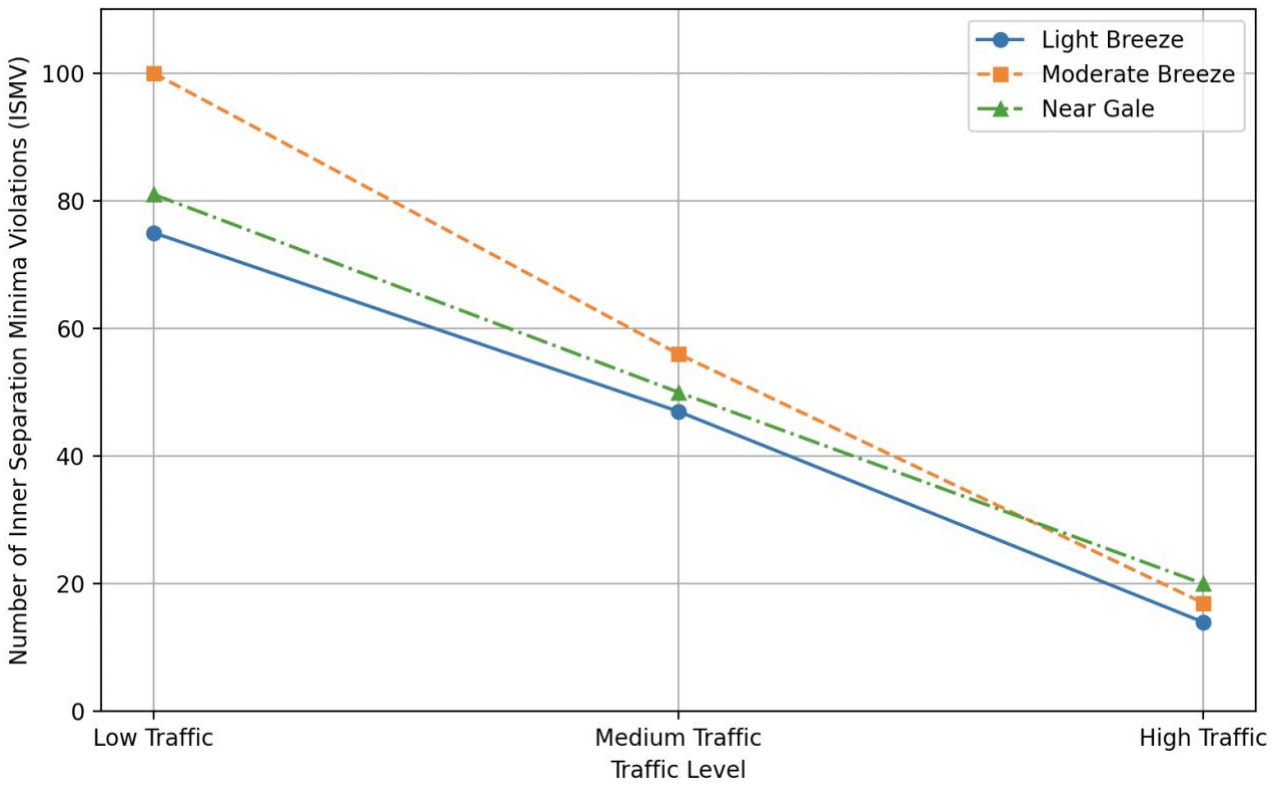

Low
Medium
High
Density of False Target Report
Max: 0.6438
Min: 0.1523
Max: 0.6438
Min: 0.1343
Max: 0.6438
Min: 0.0343

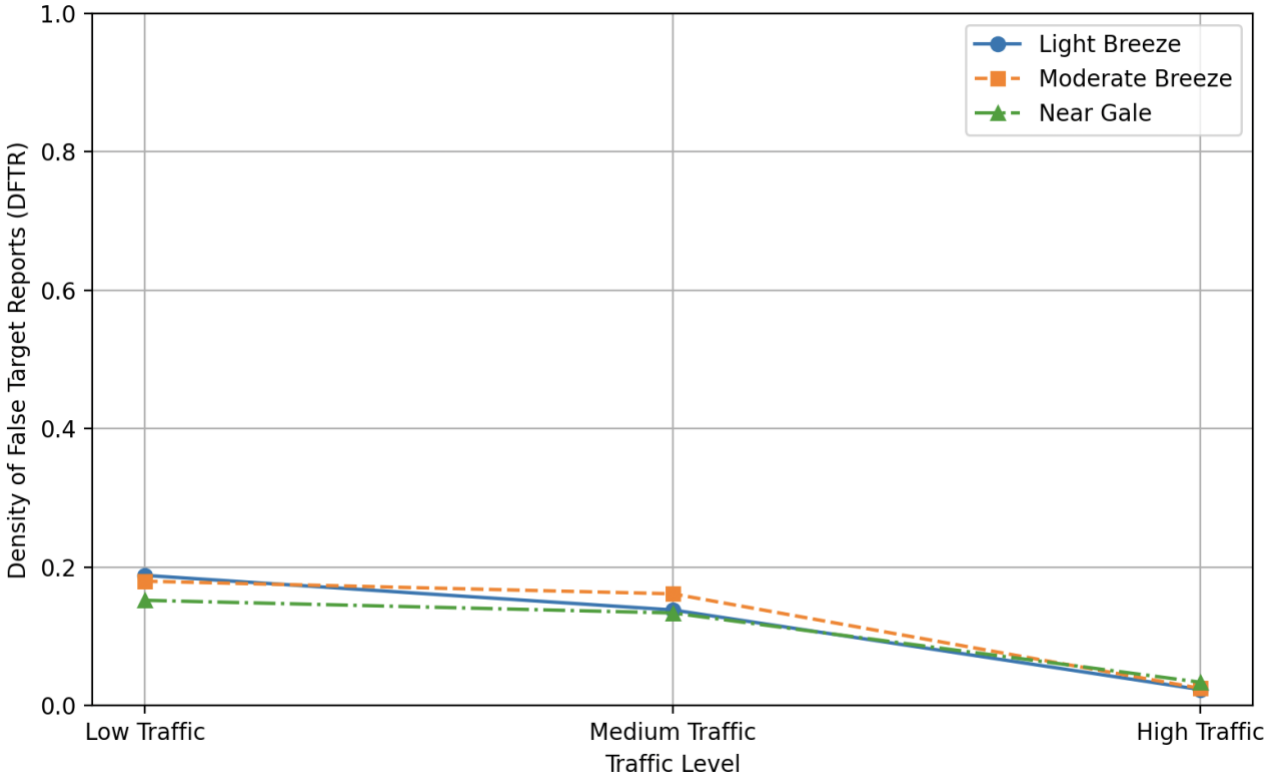

Low
Medium
High
Probability of Update
Max: 0.8448
Min: 0.3552
Max: 0.8631
Min: 0.3552
Max: 0.9636
Min: 0.3552

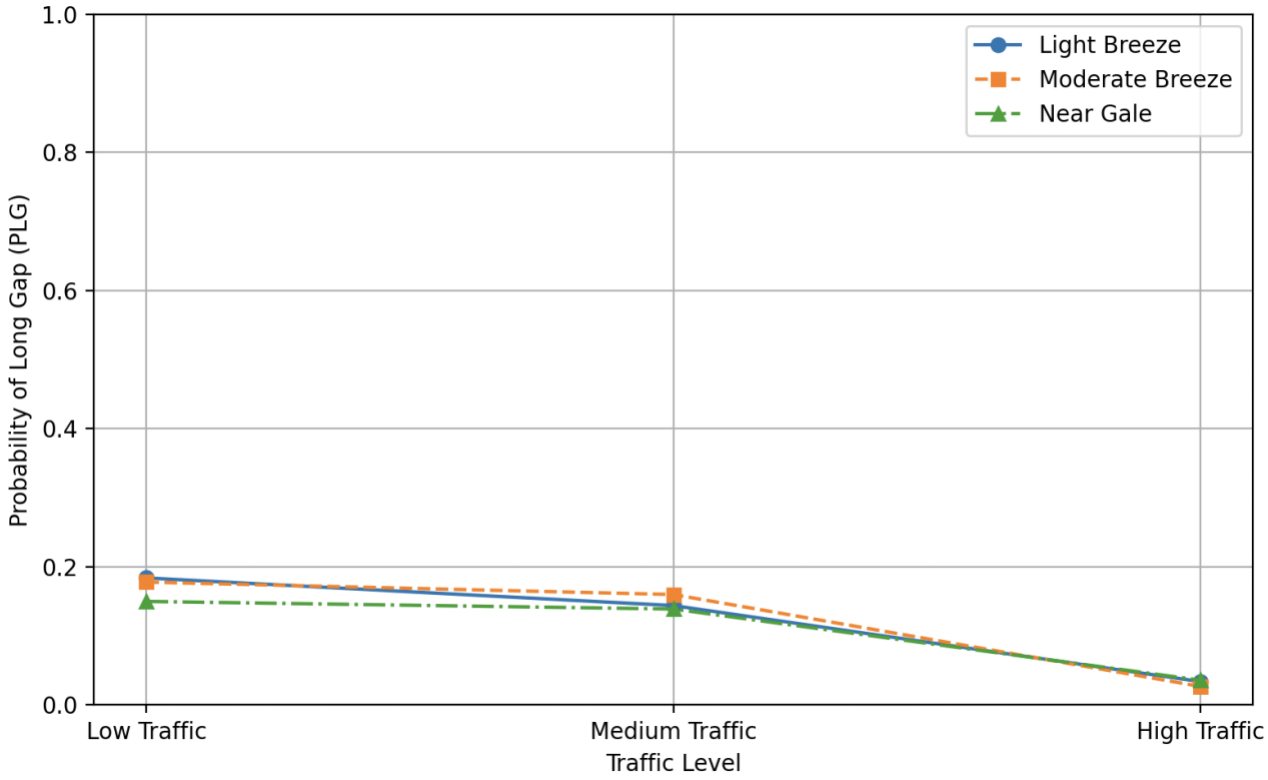

Low
Medium
High
Number of Conflict
Max: 41
Min: 5
Max: 106
Min: 10
Max: 142
Min: 35

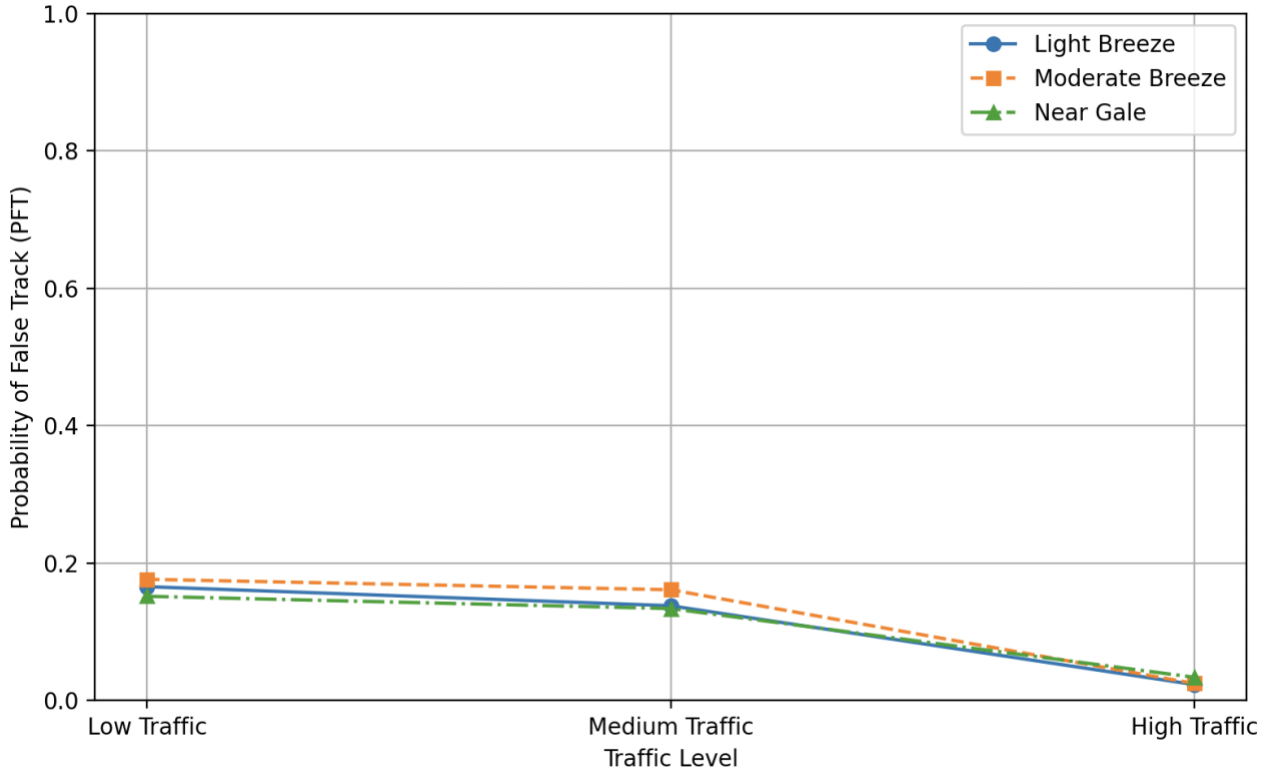


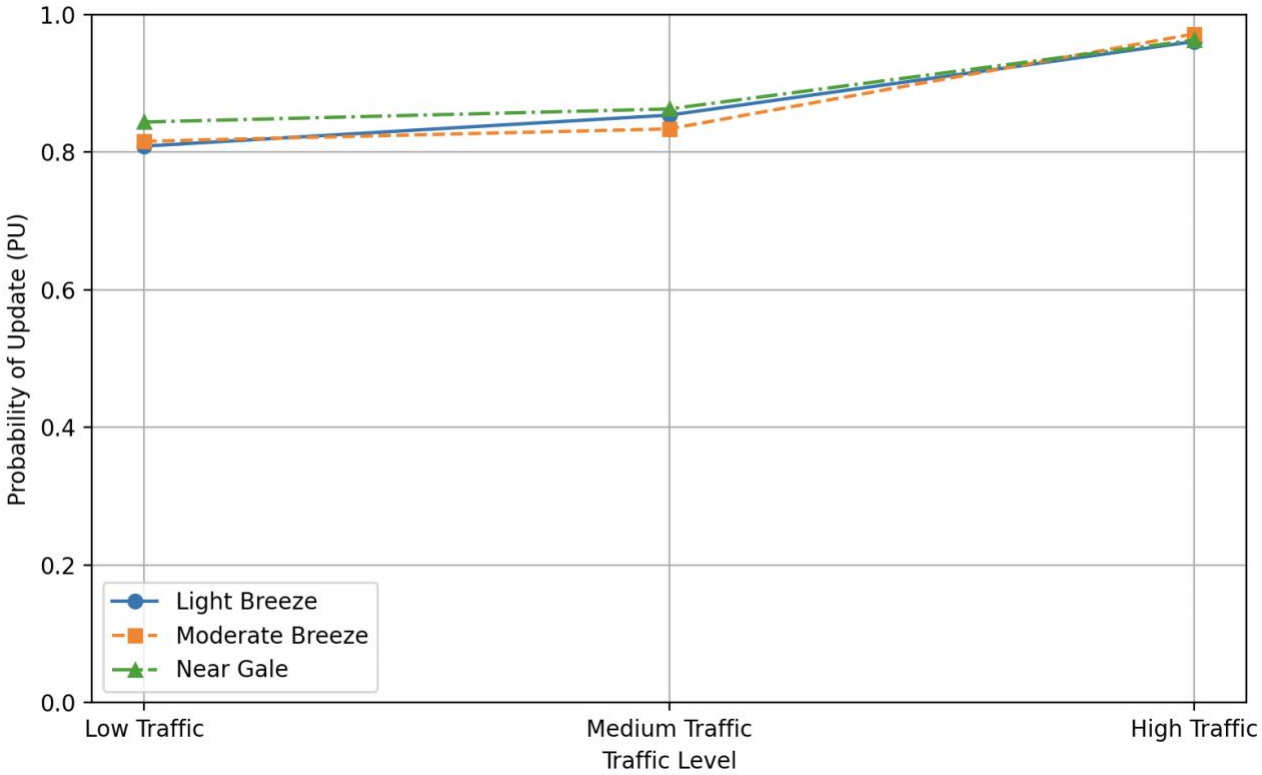
Based on these results we considered worst-case scenario as reliable risk threshold for critical metrics across traffic levels under GPS faults and varying wind conditions. The following figures shows reliable thresholds outcome from pervious boxplots.

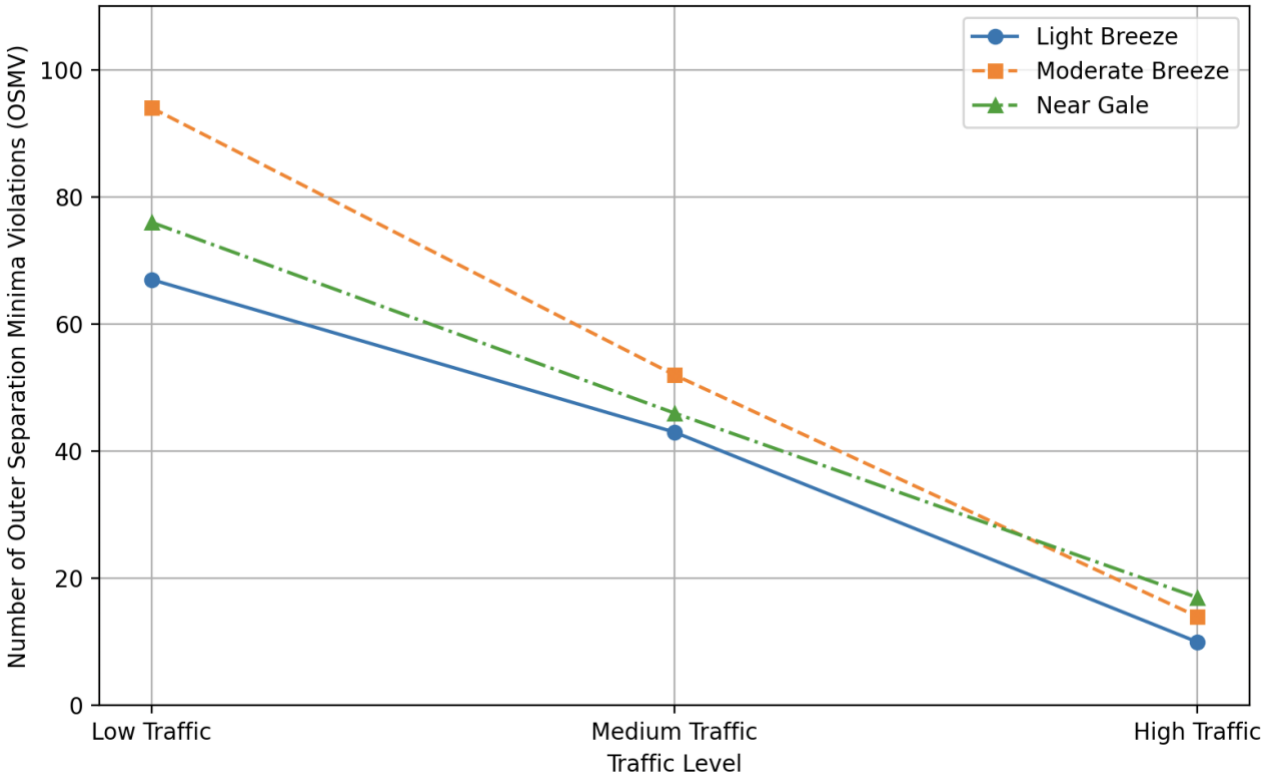


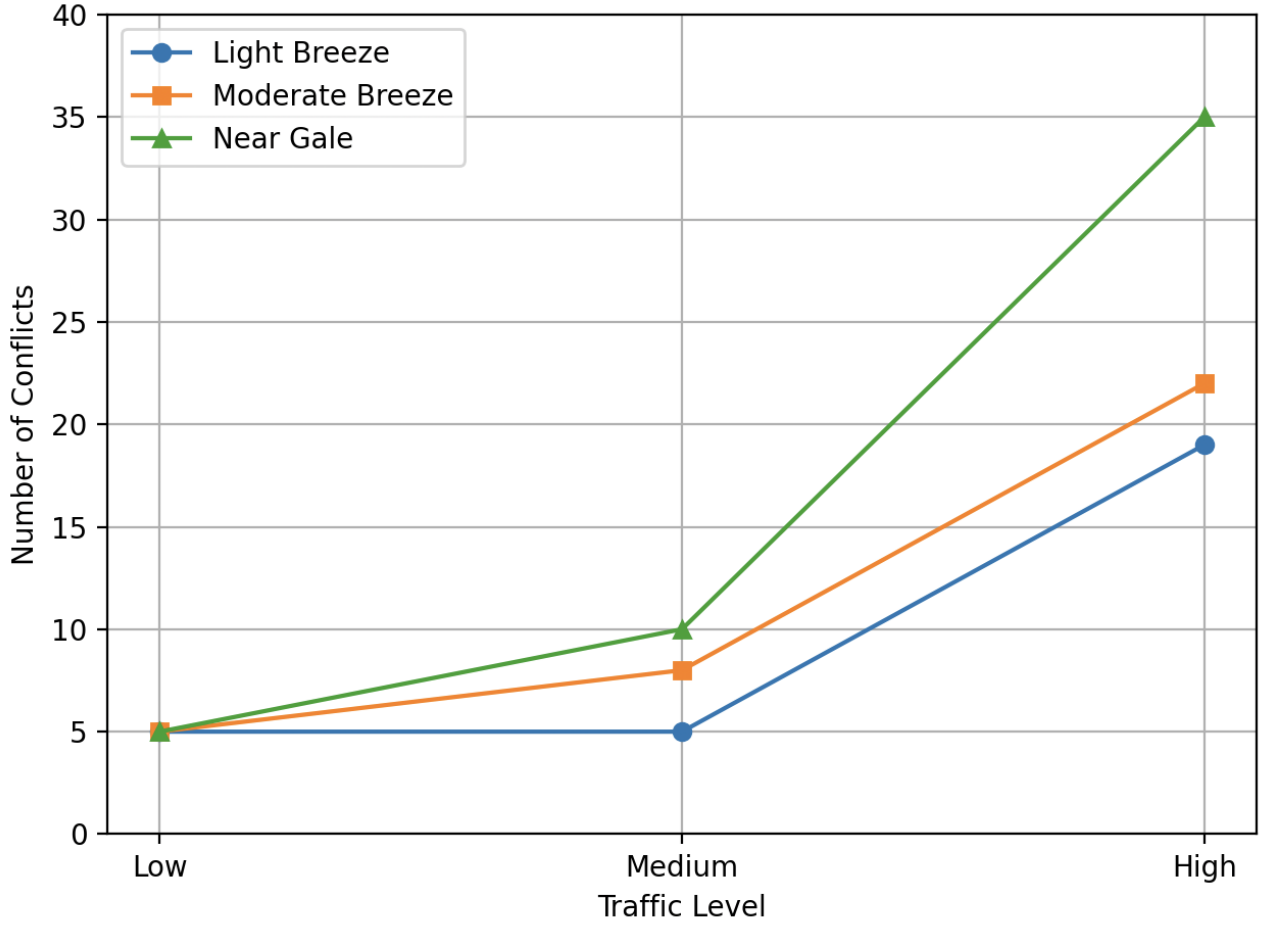

Density of False Target Reports (DFTR)
1.0
0.8
0.6
0.4
0.2
0.0
Light Breeze
Moderate Breeze
Near Gale
Low Traffic
Medium Traffic
High Traffic
Traffic Level


Probability of Long Gap (PLG)
1.0
0.8
0.6
0.4
0.2
0.0
Light Breeze
Moderate Breeze
Near Gale
Low Traffic
Medium Traffic
High Traffic
Traffic Level


1.0
0.8
0.6
0.4
0.2
0.0
Probability of False Track (PFT)
Light Breeze
Moderate Breeze
Near Gale
Low Traffic
Medium Traffic
High Traffic
Traffic Level


1.0
0.8
0.6
0.4
0.2
0.0
Probability of Update (PU)
Light Breeze
Moderate Breeze
Near Gale
Low Traffic
Medium Traffic
High Traffic
Traffic Level


Light Breeze
Moderate Breeze
Near Gale
Number of Outer Separation Minima Violations (OSMV)
0
20
40
60
80
100
Low Traffic
Medium Traffic
High Traffic
Traffic Level


Light Breeze
Moderate Breeze
Near Gale
Number of Conflicts
0
5
10
15
20
25
30
35
40
Low
Medium
High
Traffic Level