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A Digital Twin–Based Framework for Air Quality Management in Road Construction Work Zones

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Air Quality Impacts of Road Work Zones in Saudi Arabia

- **Traffic-related air pollution remains a critical global challenge, causing significant environmental, health, and economic impacts.**

- **Road maintenance and construction activities introduce temporary work zones that disrupt normal traffic flow and increase emissions due to:**
  - Traffic congestion and reduced speeds
  - Vehicle idling and stop-and-go conditions
  - Detours and rerouted traffic.
- **Construction operations themselves contribute additional sources of pollution, including dust, noise, and equipment emissions.**

Accurately capturing and managing these impacts is essential for protecting public health and ensuring the sustainability of transportation infrastructure.

Health and Air Quality Concerns

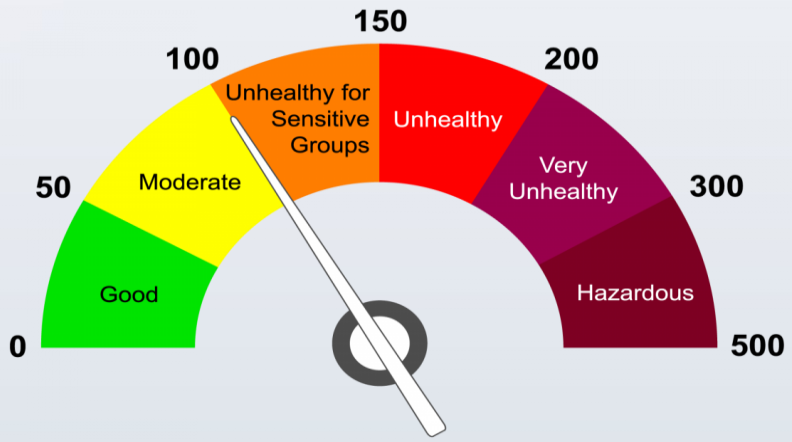
- **Exposure to air pollution is a major global public health risk, particularly in areas affected by traffic congestion and construction activities.**

- **The WHO estimated that the outdoor air pollution in both urban and rural areas likely contributed to approximately 4.2 million deaths globally in 2016.**

- **Fine particulate matter ($PM_{2.5}$) is identified as one of the most harmful pollutants due to its ability to penetrate deep into the lungs and bloodstream (WHO, 2025).**

World Health Organization

Air Quality (Level of Concern)



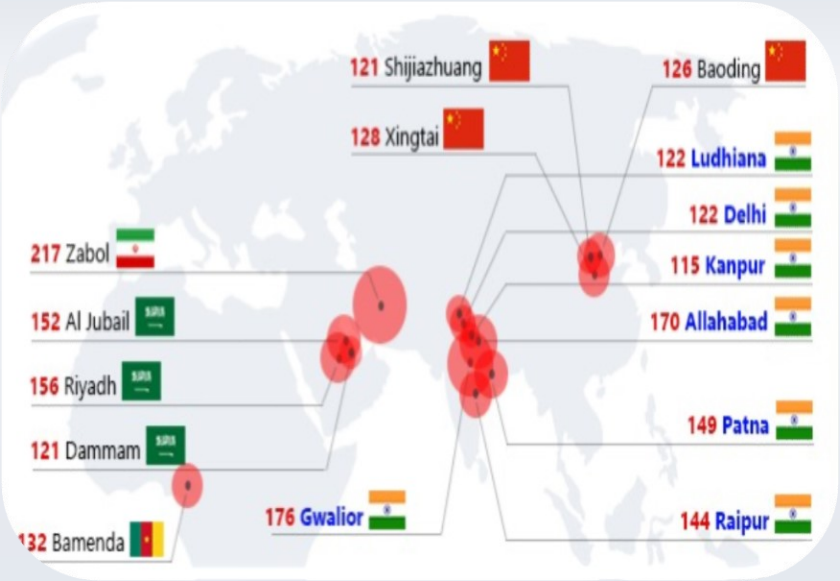
Air Quality Index		
AQI Category and Color	**Index Value**	**Description of Air Quality**
Good Green	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk.
Moderate Yellow	51 to 100	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
Unhealthy for Sensitive Groups Orange	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Unhealthy Red	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Very Unhealthy Purple	201 to 300	Health alert: The risk of health effects is increased for everyone.
Hazardous Maroon	301 and higher	Health warning of emergency conditions: everyone is more likely to be affected.

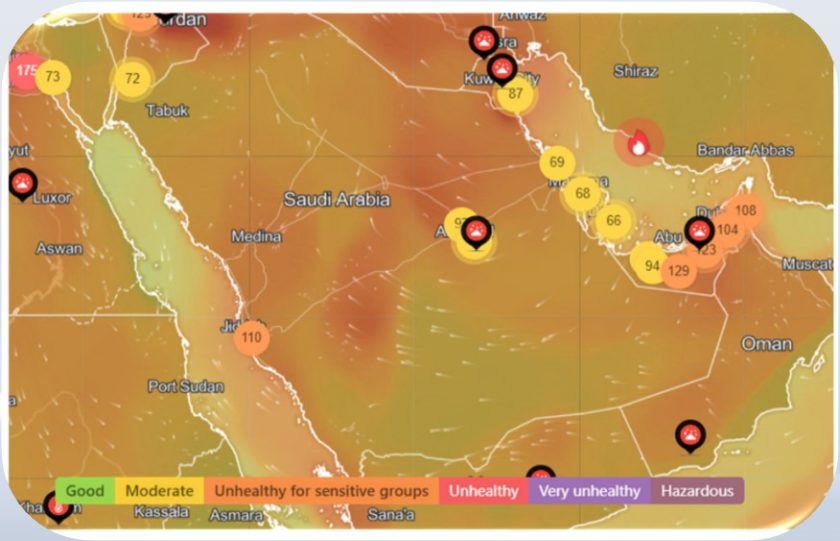
Saudi Arabia Air Quality Context

- **Saudi Arabia is experiencing rapid urbanization and extensive road infrastructure expansion as part of Vision 2030 development initiatives.**

- **The growth of urban corridors and increased vehicle usage have intensified traffic-related emissions, particularly in major cities such as Riyadh, Jeddah, and Dammam.**

- **These urban areas frequently record exceedances of air quality limits for key pollutants, including:**
  - Nitrogen dioxide (NO_2)
  - Ozone (O_3)
  - Particulate matter (PM_{10} and $PM_{2.5}$)

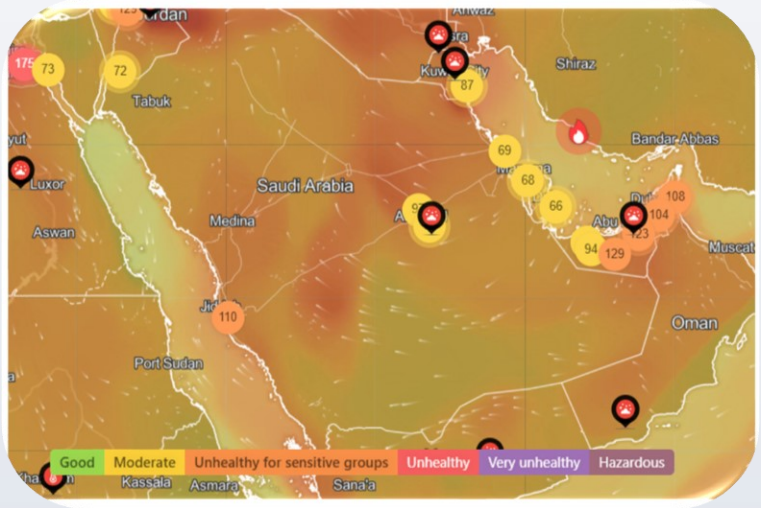




Saudi Arabia Air Quality Context

- **According to the WHO, air pollution in Saudi Arabia contributes to approximately 26% of deaths from stroke and ischemic heart disease.**

- **Average $PM_{2.5}$ concentrations in the Kingdom are reported to be nearly 11 times higher than WHO air quality guideline values, highlighting the severity of the issue and the urgency for effective mitigation strategies.**



Limitations of Current Air Quality Assessment Practices

- **Current air quality assessment in transportation projects relies largely on static and retrospective models.**
- **These conventional models are not well suited to capture the short-term, high-impact changes associated with temporary road work zones.**
- **Key limitations include:**
  - Inability to process real-time traffic and environmental data
  - Limited sensitivity to dynamic traffic conditions such as congestion, detours, and lane closures
  - Lack of predictive capability to anticipate pollution peaks during construction activities
- **As a result, existing approaches provide limited support for:**
  - Operational planning
  - Proactive pollution mitigation
  - Environmental decision-making during work zone implementation

Need for a Digital Twin–Based Approach

- **Emissions in road work zones are influenced by multiple interacting factors, including:**
    - Traffic volume and flow variability
    - Weather and meteorological conditions
    - Construction activities and equipment operations

- **Addressing these complexities requires a dynamic, integrated assessment framework rather than static modeling approaches.**

- **Digital Twins (DTs) provide a virtual representation of road segments that are continuously updated using real-time traffic and air quality data.**

Need for a Digital Twin–Based Approach

- **This approach enables:**
  - Real-time monitoring and simulation of emissions and air quality
  - Predictive evaluation of different work zone and traffic management scenarios
  - Data-driven identification of mitigation strategies to reduce pollution exposure

The adoption of Digital Twin technology supports smart and sustainable infrastructure goals and aligns with Saudi Arabia's Vision 2030 focus on digital transformation and environmental stewardship

Study Motivation

- **Despite the scale of road infrastructure development in Saudi Arabia, air quality impacts of temporary road work zones remain under-studied, particularly at the operational level.**

- **Existing studies in the Kingdom mainly focus on:**
  - Long-term urban air quality trends
  - Regional pollution patterns
  - Dust storm impacts
- **There is a lack of integrated frameworks that link:**
  - **Real-time traffic conditions**
  - **Construction activities**
  - **Short-term air quality degradation**

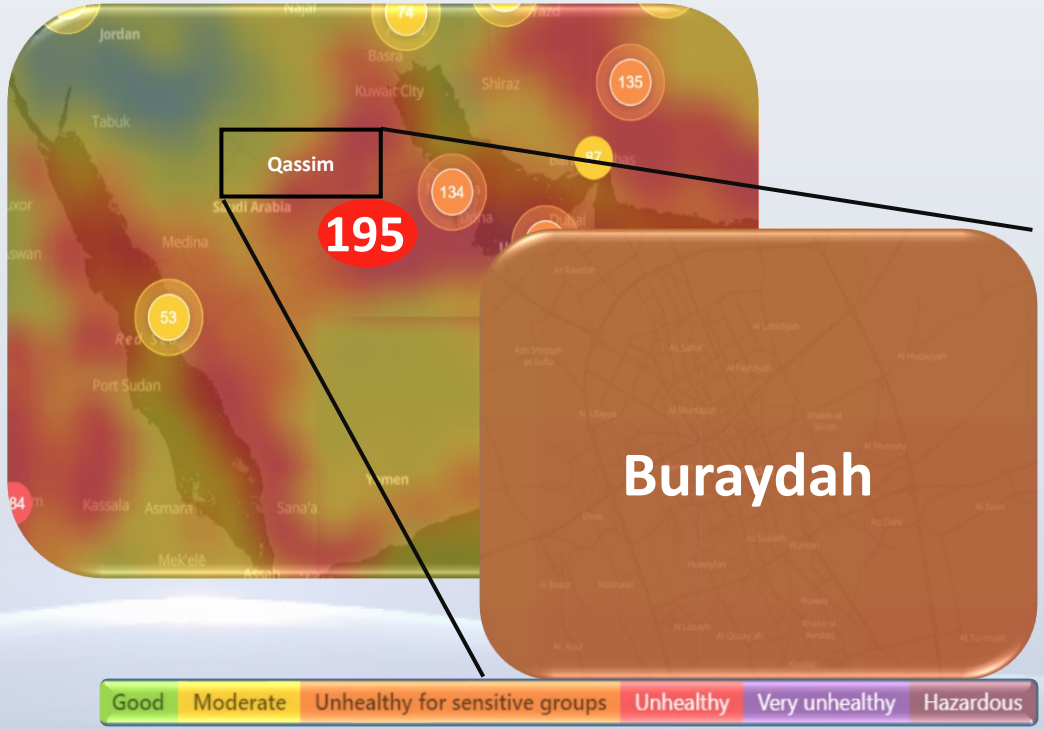
Study Motivation

- **Transportation agencies currently have limited tools to:**
  - **Predict emission spikes during work zone implementation**
  - **Evaluate alternative traffic management and construction scenarios**

- **This study is motivated by the need to:**
  - **Bridge the gap between traffic operations and environmental assessment**
  - **Support proactive, data-driven decision-making**
  - **Enable environmentally intelligent work zone management aligned with Saudi Vision 2030**

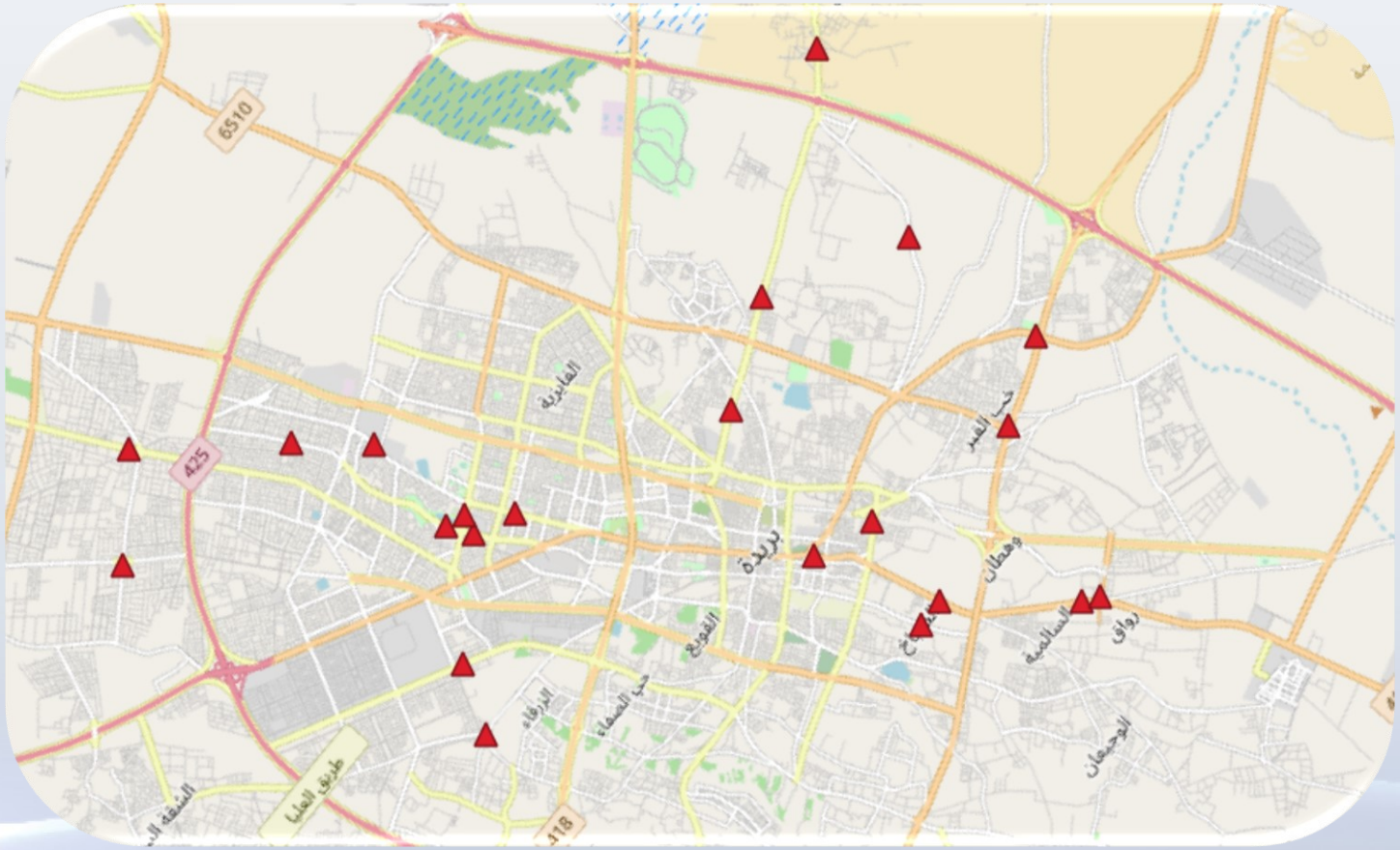
Study Area Selection

- **The study area was selected to represent typical urban road work zone conditions in Saudi Arabia.**
- **The investigation was conducted in Buraydah City, located near the geographical center of the Kingdom.**



Study Area Selection

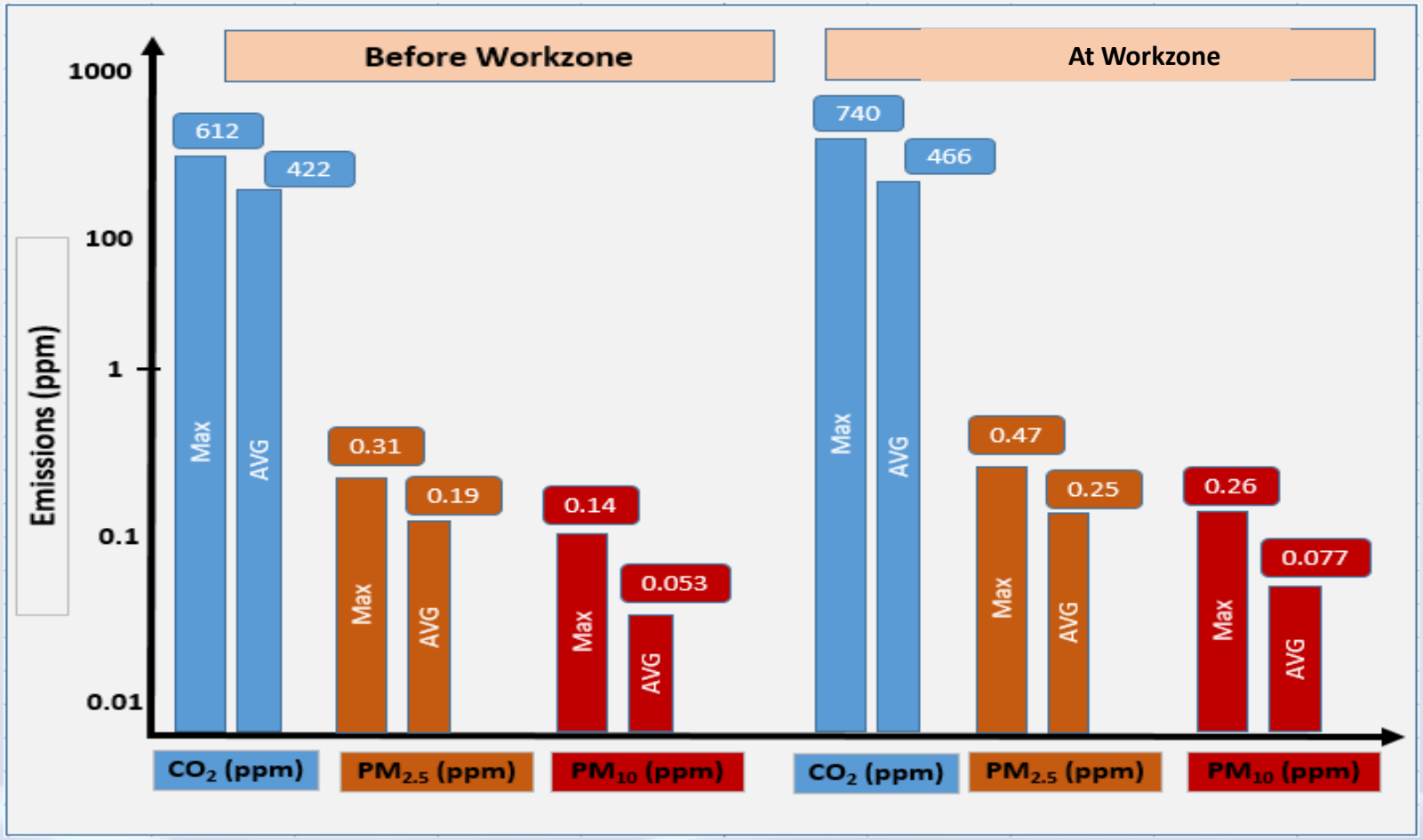
- **Multiple road work zones were identified within the city to capture variability in:**
  - **Traffic demand**
  - **Construction intensity**
  - **Roadway characteristics**



Study Area Selection

- **Work zone sites were selected based on the following criteria:**
  - Work zone length.
  - Number of open and closed lanes.
  - Average Daily Traffic (ADT): Typical peak period: 7:00 PM – 10:00 PM
  - Construction duration.
  - Quantity and type of construction equipment.
  - Posted speed limits and observed operating speeds.
  - Vehicle emissions measured using a Portable Emissions Measurement System (PEMS).
  - Pollutants monitored include:
  - CO, NO_2, O_3, PM_{10}, $PM_{2.5}$, SO_2

Results: Air Pollution Before/at Work Zone Area.



Results: ADT vs. Air Quality Relationship.

- **Analysis focused on the relationship between Average Daily Traffic (ADT) and Air Quality conditions in multiple road work zones.**

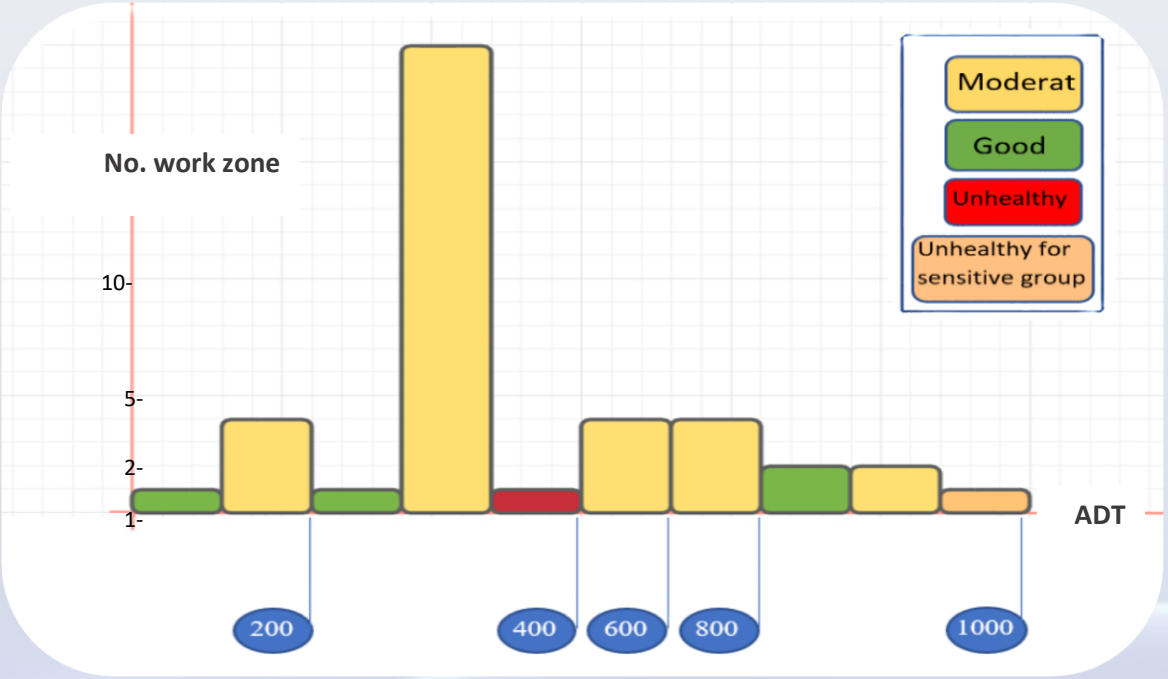
- **Changes in air quality are influenced not only by traffic volume but also by:**
  - Traffic flow characteristics (congestion vs. free flow).
  - Vehicle idling and stop-and-go conditions.
  - Construction activities within work zones.

- **Air quality was evaluated based on measured pollutant concentrations and classified into standard categories::**
  - Good
  - Moderate
  - Unhealthy for Sensitive Groups

O_3 (ppm)	PM_{10} (ppm)	$PM_{2.5}$ (ppm)	CO (ppm)	SO_2 (ppm)	NO_2 (ppm)	CO_2 (ppm)	AQI Values	Level of Health Concern
0.000 – 0.059	0 – 0.054	0.0 – 0.0154	0.0 – 4.4	0.000– 0.034	–	0-700	0 – 50	Good
0.060 – 0.075	0.05– 0.154	0.0155– 0.0404	4.5 – 9.4	0.035– 0.144	–	701-1000	51 – 100	Moderate
0.076 – 0.095	0.155– 0.254	0.0405– 0.0654	9.5 –12.4	0.145– 0.224	–	1001-1500	101 – 150	Unhealthy for SensitiveGroups
0.096 – 0.115	255– 354	65.5 – 150.4	12.5–15.4	0.225– 0.304	–	1501-2500	151 – 200	Unhealthy
0.116 – 0.374	355– 424	150.5– 250.4	15.5–30.4	0.305– 0.604	0.65–1.24	2501-5000	201 – 300	Very Unhealthy
–	0.255– 0.354	0.0655– 0.1504	30.5–40.4	0.605– 0.804	1.25–1.64	>5000	301 – 400	Hazardous
–	0.355– 0.424	0.1505– 0.2504	40.5–50.4	0.805 – 1.004	1.65–2.04	-	401 – 500	Hazardous

Results: ADT vs. Air Quality Relationship.

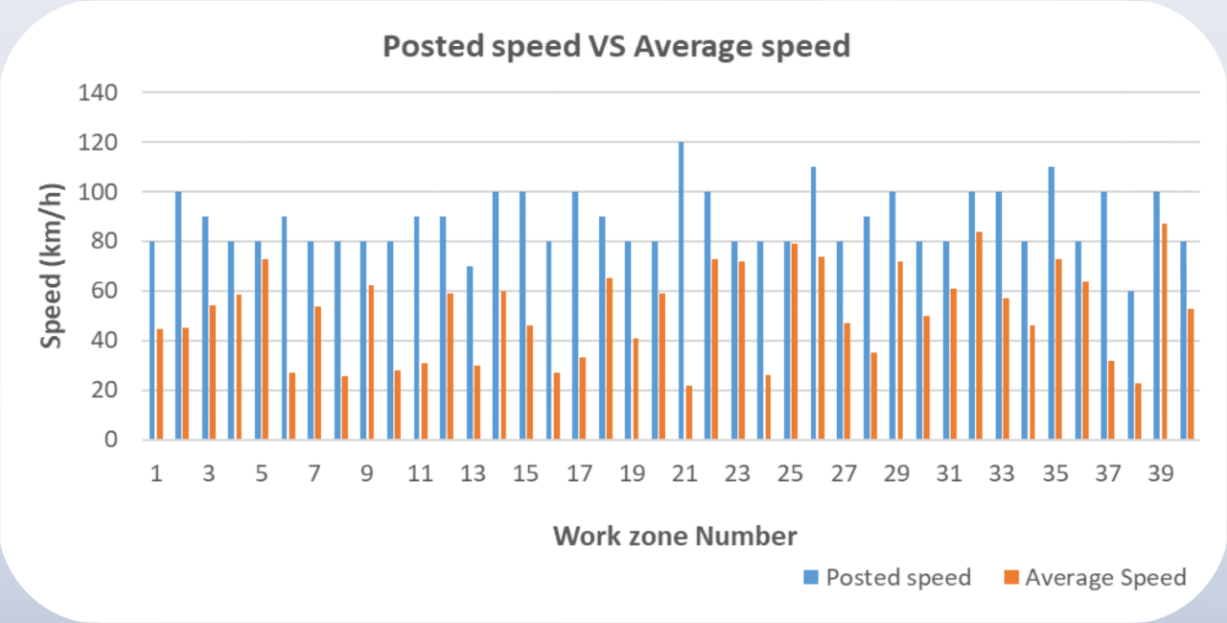
- Work zones with an Average Daily Traffic (ADT) of approximately 400 vehicles/day exhibited the most pronounced air quality degradation among all analyzed sites.
- The majority of these work zones were classified within the **"Moderate"** air quality category.
- At least one work zone within this traffic range reached the "**Unhealthy for Sensitive Groups**" classification.



Results: Posted Speed vs. Actual Travel Speed.

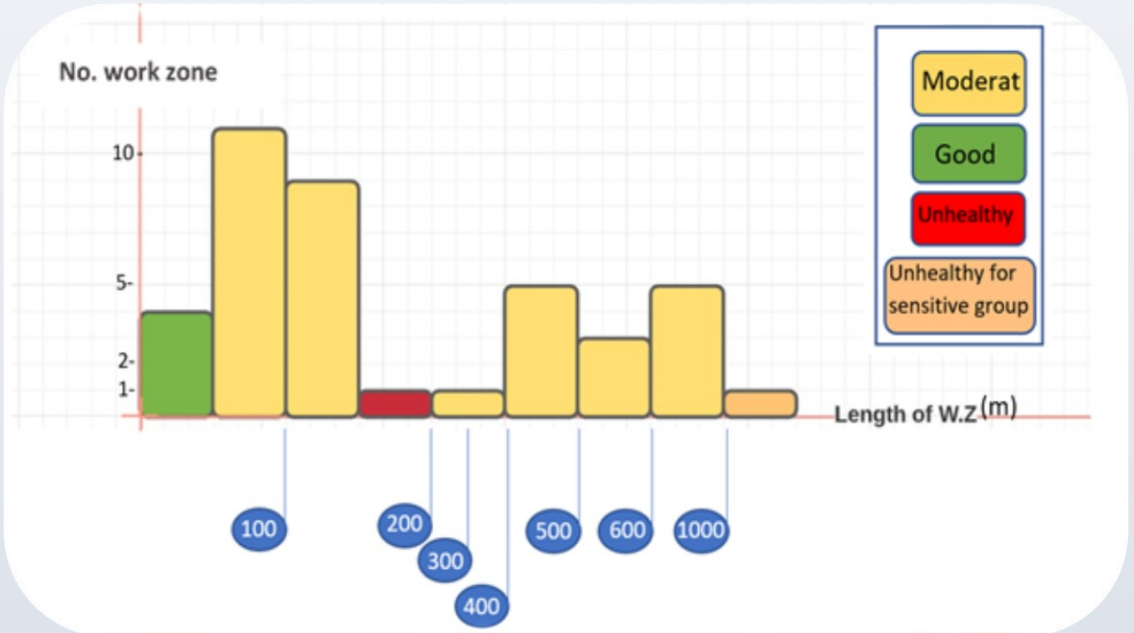
- **Comparing between posted speed limits with observed average vehicle speeds across 40 road work zones, (Ranging between 80-120km/h.**
- **The consistent gap between posted and actual speeds indicates that:**
  - Drivers substantially reduce speed when entering work zones.
  - Speed reduction occurs regardless of posted limits.
- **Reduced average speeds, particularly below 40 km/h, are associated with:**
  - Stop-and-go traffic conditions.
  - Increased vehicle idling.
  - Higher emissions of CO, HC, and CO_2

Speed reductions can therefore amplify the environmental impact of work zones



Results: Work Zone Length vs. Air Quality

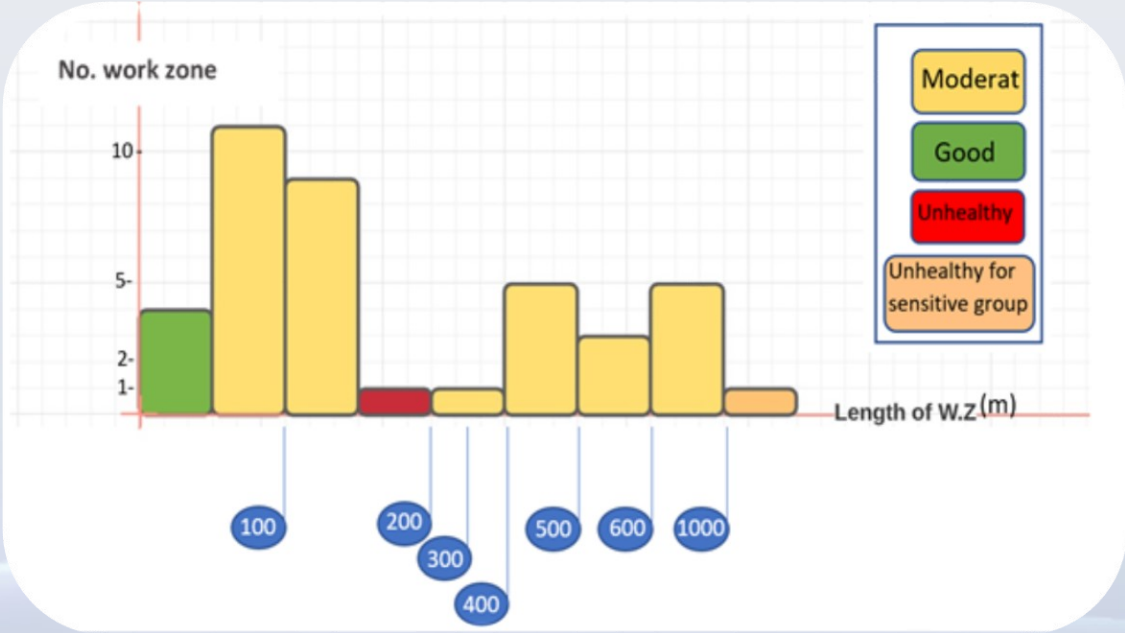
- **The figure illustrates the relationship between work zone length (m) and observed air quality classifications across multiple sites.**
- **Shorter work zones (100–200 m) showed:**
  - The highest frequency of Moderate air quality conditions.
  - Several sites with more than 10 moderate air quality occurrences.
- **Indicates that compact work zones may:**
  - Concentrate traffic and construction emissions.
  - Restrict airflow and pollutant dispersion.
- **Medium-Length Work Zones (200–300 m):**
- **One work zone within the 200–300 m range recorded (Unhealthy)**
- **Suggests that:** Dense construction activity, Limited spacing, Localized congestion



Results: Work Zone Length vs. Air Quality

- **Longer work zones (500–1000 m) exhibited:**
  - Fewer Moderate air quality occurrences.
  - No zones classified as Unhealthy or hazardous for sensitive groups.

- **Suggests improved:**
  - Emission dispersion.
  - Traffic flow distribution.
  - Reduced pollutant concentration per unit area



Results: Multiple Regression Modeling Approach

- **A multiple linear regression model was developed to predict:**
    - Carbon dioxide (CO_2) emissions in road work zones.
- **CO_2 selected as the dependent variable due to:**
    - Its role as a major greenhouse gas.
    - Strong link to traffic and construction activities
- **The final regression equation is:**

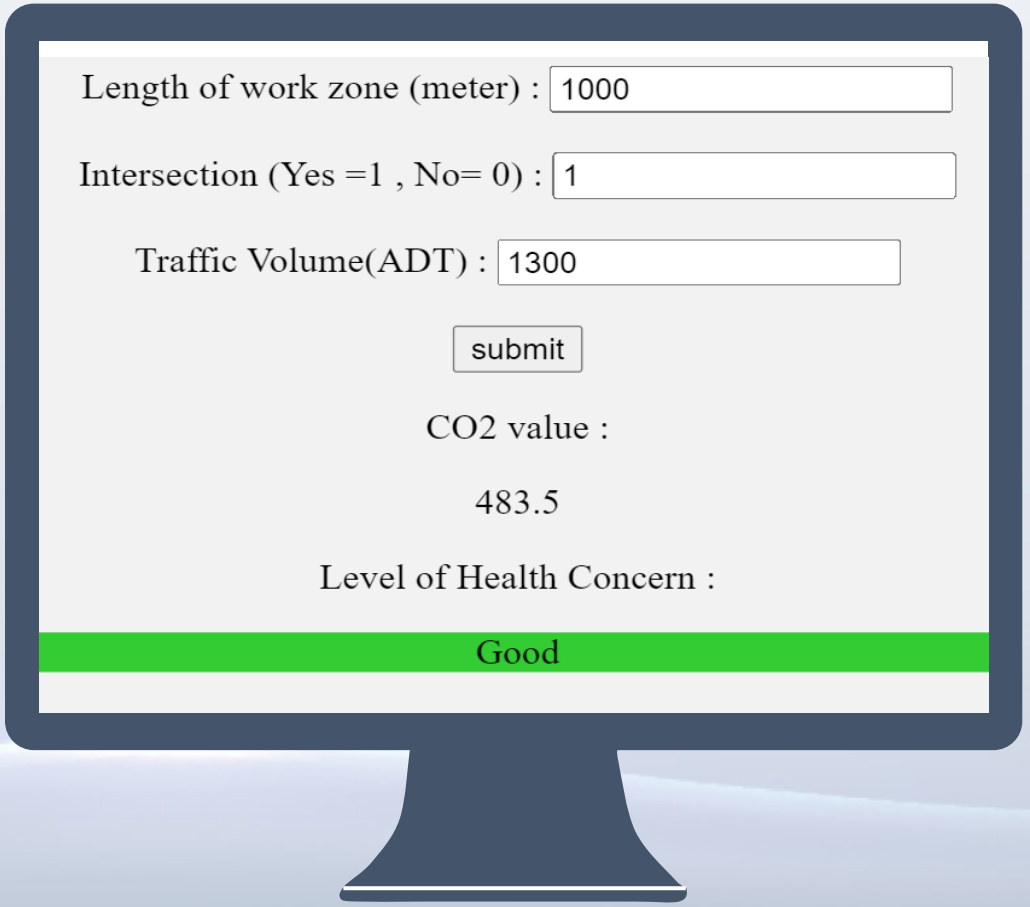
	Coefficients	Standard Error	T Stat	P-Value	Lower 95%	Upper 95%	Lower 90%	Upper 90%
Intercept	392.67	15.55	25.25	9.69E-18	360.42	424.92	365.97	419.37
Length of work zone	0.01	0.00	3.20	0.00	0.00	0.02	0.06	0.02
Is there intersection	-26.17	13.56	-1.93	0.07	-54.28	1.94	-49.45	-2.89
ADT	0.08	0.03	3.11	0.01	0.03	0.14	0.04	0.13

$$CO2=0.013L+0.08(ADT)-26.17I+392.67$$

- **Interpretation:**
    - **CO_2 emissions increase with traffic volume and work zone length.**
    - **Presence of an intersection influences emissions due to traffic control effects**

Decision Support Tool for Air Quality Management

- **Enables proactive air quality control rather than reactive monitoring.**
- **Supports decisions on:**
  - **Work zone scheduling and duration**
    - Traffic rerouting strategies
    - Speed limit adjustments
    - Signal timing optimization

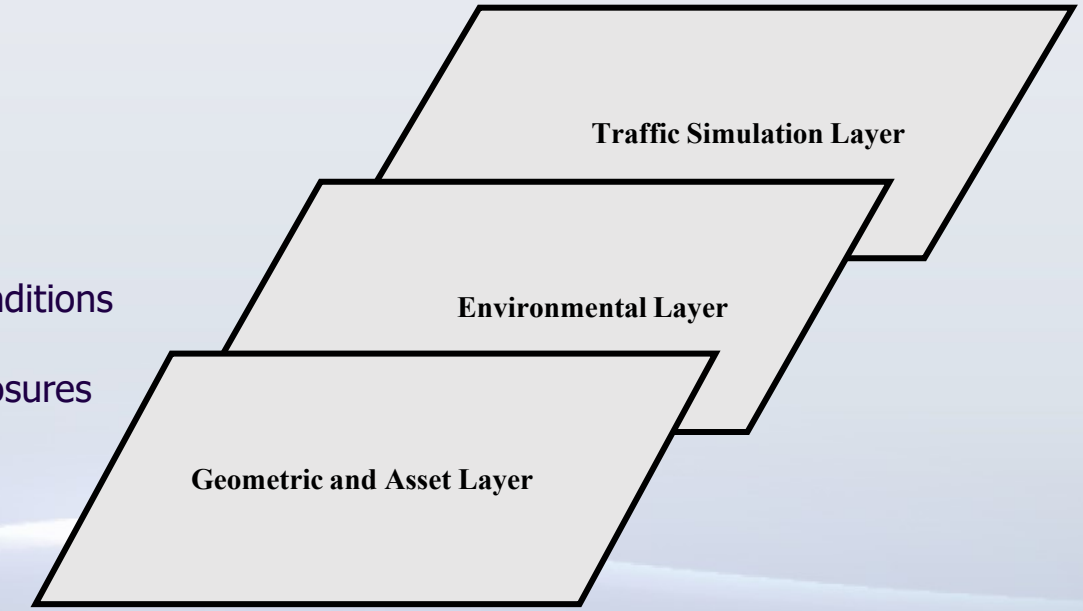


Digital Twin–Based Monitoring Framework

- **Building on the collected traffic, emission, and environmental data the Digital Twin (DT)–based framework can be developed for monitoring air quality impacts in road work zones.**

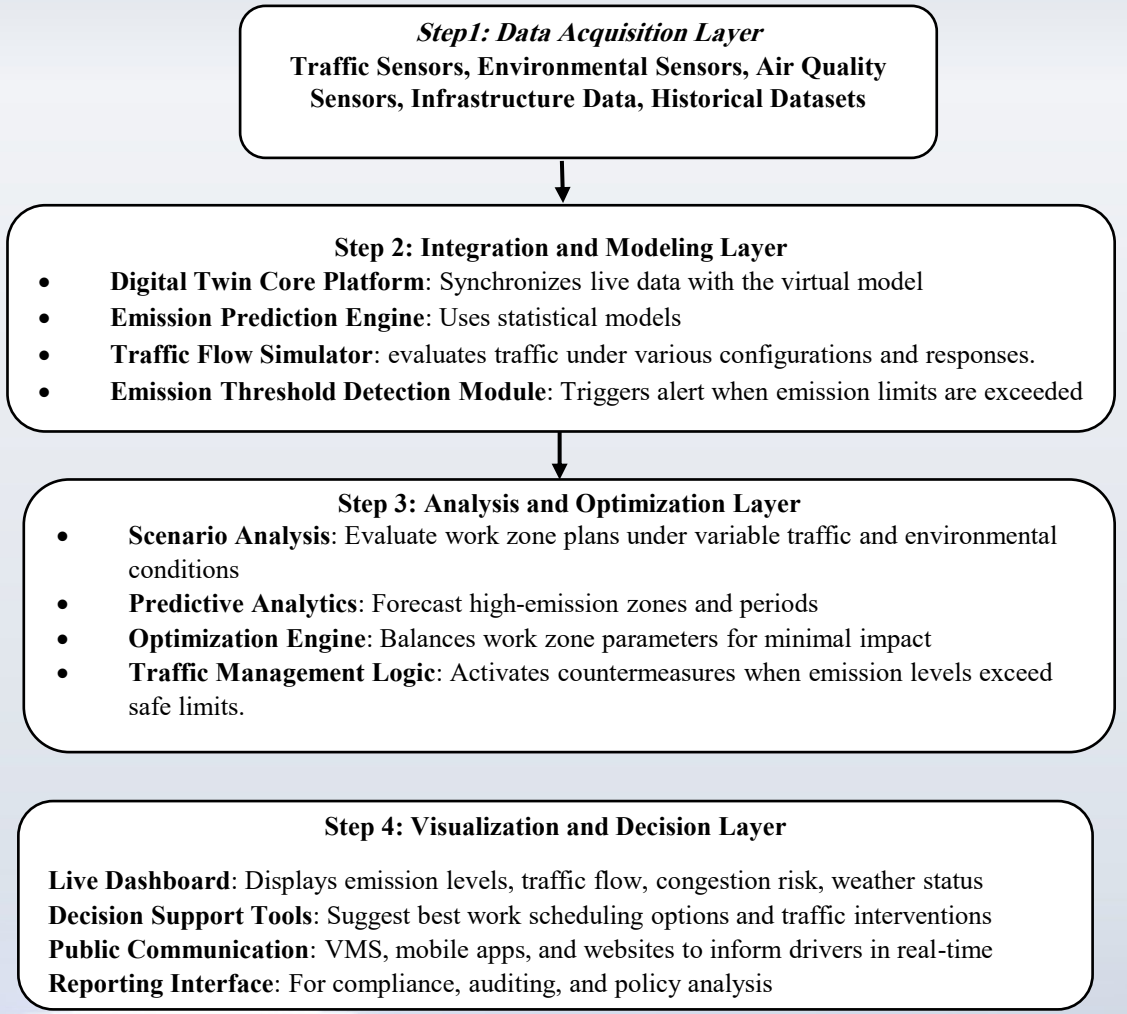
- **This framework can be developed by using Building Information Management (BIM) and Geographic Information System (GIS) integration.**

- **This integration enables:**
  - Continuous monitoring of pollutant concentrations
  - Dynamic simulation of emission generation under varying traffic conditions
  - Assessment of short-term environmental impacts caused by lane closures and congestion



Real-Time Monitoring By Using DTs.

- **DTs integrate data from:**
  - IoT-enabled air quality sensors
  - Traffic counters
  - CCTV cameras
- **Enable continuous monitoring of:**
  - Emission levels
  - Traffic behavior within work zones
- **Support:**
  - Identification of emission hotspots
  - Detection of exceedances beyond acceptable thresholds
- **Provide immediate situational awareness during construction activities.**



Suggested framework for DT at Work Zones

Conclusions

- **Road construction work zones play a critical role in influencing local air quality, requiring advanced monitoring and modeling approaches to mitigate environmental impacts.**

- **Results demonstrate that work zone length, average daily traffic, and vehicle speed significantly affect emissions of key pollutants, including CO_2, $PM_{2.5}$, and NO_2.**

- **Traditional static air quality models are insufficient for capturing the dynamic and short-term conditions within work zones, highlighting the need for real-time and predictive assessment methods.**

- **The DT framework enables proactive decision-making for work zone design, traffic management, and emission mitigation, improving emission estimation accuracy and supporting sustainable urban transportation.**

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