Managing complexity in Cities

with Predictive Digital Twins

for Liveable & Resilient Cities

Bart Vuijk TNO | 2024

TNO – Dutch Organization for Applied Research

- Established by law in 1932
- Not for profit, independent
- “Innovation for life”
- 75+ Professors & Lecturers
- Connecting Government, Academia and Business
- 5,000 professionals
- 600 million € revenue

Urban Challenges

- Urbanisation
- Aging population
- Scarcity of space
- Pollution
- Infectious diseases
- Decarbonisation
- Reliable & affordable Energy
- Traffic / Mobility / Accessibility
- Legacy infrastructure / heritage
- Inclusion
- Crime

City: a complex organism

All things interconnected

Urban Strategy

Digital Twins for Sustainable and Liveable Cities

Problem statement

Increasing complexity of decision making

Silo's lead to costly, sub-optimal solutions

Time to decision

Quality of decision

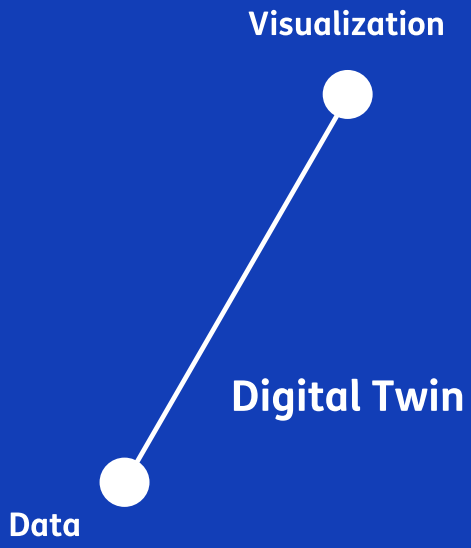
Infrastructure decisions: Billions of EUR

TNO innovation for life

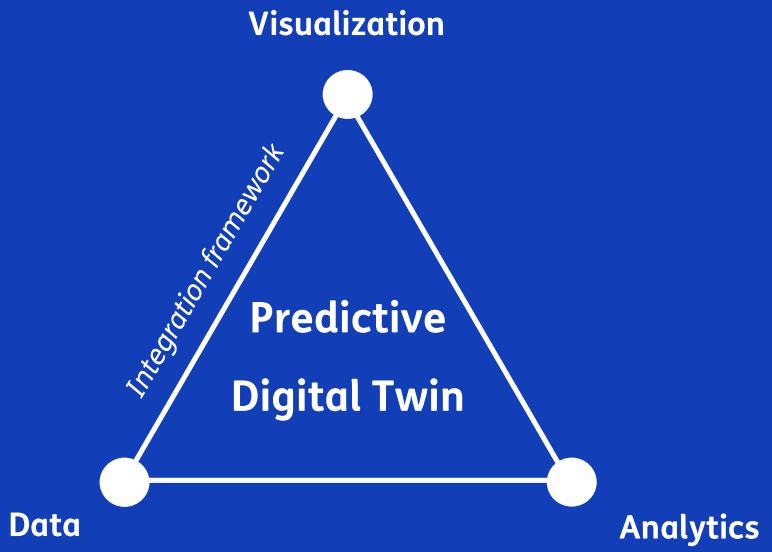
Vision: making complexity manageable

Interactive analysis of complex what-if scenario's with Digital Twins

Urban Strategy: making complexity manageable



Urban Strategy: making complexity manageable

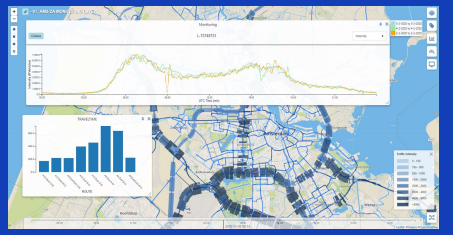


Urban Strategy

Digital Twins for Sustainable and Liveable Cities

TNO Urban Strategy – interactive Digital Twins

Multiple domains – interventions – perspectives



TNO innovation for life

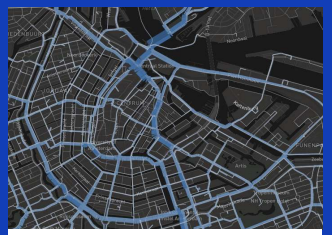
Urban Strategy | Digital Twins for Sustainable and Liveable Cities

Urban Strategy simulation modules

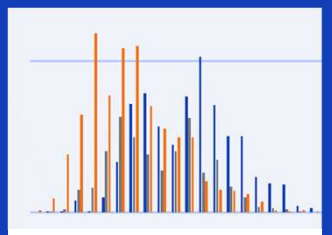
Making Complexity Manageable – across multiple domains

Mobility Demand

Multi-mode network allocation

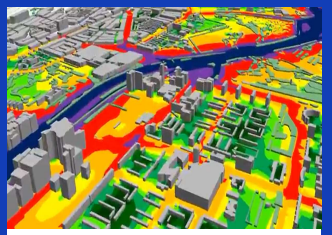


Active transport cycling & walking

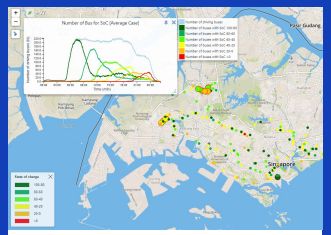


Distribution of accessibility

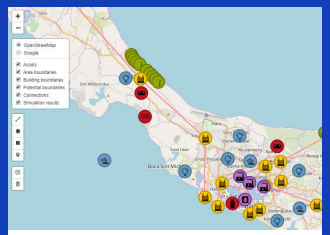
Air quality (Road & Industry)



Noise (Road, Rail & Industry)



Electric fleet simulation



EV – power grid Interaction

Greenhouse gas emissions

Infrastructure Resilience

Spatial impacts

Well-being indicators

TNO innovation for life

San Diego Digital Twin | TNO Urban Strategy

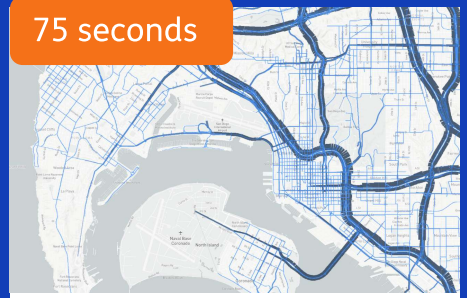
San Diego Digital Twin (2.5M residents)

Calculation times of individual models

5 seconds

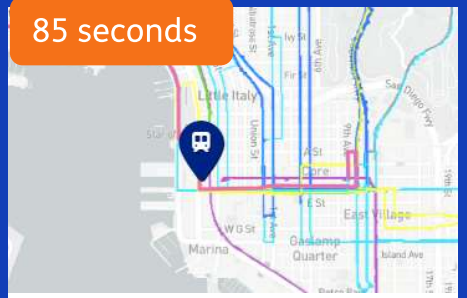
Demand

75 seconds



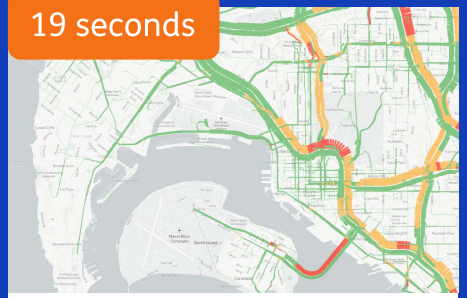
Traffic assignment

85 seconds



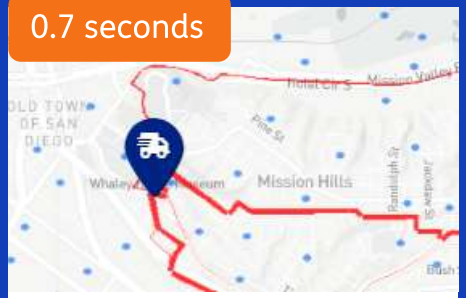
Public Transport assignment

19 seconds



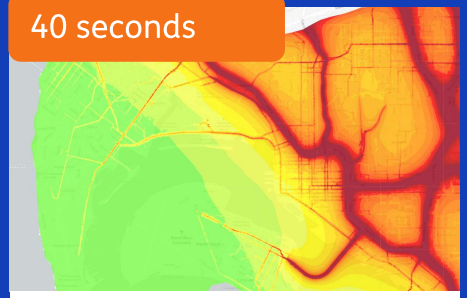
Mode choice

0.7 seconds



Hub

40 seconds



Air

100 seconds

Noise

90 seconds

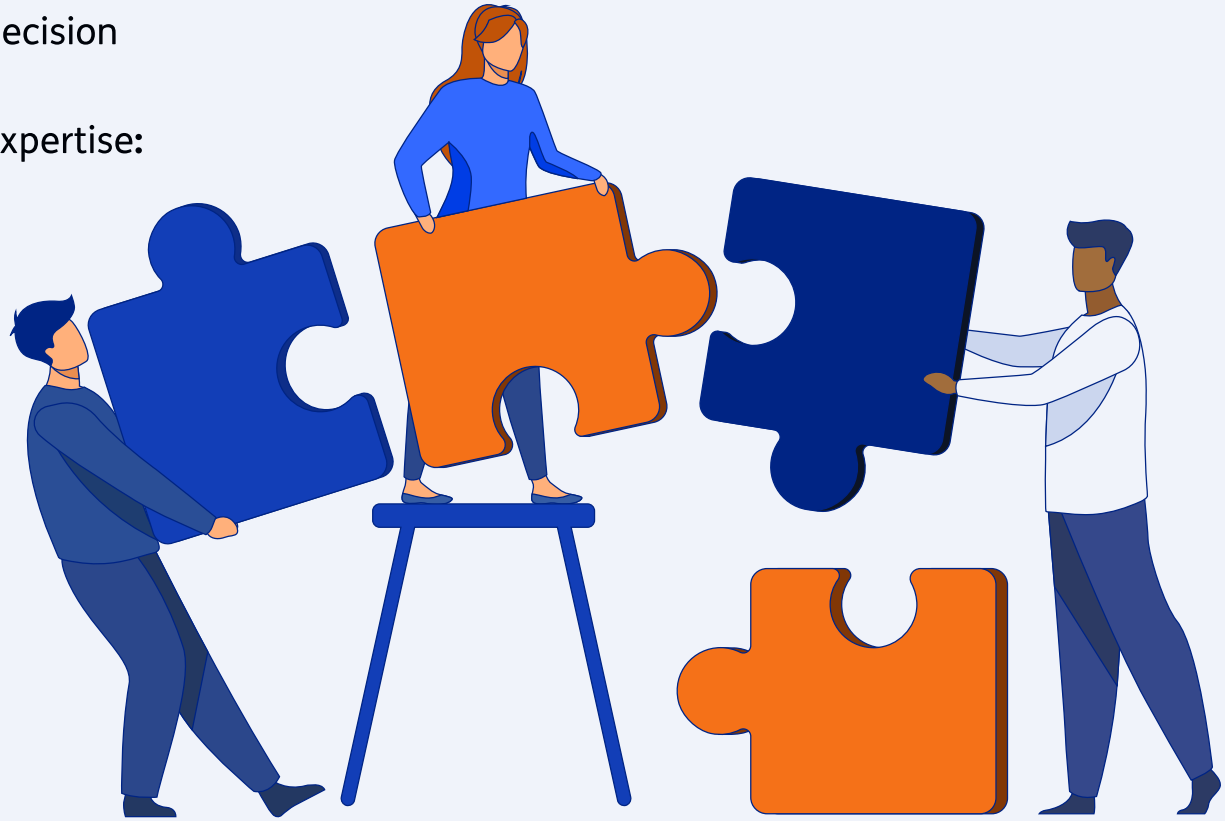
Traffic indicators

What do we do differently?

User oriented: Interactive and **Integral** for better decision making

Science based: Marriage of next level IT & domain expertise:

- **IT - High Performance Computing Technology**
  - Distributed computing & storage architecture
  - GPU based simulations – up to 1,000x faster
  - Extreme scaling potential
- **Multi-domain approach**
  - Traffic, Air Quality, Noise, Energy, Safety, … …
  - Parallelized algorithms for GPU infra



Modular by design – fully data driven

Seamlessly connected in one platform, tested in the real world

Urban Strategy

Digital Twins for Sustainable and Liveable Cities

Traction

Amsterdam and TNO

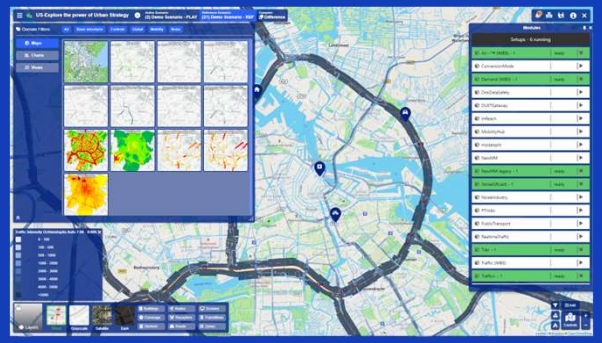
- Innovation collaboration since 2017 (extended to 2026)
- TNO: responsible for innovations
  - Application of Digital Twin platform Urban Strategy
  - Model development
  - Support
- City of Amsterdam: innovative Use Cases
- Initiated by City of Amsterdam's CTO office
  - Adopted by strategic traffic planning office

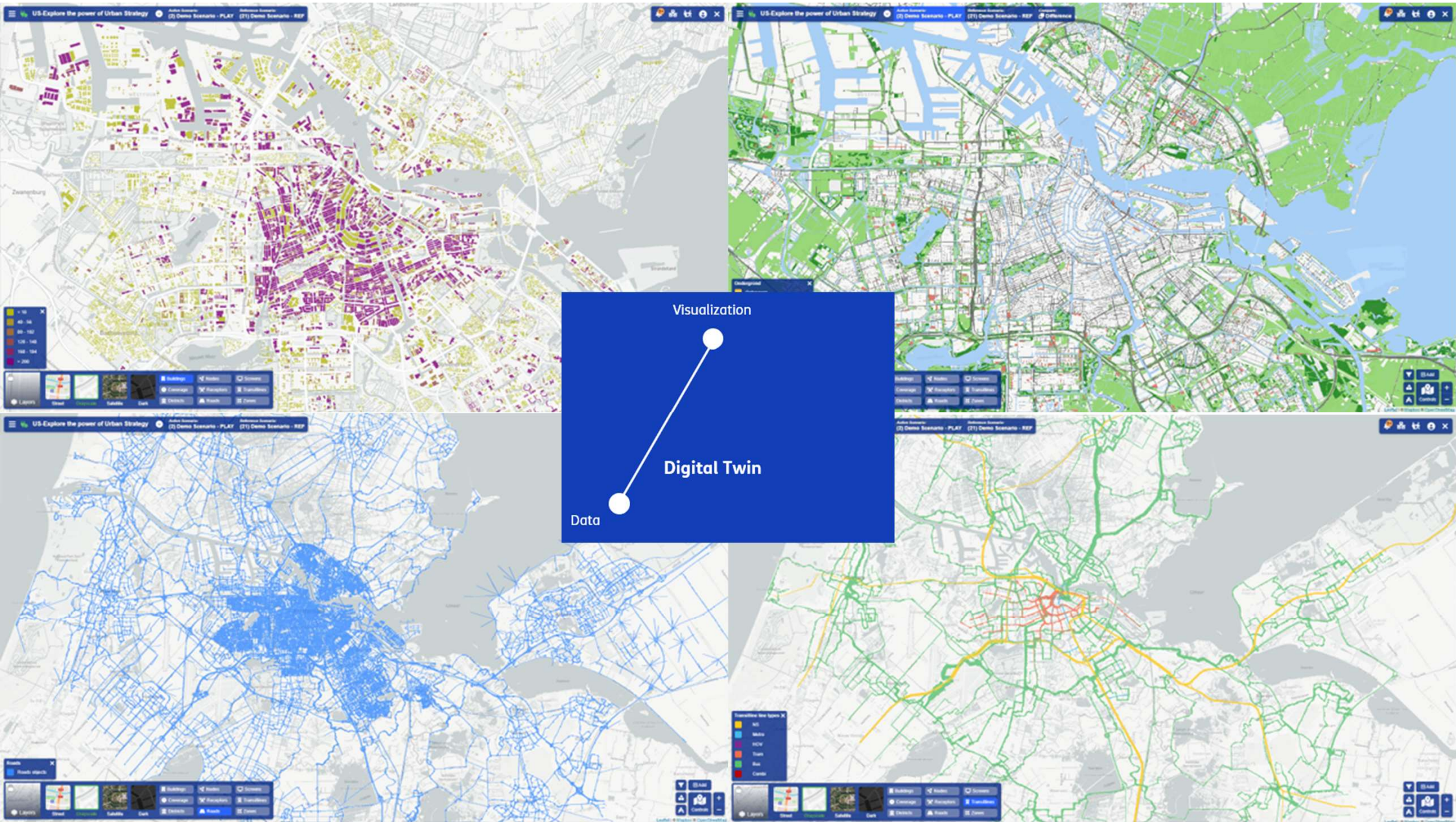
TNO innovation for life
How to plan large renovation of >100 km of quays and bridges?
What will be the impact of large scale new residential housing on accessibility and environment?
How will mega-events affect accessibility of the city?
How does lowering the speed limit improve Air Quality and Safety?
How do we optimize the impact of shared vehicles?
What will be the Air Quality and CO2-effects of a ZE zone?
What is the best location for mobility hubs?
What is the impact of introducing robotaxis?
How to improve well-being & inclusion for various communities?
What is the impact of changing parking tariffs on use of Public Transport and Livability?

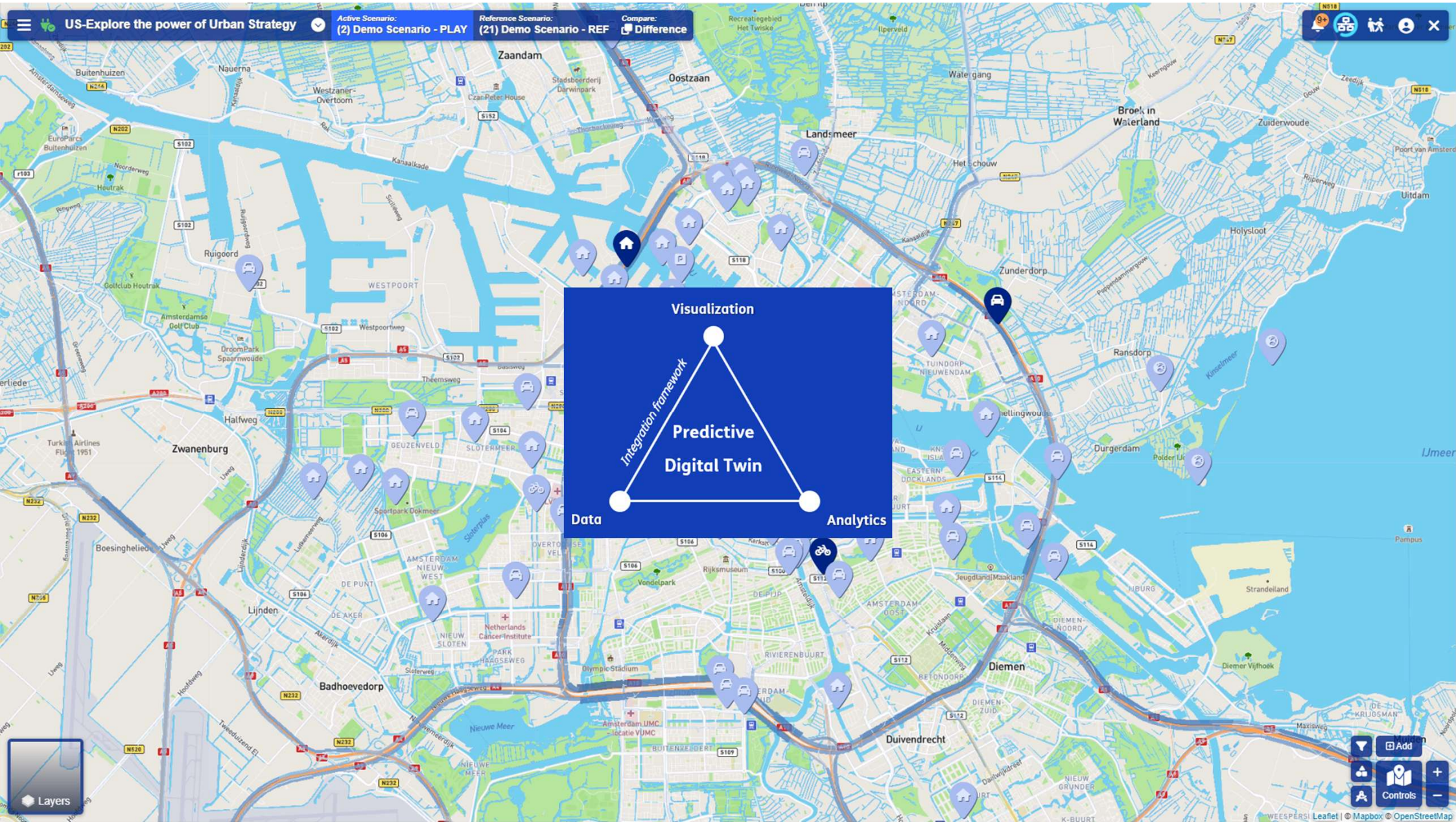
Urban Strategy | Digital Twins for Liveable and Resilient Cities

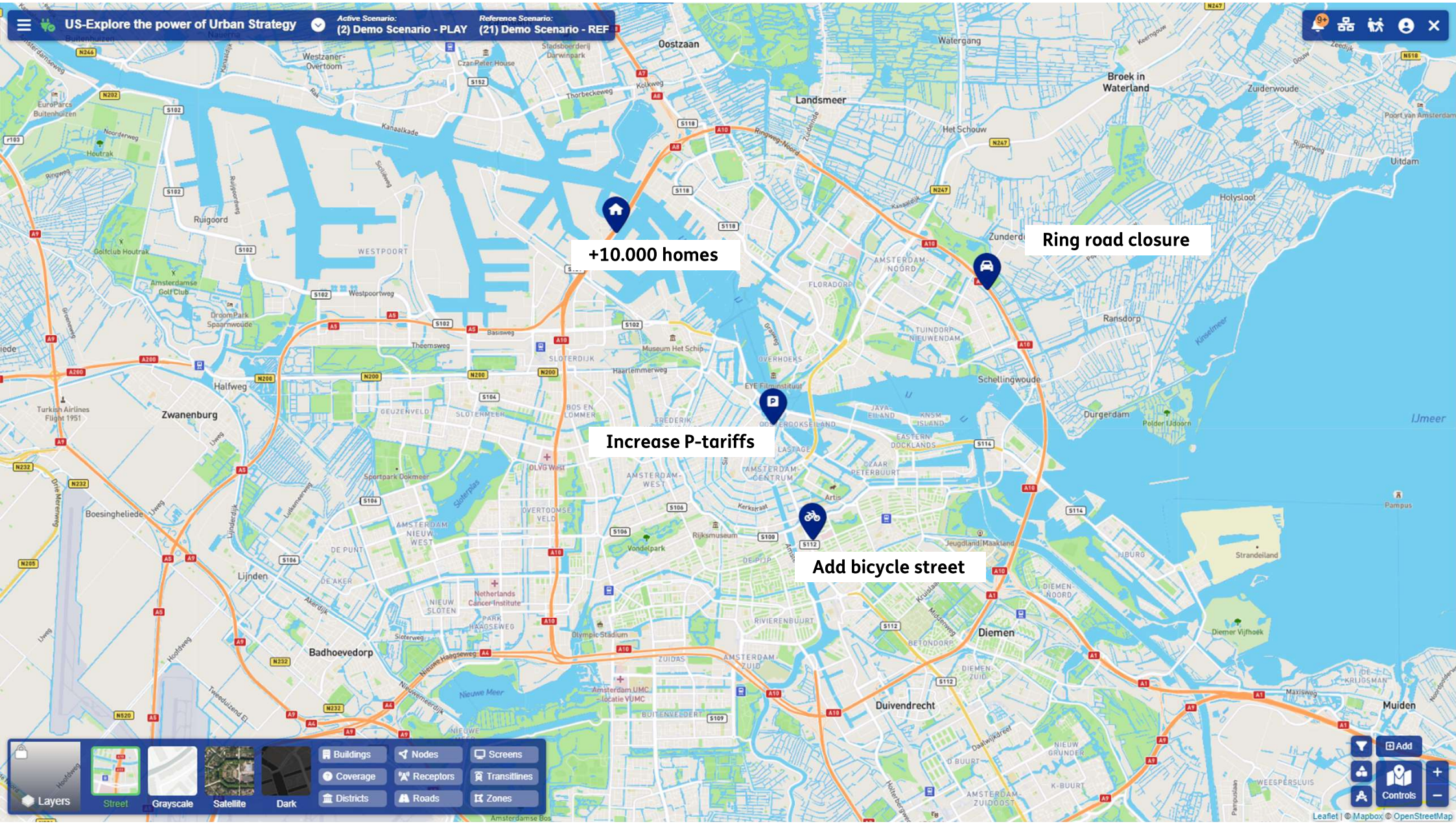
Amsterdam – Use Cases

- Integral Strategic Mobility Planning
- Shared Mobility
- Large scale infrastructure renovations
- Environmental impact (NO_x, PM)
- Parking policies
- CO_2 impact
- Equity use cases
- Accessibility & transport poverty
- Maximum speed reduction
- City redevelopment
- Events
- Noise impact
- Zero emission zones
- Bus fleet electrification
- AV introduction scenario's
- Safety impact
- Logistics (road, water)
- Future mobility modes




Visualization
Digital Twin
Data


US-Explore the power of Urban Strategy
Active Scenario:
(2) Demo Scenario - PLAY
Reference Scenario:
(21) Demo Scenario - REF
Compare:
Difference
Visualization
Integration framework
Predictive
Digital Twin
Data
Analytics
Layers
Add
Controls
Leaflet | © Mapbox © OpenStreetMap


US-Explore the power of Urban Strategy
Active Scenario:
(2) Demo Scenario - PLAY
Reference Scenario:
(21) Demo Scenario - REF
+10.000 homes
Ring road closure
Increase P-tariffs
Add bicycle street
Layers
Street
Grayscale
Satellite
Dark
Buildings
Nodes
Screens
Coverage
Receptors
Transitlines
Districts
Roads
Zones
Add
Controls
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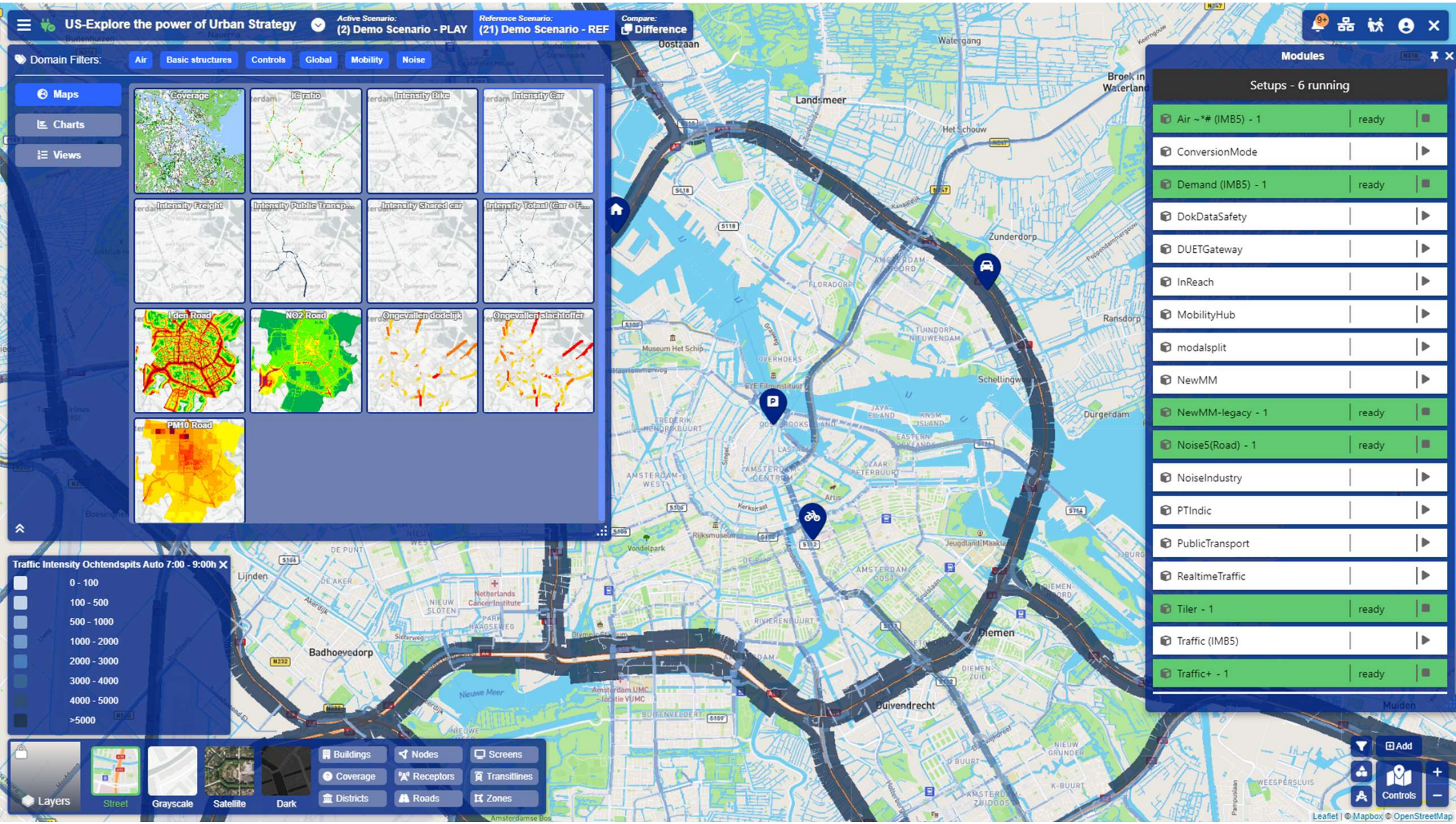
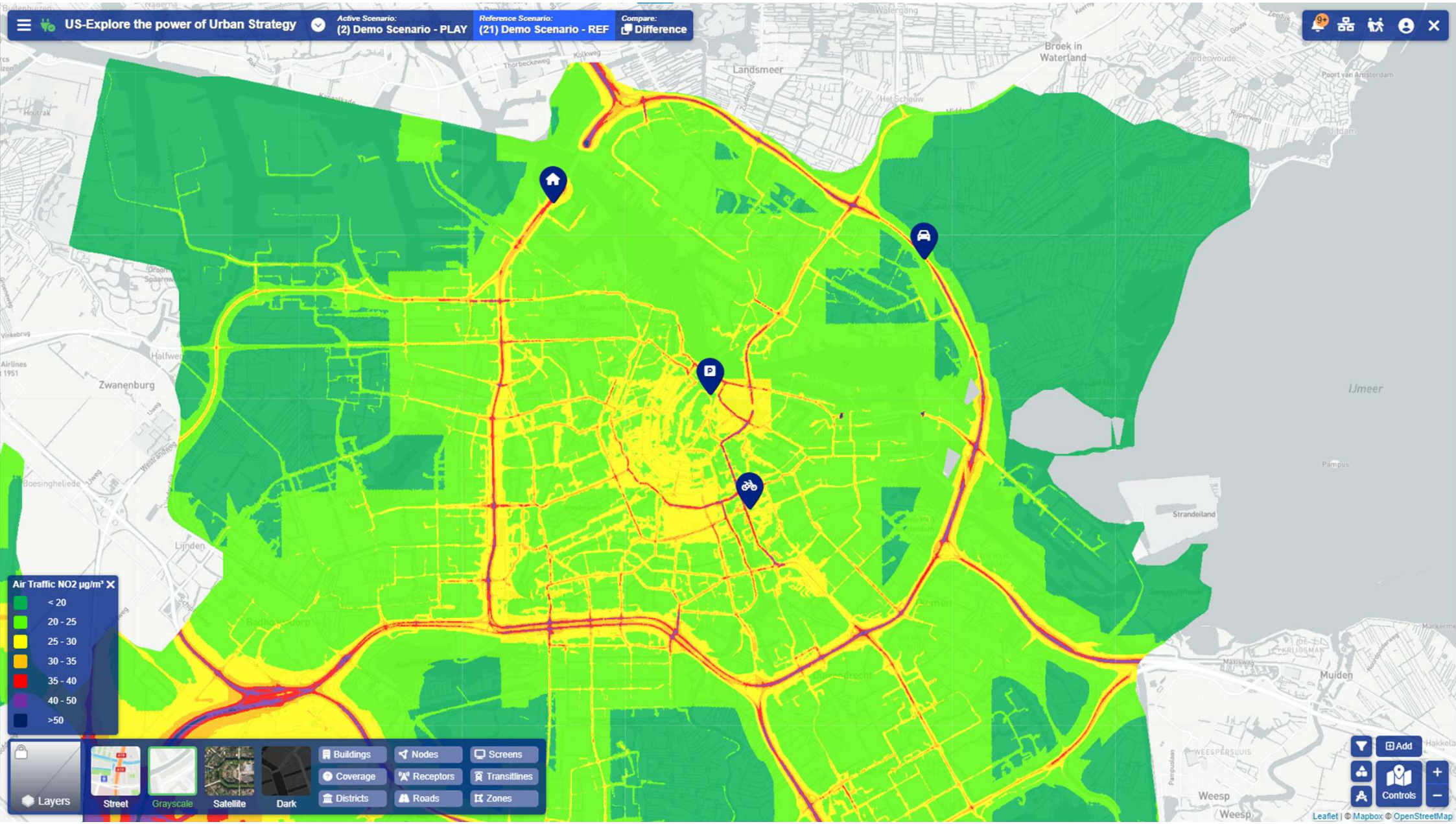
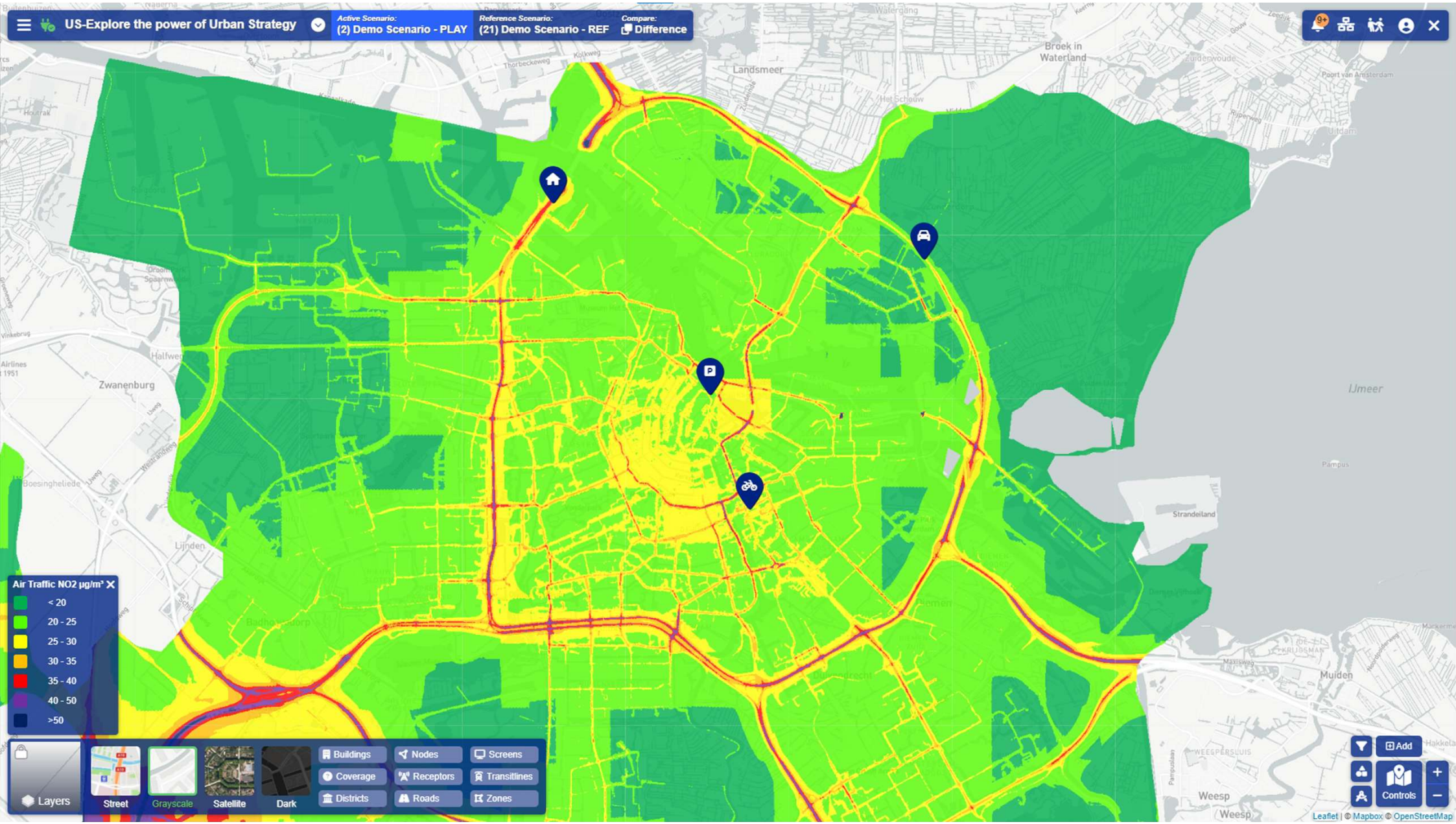

US-Explore the power of Urban Strategy
Active Scenario:
(2) Demo Scenario - PLAY
Reference Scenario:
(21) Demo Scenario - REF
Compare:
Difference
Domain Filters:
Air
Basic structures
Controls
Global
Mobility
Noise
Maps
Charts
Views
Coverage
IC ratio
Intensity Bike
Intensity Car
Intensity Freight
Intensity Public Transp...
Intensity Shared car
Intensity Totaal (Car + F...
Lden Road
NO2 Road
Ongevallen dodelijk
Ongevallen slachtoffer
PM10 Road
Traffic Intensity Ochtendspits Auto 7:00 - 9:00h
0 - 100
100 - 500
500 - 1000
1000 - 2000
2000 - 3000
3000 - 4000
4000 - 5000
>5000
Modules
Setups - 6 running
Air ~*# (IMB5) - 1
ready
ConversionMode
Demand (IMB5) - 1
ready
DokDataSafety
DUETGateway
InReach
MobilityHub
modalsplit
NewMM
NewMM-legacy - 1
ready
Noise5(Road) - 1
ready
NoiseIndustry
PTIndic
PublicTransport
RealtimeTraffic
Tiler - 1
ready
Traffic (IMB5)
Traffic+ - 1
ready
Layers
Street
Grayscale
Satellite
Dark
Buildings
Nodes
Screens
Coverage
Receptors
Transitlines
Districts
Roads
Zones
Add
Controls
Oostzaan
Landsmeer
Zunderdorp
Ransdorp
Durgerdam
Schellingwoude
Diemen
Duivendrecht
Badhoevedorp
Lijnden
Leaflet | © Mapbox © OpenStreetMap


US-Explore the power of Urban Strategy
Active Scenario:
(2) Demo Scenario - PLAY
Reference Scenario:
(21) Demo Scenario - REF
Compare:
Difference
Air Traffic NO2 µg/m³
< 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 50
>50
Layers
Street
Grayscale
Satellite
Dark
Buildings
Nodes
Screens
Coverage
Receptors
Transitlines
Districts
Roads
Zones
Add
Controls
Landsmeer
Broek in Waterland
Zwanenburg
IJmeer
Strandeiland
Muiden
Weesp
Leaflet | © Mapbox © OpenStreetMap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Compare:
Difference
Air Traffic NO2 µg/m³
< 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 50
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Grayscale
Satellite
Dark
Buildings
Nodes
Screens
Coverage
Receptors
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Landsmeer
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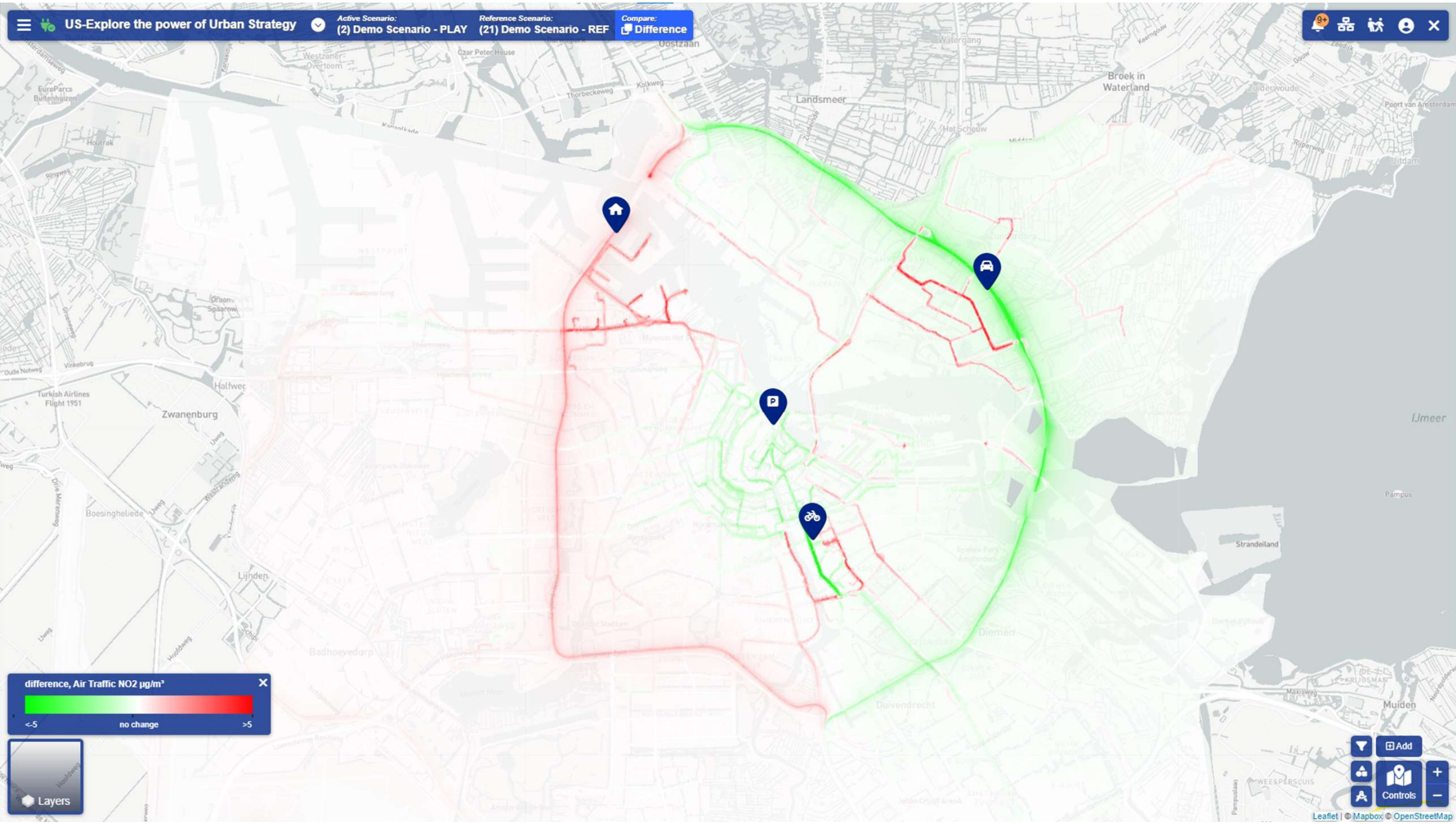
Zwanenburg
IJmeer
Strandeiland
Muiden
Weesp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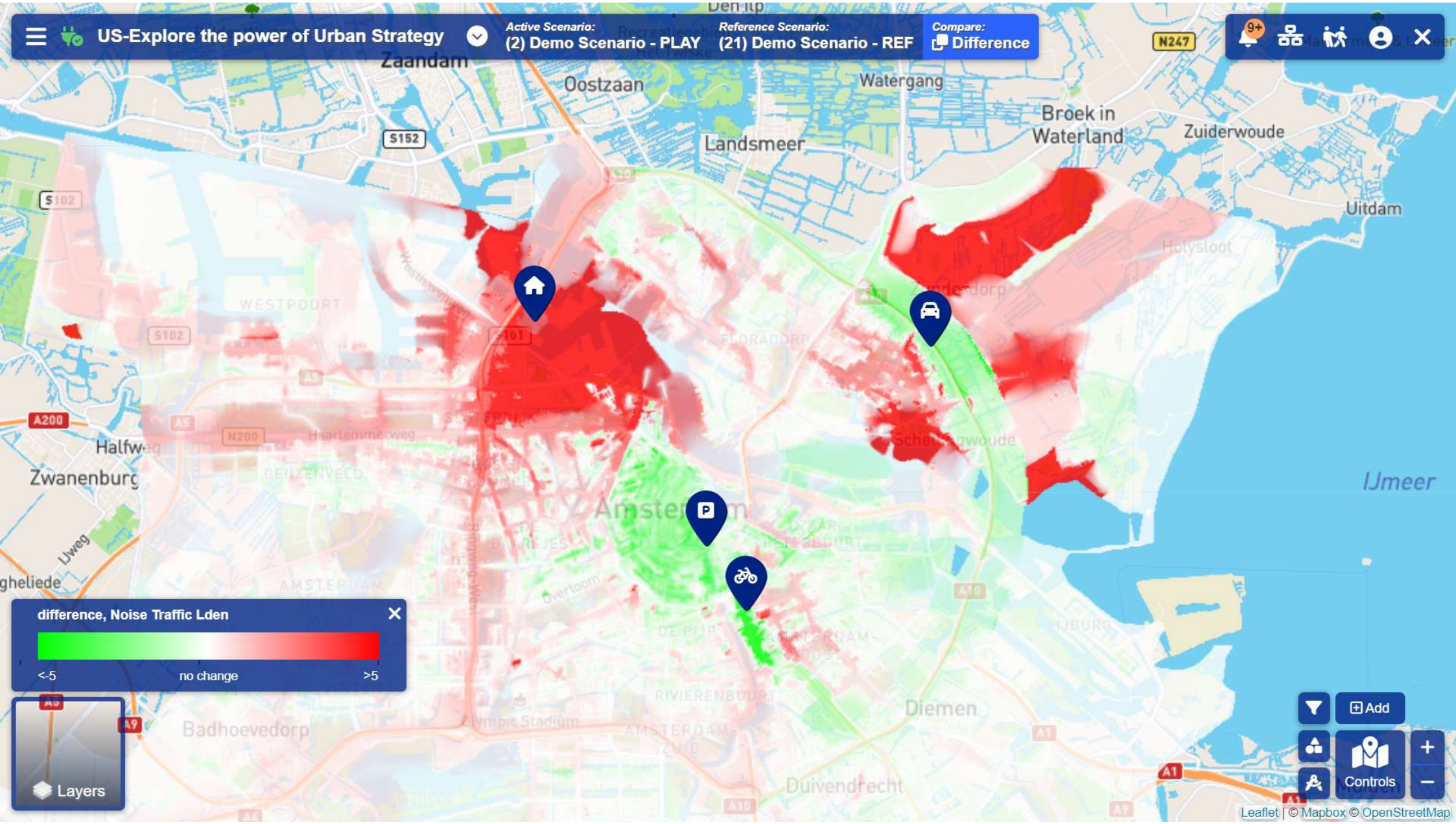
Active Scenario:
(2) Demo Scenario - PLAY
Reference Scenario:
(21) Demo Scenario - REF
Compare:
Difference
difference, Air Traffic NO2 µg/m³
<-5
no change
>5
Layers
Add
Controls
Leaflet | © Mapbox © OpenStreetMap
Landsmeer
Broek in Waterland
Zwanenburg
Halfweg
Lijnden
Badhoevedorp
Diemen
Duivendrecht
Strandeiland
Muiden
IJmeer
Pampus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(21) Demo Scenario - REF
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Oostzaan
Watergang
Broek in Waterland
Zuiderwoude
Landsmeer
Uitdam
Holysloot
S152
S102
N247
A200
N200
Halfweg
Zwanenburg
IJmeer
Diemen
Badhoevedorp
Duivendrecht
difference, Noise Traffic Lden
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no change
>5
Layers
Add
Controls
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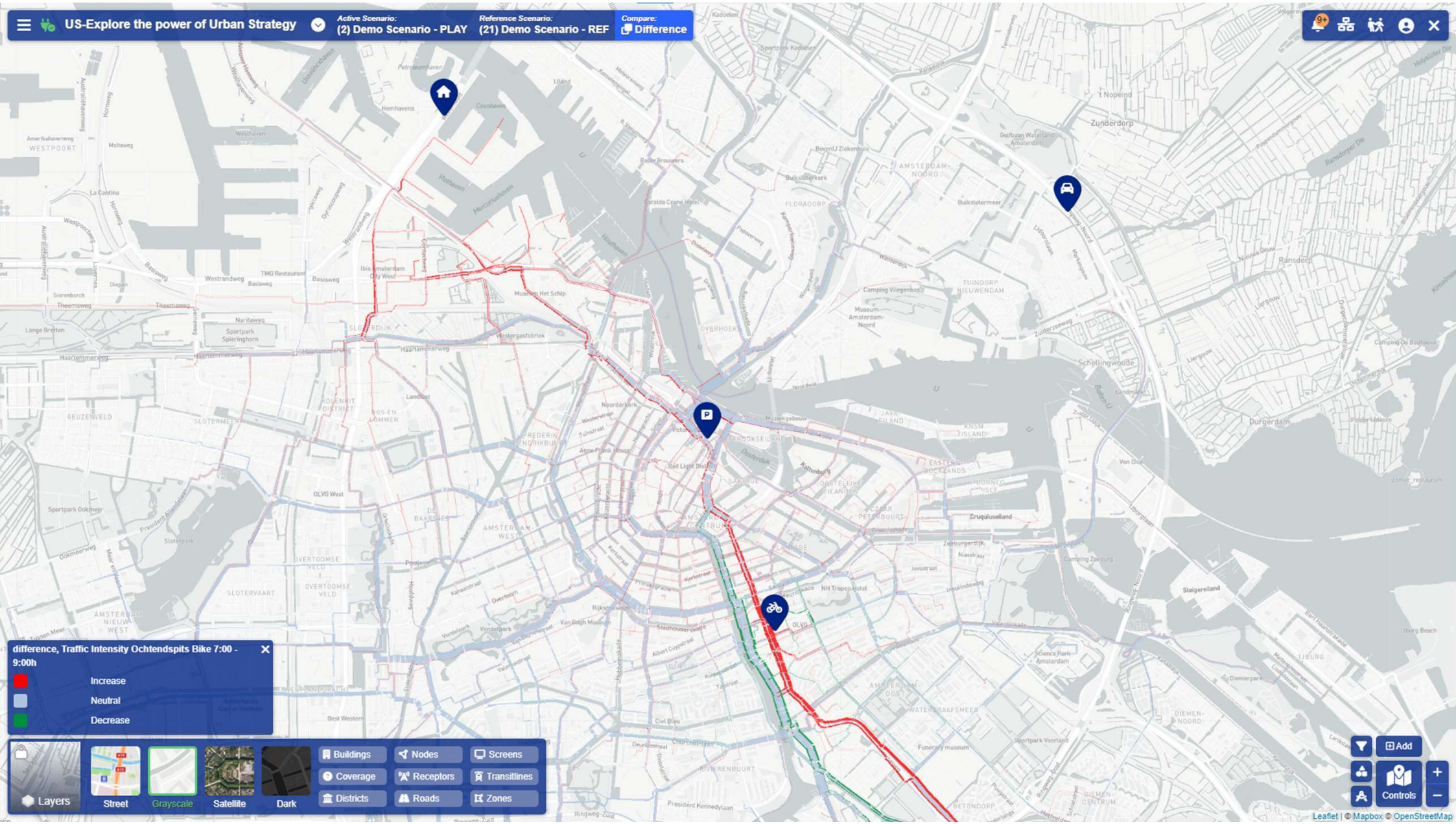
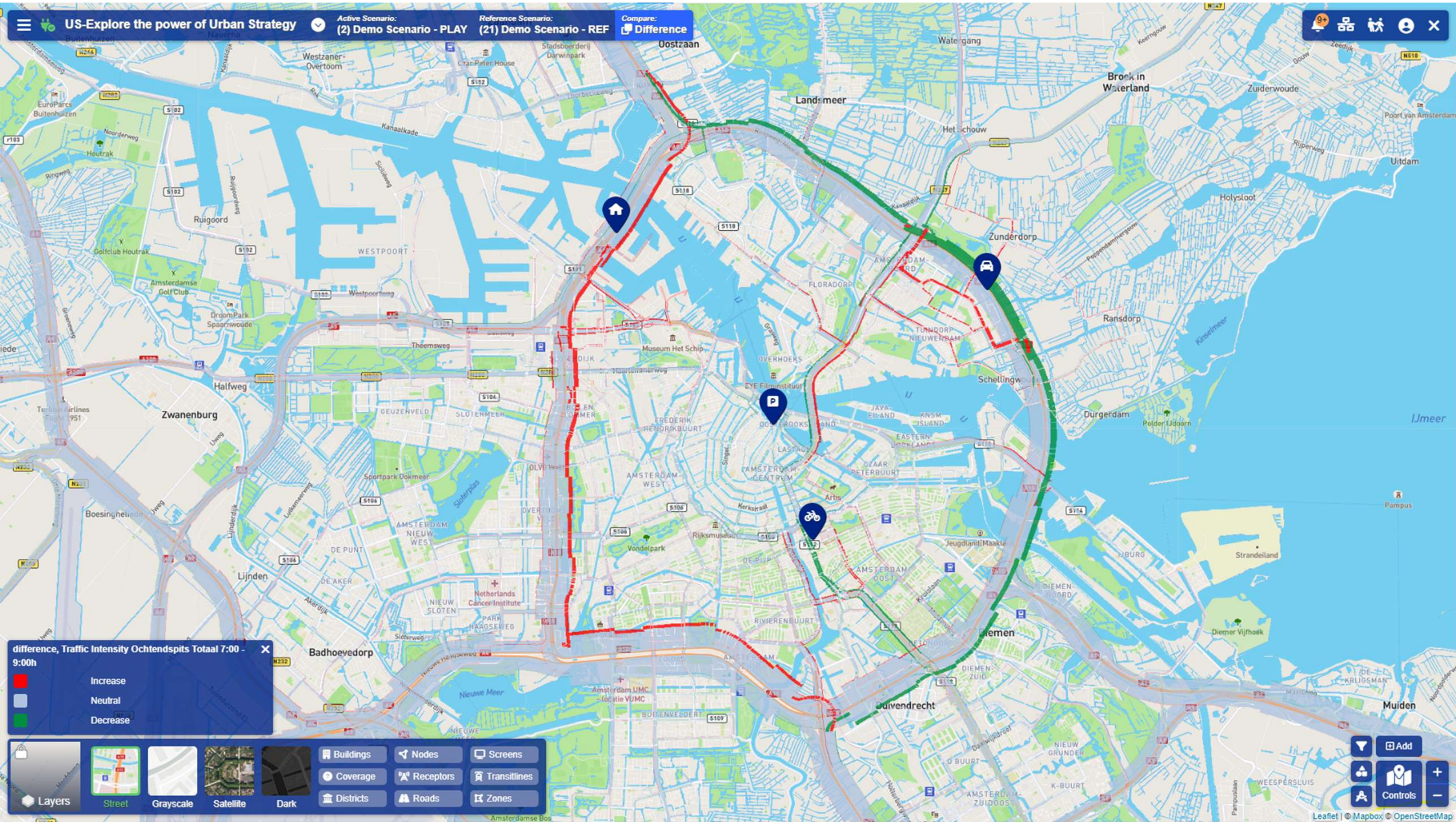

US-Explore the power of Urban Strategy
Active Scenario:
(2) Demo Scenario - PLAY
Reference Scenario:
(21) Demo Scenario - REF
Compare:
Difference
difference, Traffic Intensity Ochtendspits Bike 7:00 - 9:00h
Increase
Neutral
Decrease
Layers
Street
Grayscale
Satellite
Dark
Buildings
Nodes
Screens
Coverage
Receptors
Transitlines
Districts
Roads
Zones
Add
Controls
Leaflet | © Mapbox © OpenStreetMap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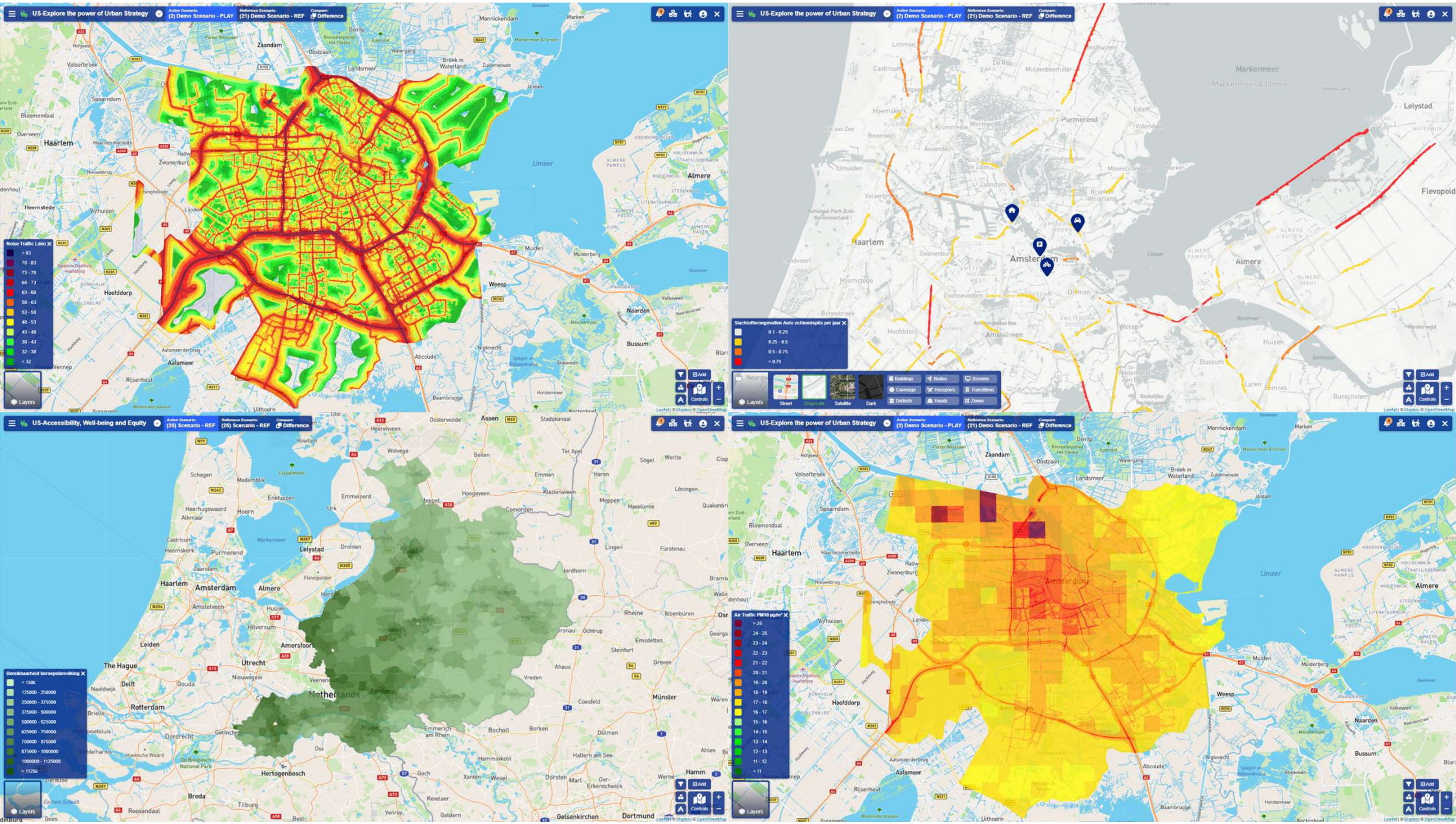
US-Explore the power of Urban Strategy
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Reference Scenario: (21) Demo Scenario - REF
Compare: Difference
Noise Traffic Lden
> 83
78 - 83
73 - 78
68 - 73
63 - 68
58 - 63
53 - 58
48 - 53
43 - 48
38 - 43
32 - 38
< 32
Slachtofferongevallen Auto ochtendspits per jaar
0.1 - 0.25
0.25 - 0.5
0.5 - 0.75
> 0.75
Buildings
Nodes
Screens
Coverage
Receptors
Transitlines
Districts
Roads
Zones
Street
Grayscale
Satellite
Dark
US-Accessibility, Well-being and Equity
Active Scenario: (25) Scenario - REF
Reference Scenario: (25) Scenario - REF
Compare: Difference
Bereikbaarheid beroepsbevolking
< 150k
125000 - 250000
250000 - 375000
375000 - 500000
500000 - 625000
625000 - 750000
750000 - 875000
875000 - 1000000
1000000 - 1125000
> 1125k
Air Traffic PM10 pg/m³
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11 - 12
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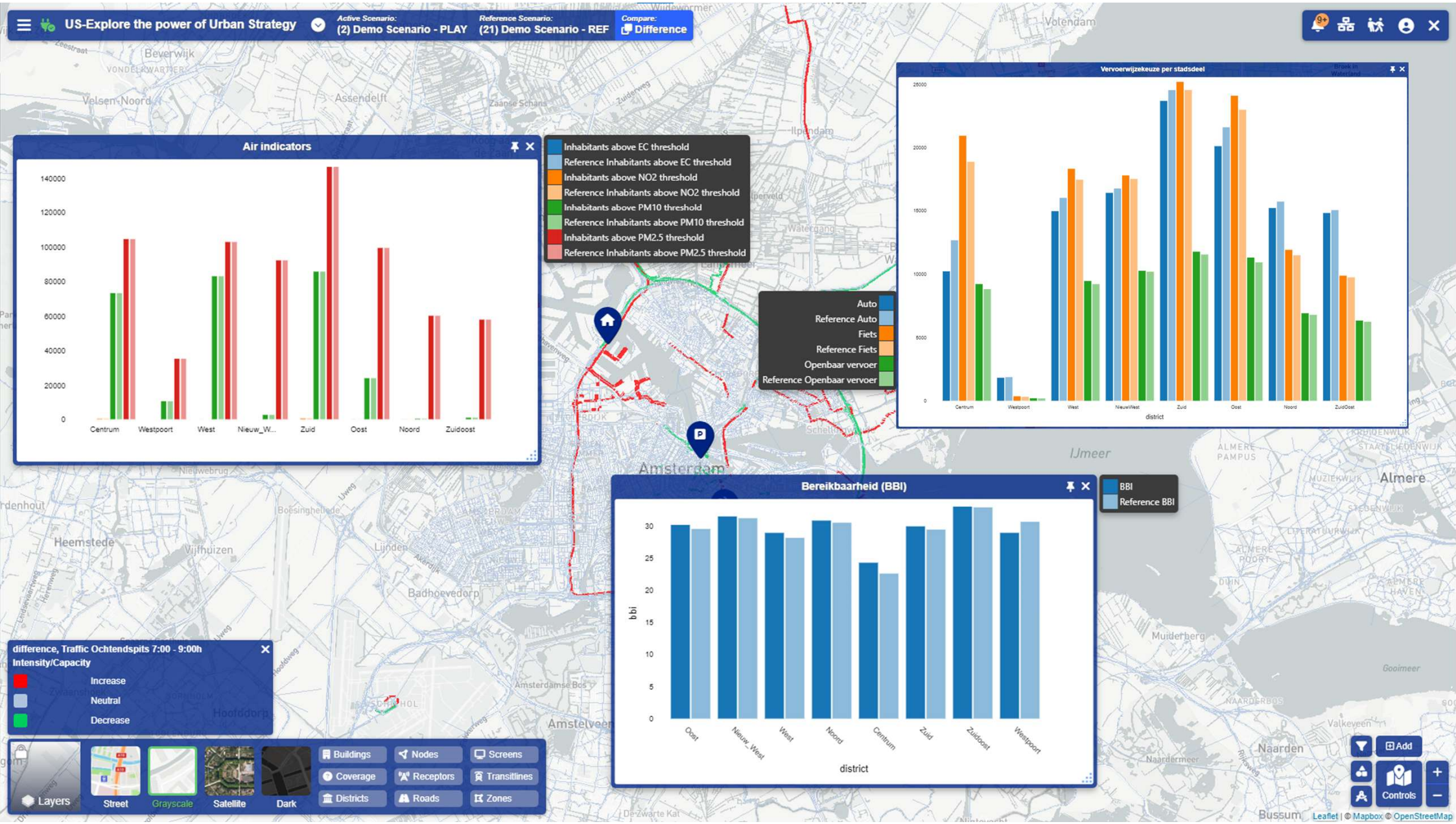
Leaflet | © Mapbox © OpenStreetMap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Reference Scenario:
(21) Demo Scenario - REF
Compare:
Difference
Air indicators
140000
120000
100000
80000
60000
40000
20000
0
Centrum
Westpoort
West
Nieuw_W...
Zuid
Oost
Noord
Zuidoost
Inhabitants above EC threshold
Reference Inhabitants above EC threshold
Inhabitants above NO2 threshold
Reference Inhabitants above NO2 threshold
Inhabitants above PM10 threshold
Reference Inhabitants above PM10 threshold
Inhabitants above PM2.5 threshold
Reference Inhabitants above PM2.5 threshold
Auto
Reference Auto
Fiets
Reference Fiets
Openbaar vervoer
Reference Openbaar vervoer
Vervoerwijzekeuze per stadsdeel
25000
20000
15000
10000
5000
0
Centrum
Westpoort
West
NieuwWest
Zuid
Oost
Noord
ZuidOost
district
Bereikbaarheid (BBI)
bbi
30
25
20
15
10
5
0
Oost
Nieuw_West
West
Noord
Centrum
Zuid
Zuidoost
Westpoort
district
BBI
Reference BBI
difference, Traffic Ochtendspits 7:00 - 9:00h
Intensity/Capacity
Increase
Neutral
Decrease
Layers
Street
Grayscale
Satellite
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Roads
Zones
Add
Controls
Leaflet | © Mapbox © OpenStreetMap

Value of interactive multi-domain predictive Twins

	Traditional	**Urban Strategy**
Decision Approach	Single domain	Integrated
Decision Process	1 mobility scenario per day	>50 Mobility + Air + Noise + Energy scenarios/iterations per afternoon
Decision Times	Weeks to (many, many) months	Hours to days
Decision Options	Limited (often just “Y” or “N”)	Range of options
Decision Cost	Large inefficiencies through silo’s	Significantly reduced: One Instrument – One Language – One View for all stakeholders
Output	External paper report after 3 months	Immediate, self-generated, results in 2D/3D
Cost of Solutions	(Sub-)Optimized for 1 policy domain	Optimized across multiple domains

Lessons learned in Amsterdam: practical value of science driven innovation in Digital Twins

- Digital Twins are here to stay ➔ from Innovation to Operation
- Digital Twins replace gut feeling by science based support
- Interactive decision making for cities is a game changer for decision makers
- Interactive Digital Twins increase the solution space for decision makers
- For the adoption of Digital Twins, it is key to find ambassadors in a city for this new way of decision support
  - Both on vision (CTO, innovation office, city leadership) and execution (domain specialists)
- A Multi-domain Digital Twin creates a common language and shared perspective that improves collaboration
- Digital Twins support people, they don't make decisions
  - Digital Twins support in assessing scenario's - People make decisions
- We ain't seen nothing yet !
  - Next step: AI assisted Digital Twins for optimized scenario planning

Urban Strategy Digital Twins for Sustainable and Liveable Cities

Kiitos!

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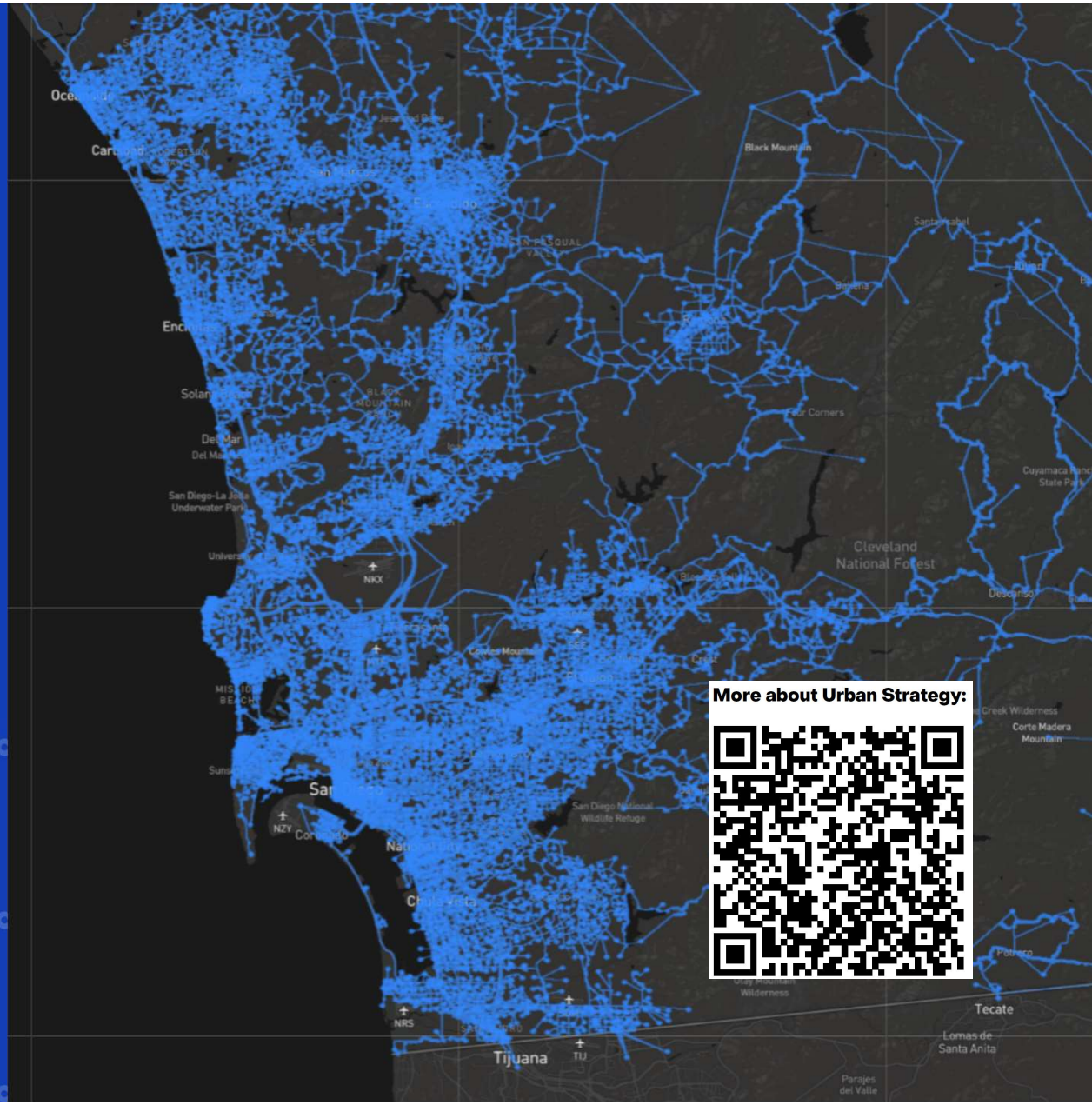

Urban Strategy – the principles

Future Generation Computer Systems – Nov. 2023

Future Generation Computer Systems 148 (2023) 501–513

Contents lists available at ScienceDirect

Future Generation Computer Systems

journal homepage: www.elsevier.com/locate/fgcs

Building digital twins of cities using the Inter Model Broker framework

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ARTICLE INFO

Article history:
Received 4 December 2022
Received in revised form 16 June 2023
Accepted 30 June 2023
Available online 3 July 2023

Keywords:
Digital twin
Urban planning
Integration framework
Smart city
Distributed simulation
Big data analytics

ABSTRACT

Urban areas are becoming increasingly crowded, and as a result it is challenging to ensure that these areas remain liveable and accessible. Municipalities need to make strategic long-term decisions regarding urban planning, which is often a difficult and time-consuming task. Digital twins of cities can assist policy makers during this process, providing an integral view on e.g. traffic intensities, air quality and noise. Furthermore, a digital twin enables policy makers to simulate 'what if scenarios' in a scenario-based analysis. Digital twins connect data, analytics and visualizations, which requires a system which integrates all these aspects in a single framework. This paper presents the Inter Model Broker framework, which is a scalable framework based on which large-scale digital twins can be built. A key property of our framework is that all connected system modules hold the relevant data locally in memory, which means that no central database is required. The effectiveness of our framework is demonstrated in a case study based on the city of Amsterdam in The Netherlands.

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1. Introduction

Cities are becoming increasingly more complex ecosystems. Urban population numbers and densities continue to grow: experts forecast an urban population growth from 4 to 5 billion in the period 2015-2030 [1]. The cities face complex problems in a wide range of areas, in particular economy, mobility, public health, safety and environment [2]. As a consequence, it is increasingly difficult to ensure that urban areas are livable, accessible and attractive from societal point of view [3,4]. Current developments in urban areas related to digitalization, automation, new mobility concepts and climate goals will impose additional requirements and restrictions on urban planning, which need to be taken into account [5]. IT technology is indispensable to solve these urban problems and to control and optimize urban processes in such complex city ecosystems.

Municipalities and provinces need to make decisions regarding the development of urban areas, but they need an integral view of several interrelated domains when working in urban planning projects. This involves often complex and time-consuming strategic decision making regarding, e.g., planning of mobility, environmental impact analysis and impact on indicators such as social inclusion and well-being [6,7]. Example questions that are confronted by city planners are: What is the impact on traffic near the train station when closing several access roads? and What is the additional air pollution when creating a shopping area in the south of the city?. In order to find answers to such questions, a scenario-based analysis is performed in which stakeholders can study the effects on e.g. traffic intensities, air quality and noise before and after the intervention. Existing software packages (such as transport modeling software) do not suffice for providing an integral view across the relevant domains, or the simulations take too much time (e.g., multiple hours) to be useful in an interactive workshop setting with stakeholders.

A recent trend is the development of digital twins to study integral effects to support the decision making process [8]. A digital twin for a city is a 'system-of-systems' [9,10] often containing three pillars: data, simulation models (i.e., analytics) and interconnected visualization systems using an integration framework. The data part contains, for example, the road network of the city, information about buildings, land use and the public transport lines. Simulation software is used to predict traffic intensities, air- and noise pollution, based on this data. The visualization system provides the end-user with the tools that are needed to find answers to the stakeholder questions.

The inter-domain dependencies require data and simulation models to be interconnected and form a computational chain of simulation processes. For example, the air pollution is influenced by car traffic, and therefore both traffic and air simulations need to be executed when studying a road closure. The increasing complexity of the city ecosystem will put a high claim on the scalability of the digital twin system in terms of data storage and computation time. The system should enable quick assessment of the effects of interventions in a city and should facilitate the increasingly complex questions from stakeholders in the future.

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https://doi.org/10.1016/j.future.2023.06.024
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https://www.sciencedirect.com/science/article/pii/S0167739X23002455