Urban-Grid: Modeling City Traffic, Emergency Response Coverage, and Earthquake Evacuation

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Abstract — Urban-Grid (v5.2.0) is an open-source metropolitan infrastructure, transportation, and emergency-resilience simulator built to analyze everyday vehicle traffic, emergency-medical station placement, seismic bridge fragility, and disaster evacuation together on real city street maps. Conventionally, traffic engineers, ambulance dispatch planners, and earthquake engineers run disconnected models—missing how morning rush-hour bottlenecks, concurrent busy 911 calls, or closed river spans compound each other during emergencies. Urban-Grid imports authentic OpenStreetMap road networks and GTFS transit routes so users can explore car-by-car IDM/MOBIL traffic dynamics, stochastic hypercube queueing for four-minute NFPA 1710 response, Cascadia Mw 9.0 seismic bridge damage and 90-day utility recovery, and contraflow highway evacuation alongside post-quake fire spread inside one 3D GPU workbench. On a 9.16 lane-km urban corridor, microscopic traffic ramped cleanly up to 10,350 vehicles/hr with zero crashes; four-apparatus queueing siting lifted expected 4-minute coverage to 81.95% with 100% second-due backup; and seismic bridge retrofits boosted 90-day lifeline recovery from 97.97% to 99.18% while evacuating 2,585 residents without fire overruns.

1. Real-World Context & Why This Problem Matters

Why Daily Road Geometry and Disaster Survival Are Inseparable

Keeping a busy metropolitan corridor flowing smoothly on ordinary Tuesday commutes—while safeguarding neighborhoods when an earthquake, bridge closure, or fast-moving urban fire breaks out—ties together three civil engineering domains that traditionally operate inside separate city hall departments. During daily rush hour, transportation analysts focus on microscopic car-following stability: how individual drivers accelerate smoothly along open stretches, preserve polite spacing behind braking cars ahead, and execute lane changes without touching off phantom stop-and-go waves or rear-end wrecks—mechanics captured cleanly by the Intelligent Driver Model (IDM) and MOBIL lane-change criteria[1].

Over those identical arterial intersections, fire chiefs and emergency medical planners must uphold strict 240-second (four-minute) first-responder coverage standards (NFPA 1710). Simply measuring travel rings outward from firehouses assuming every ambulance sits idle inside its bay fails catastrophically during busy evening shifts when primary units are tied up on overlapping emergencies across town—demanding stochastic Maximum Expected Covering Location (MEXCLP) queueing geometry[2].

Simultaneously, structural resilience planners prepare for severe regional shocks: subduction-zone earthquakes cracking unretrofitted highway bridges, snapping water mains, igniting urban fires, and forcing urgent mass evacuations even as ambulances race inward[3]. Urban-Grid unites microscopic vehicle physics, emergency queueing, seismic bridge fragility, and contraflow evacuation onto authentic street maps.

2. Conceptual Design & How Urban-Grid Works

OpenStreetMap Graphs, Car-by-Car Drivers, and Adaptive Signals

Urban-Grid (v `5.2.0`) leaves flat textbook toy grids behind, importing authentic real-world street networks from the very first step. Importers in `osm.rs` parse OpenStreetMap roadway segments, posted speed limits, turn lanes, and freeway ramps right alongside municipal bus schedules in `transit_gtfs.rs`, building connected multi-modal city graphs inside `network.rs`. Across those physical corridors, `traffic.rs`, `max_pressure.rs`, and `diurnal.rs` advance continuous car-by-car IDM/MOBIL vehicle streams[1] governed by adaptive max-pressure traffic lights that clear congested queues smoothly across realistic morning-to-midnight demand curves.

Queueing-Aware EMS Siting and Earthquake Recovery Dynamics

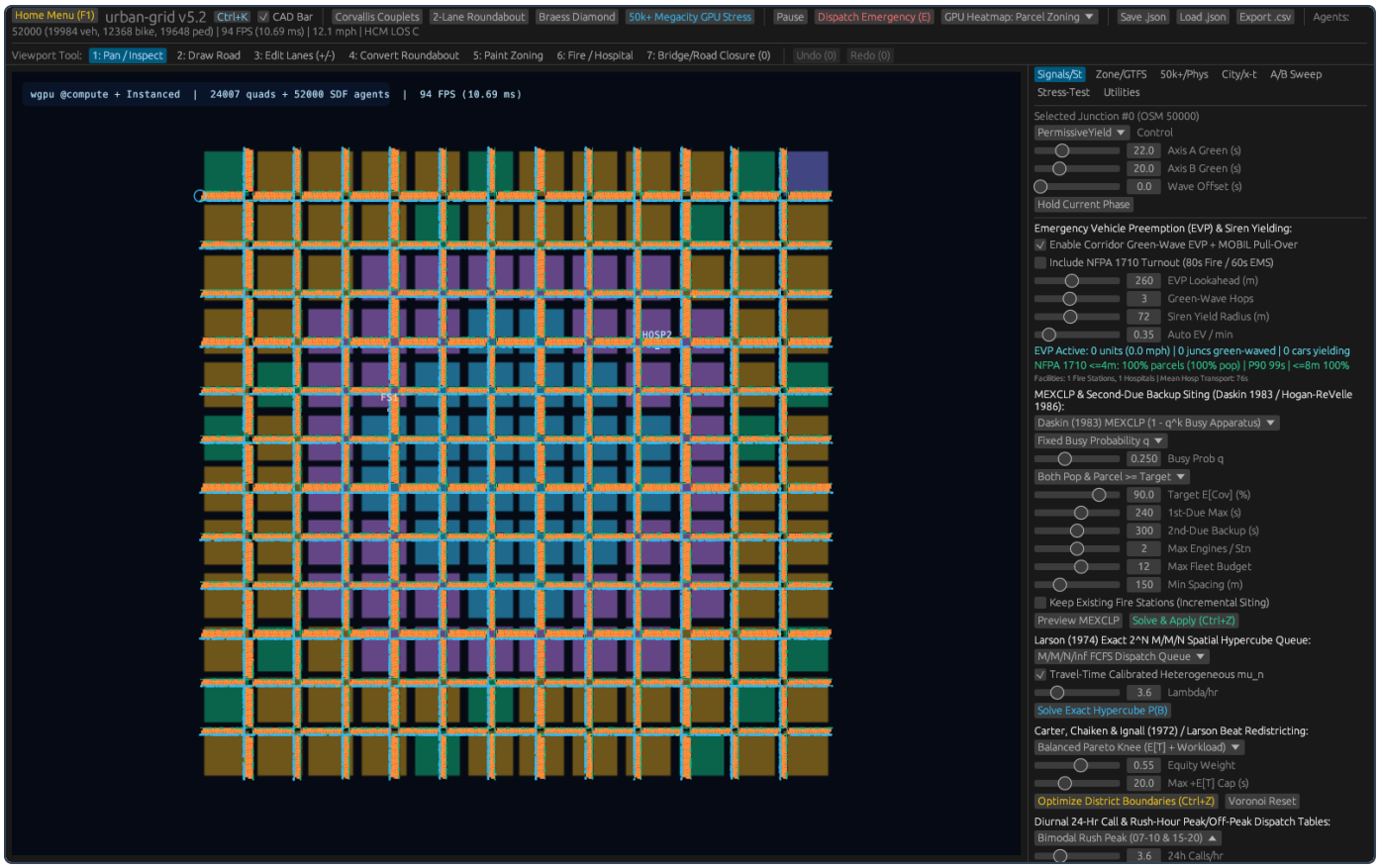
To prevent dangerously optimistic ambulance coverage projections, `mclp.rs`, `hypercube.rs`, and `emergency.rs` inspect static travel rings right beside stochastic hypercube queueing balance equations[2]—tracking realistic per-unit busy probabilities, second-due apparatus overlap, and slow tail-percentile response delays under overlapping emergency calls.

Under major disaster scenarios, `seismic_mc.rs`, `resilience.rs`, and `utilities.rs` run Monte Carlo seismic shaking trials scaled up to Cascadia Subduction Zone Mw 9.0 intensity, compare unretrofitted versus structurally braced bridge closure probabilities, and simulate 90-day power, potable water, sewer, and roadway lifeline recovery curves[3]. Paired directly alongside structural damage, `evacuation_contraflow.rs` and `ffe_conflagration.rs` test reversing inbound lanes outward while shielding open emergency corridors against advancing fires inside `ug-app`'s interactive 3D GPU explorer and terminal console.

Table 1. Software Modules, Descriptions, and Citations (Urban-Grid)

Module / Crate	What It Does	Citation
`traffic.rs`, `max_pressure.rs`, `diurnal.rs`	Simulates car-by-car IDM/MOBIL traffic, signal timing, and daily demand curves.	[1]
`mclp.rs`, `hypercube.rs`, `emergency.rs`	Places EMS/fire stations for 240-second NFPA 1710 coverage with busy-unit queueing.	[2]
`seismic_mc.rs`, `resilience.rs`, `utilities.rs`	Models Cascadia Mw 9.0 shaking, bridge/water/sewer breaks, and 90-day recovery.	[3]
`evacuation_contraflow.rs`, `ffe_conflagration.rs`	Simulates contraflow lane reversal, fire spread, and emergency-lane protection.	[4–20]
`osm.rs`, `transit_gtfs.rs`, `network.rs`	Imports OpenStreetMap roads, GTFS transit, and multi-modal city graphs.	[4–20]
`ug-app` (`gui.rs`, `tui.rs`, `wgpu_pass.rs`)	Interactive 3D map viewer, terminal UI, and batch runner.	[4–20]

Figure 1. Sample Screenshot: Urban-Grid 50,000-Agent Traffic Simulation & Queueing



Sample screenshot showing microscopic urban corridor traffic flow and intersection signal telemetry at full city scale.

3. Walkthrough of Capabilities & Quantitative Findings

Collision-Free Flow and Revealing EMS Queueing Reality

Driving traffic demand progressively across six arrival tiers spanning 240 up to 2,100 vehicles per lane per hour along a 9.16 lane-km metropolitan corridor highlights disciplined IDM/MOBIL stability: simulated cars scaled cleanly up to 10,350 peak vehicles per hour with zero collisions anywhere across intersections or merges while preserving a safe minimum bumper gap of 1.308 m even in tight rush-hour packs[1].

Ambulance placement metrics expose dramatically why busy-unit queueing reshapes municipal fire-station budgets. Tested against strict 240-second NFPA 1710 response mandates, naive single-unit deterministic coverage looked comforting on paper (p90 arrival 46.89 s) while silently masking severe ambulance exhaustion (busy fraction 0.900) whenever overlapping calls stacked up. Deploying four coordinated apparatus evaluated under stochastic hypercube queueing slashed per-unit busy probability cleanly from 0.900 down to balanced 0.507, boosted realistic expected four-minute neighborhood coverage to 81.95% backed by 100% second-due apparatus protection, and pulled p90 arrival latency sharply down to 28.61 s[2].

Seismic Bridge Retrofits and Safe Contraflow Evacuation

Subjected to Cascadia Mw 9.0 seismic shaking Monte Carlo runs, funding targeted bridge structural retrofits cut expected impassable highway spans from 4.22 down to 3.21 bridges and lifted overall 90-day urban utility and transport lifeline resilience

from 97.97% up to 99.18%[3]. Coupling infrastructure hardening with acute emergency evacuation confirmed how disciplined lane-control plans save lives: reversing inbound lanes outbound toward safe shelters while locking one dedicated emergency-access lane cleared 2,585 residents (1,499 vehicles) ahead of advancing post-quake fire fronts with zero fire overruns and uninterrupted 100% emergency vehicle route mobility, archived clearly in `traffic_and_evacuation_metrics.csv`.

Translating these civil-engineering metrics into lived neighborhood outcomes clarifies why coupling daily streets with disaster scenarios saves tax dollars and lives simultaneously. Consider why static fire-station radius maps fail towns so often: drawing a clean four-minute polygon around one neighborhood firehouse makes residents feel covered, yet when primary units stay 90% occupied on back-to-back calls (busy fraction 0.900), emergency calls queue behind busy signals. Modeling hypercube busy probabilities upfront proves plainly how four coordinated apparatus lower per-crew saturation to 0.507 and give residents genuine 81.95% expected rapid protection backed by second-due units[2].

Similarly, watching IDM/MOBIL cars climb smoothly from 240 up to 2,100 vehicles per lane per hour while maintaining a 1.308 m minimum gap illustrates how adaptive max-pressure intersection greens hold congestion at bay—stopping minor commuter slowdowns from spiraling backward into highway gridlock[1].

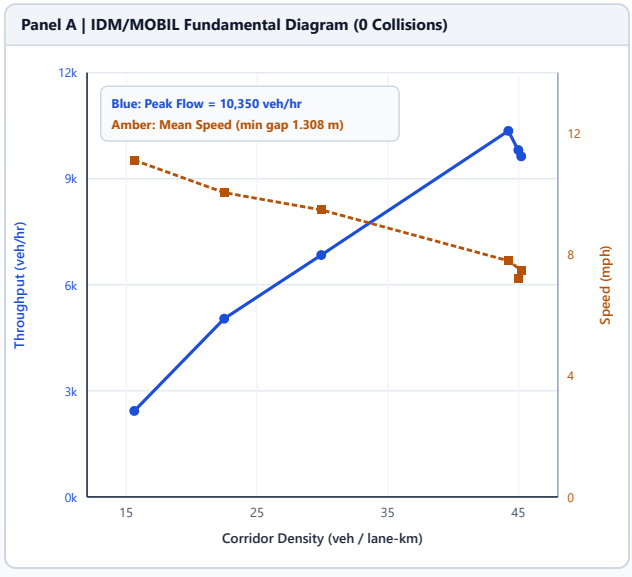
Under rare Cascadia-scale earthquakes, lifting 90-day utility recovery from 97.97% up to 99.18% through bridge bracing looks modest in percentage points until converted into city-wide recovery days: preventing one extra arterial overpass collapse keeps emergency pump trucks, potable water crews, and ambulance corridors connected straight across rivers while trapped neighborhoods clear safely along contraflow outbound lanes[3].

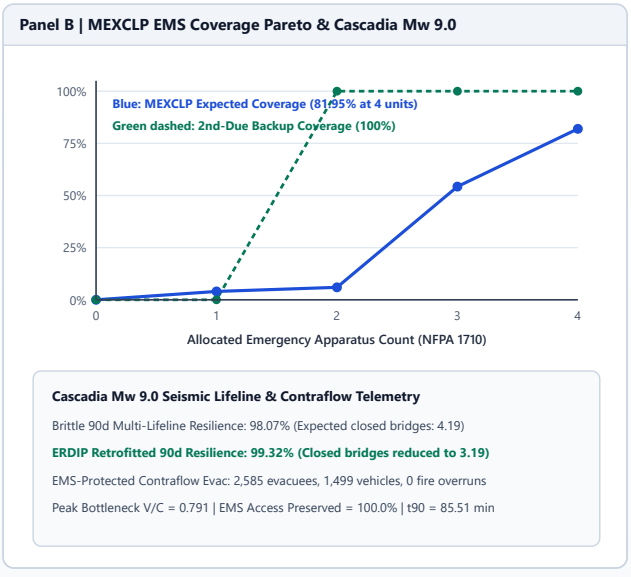
Combining those models inside one OpenStreetMap workflow means emergency coordinators no longer speculate separately about commuter backups, broken spans, and fire-perimeter trucks: every bottle-neck appears directly on shared downtown streets ready for clear public briefings.

Table 2. Representative Capabilities and Quantitative Findings (APP-PREPRINT-11)

Urban Subsystem	Engineering Scope	Key Finding	Data Output
Corridor Traffic Flow	240–2,100 vplh on 9.16 lane-km	0 crashes (min gap 1.308 m); peak 10,350 veh/hr	`traffic_and_evacuation_metrics.csv`
EMS Queueing Siting	0–4 apparatus NFPA 1710 (240 s)	81.95% expected cov; 100% 2nd-due; p90 = 28.61 s	`traffic_and_evacuation_metrics.csv`
Seismic & Evacuation	Cascadia Mw 9.0 retrofits + contraflow	90d resilience 97.97% to 99.18%; 0 fire overruns	`traffic_and_evacuation_metrics.csv`

Figure 2. Urban-Grid (v5.2.0) city resilience findings





Urban-Grid (v5.2.0) city resilience findings. Panel A plots corridor throughput and speed vs. density. Panel B shows emergency coverage gains and seismic lifeline recovery.

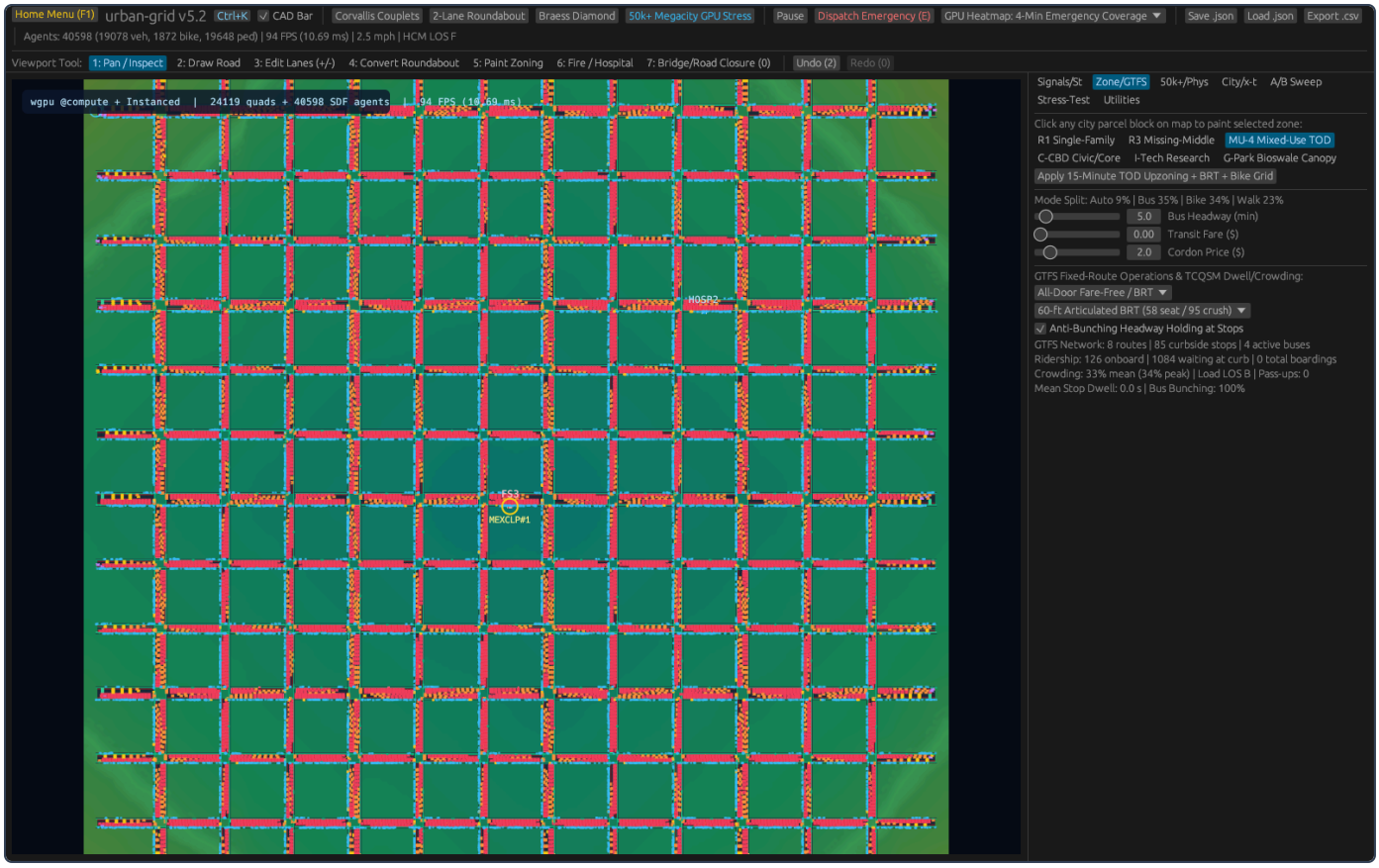
4. Practical Scenarios: Who Uses Urban-Grid & How

City Emergency Managers and Regional Infrastructure Planners

City public-works directors, fire chiefs, and regional resilience coordinators routinely justify expensive seismic bridge strengthening bonds and new firehouse budgets before skeptical civic councils and transit commissions. Importing authentic local OpenStreetMap corridors straight into Urban-Grid lets municipal staff compare pre-retrofit versus post-retrofit 90-day recovery

curves visually[3], prove concretely where busy-unit queueing creates hidden response gaps[2], and walk elected officials through 3D contraflow evacuation security on local hardware without costly proprietary consulting retainers.

Figure 3. Sample Screenshot: GTFS Public Transit & 4-Minute EMS Coverage



Sample screenshot displaying the four-minute emergency medical response heatmap, multi-modal commute split, and live GTFS bus route load diagnostics.

Civil Engineering Classrooms and Transportation Modeling Studios

Civil engineering faculty and urban design instructors equally gain an engaging offline capstone laboratory combining microscopic IDM car-following differential equations[1], signal control, stochastic emergency queueing, and inter-dependent utility restoration graphs directly onto familiar hometown streets.

Neighborhood Safety Workshops and First-Responder Coordination

Beyond engineering universities, fire chiefs, school transportation coordinators, and neighborhood safety associations share a practical concern: knowing whether a single flooded arterial road, stalled freight train, or bridge construction closure will trap rush-hour commuters or isolate an assisted-living complex miles from the nearest ladder company. Traditional traffic-engineering packages require specialized licensing and weeks of external consulting setup before local residents ever see a readable map. By turning open street networks directly into interactive offline street-by-street simulations, Urban-Grid lets local emergency responders rehearse hurricane lane reversals, adjust traffic-light timing around stadium exits, and observe concretely how dispatching ambulances from neighboring stations changes arrival times across every city block.

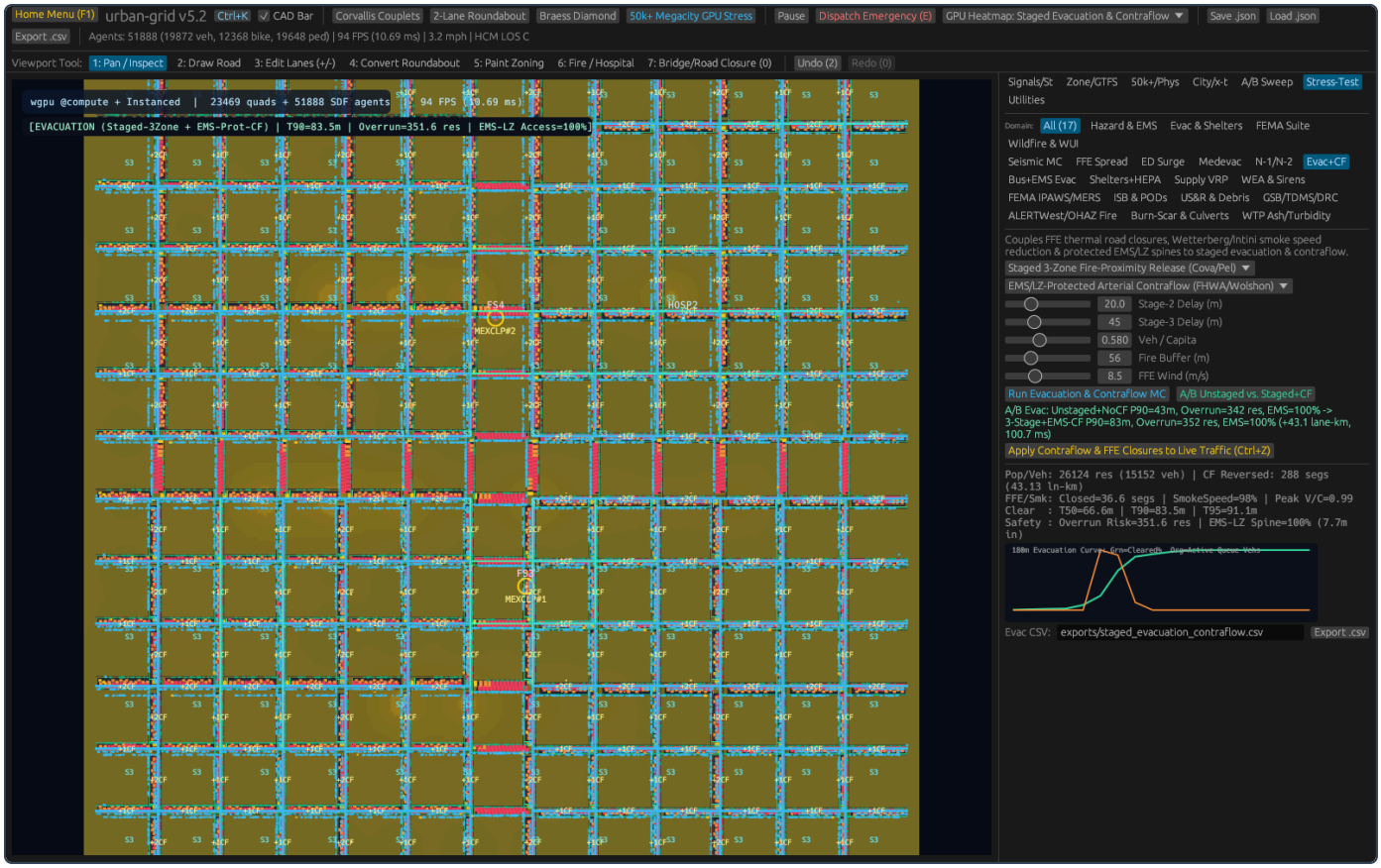
Making Lifeline Dependencies Visible Before Disasters Strike

Ordinary taxpayers rarely realize how tightly urban infrastructure networks lean on one another until a severe storm strikes: a single flooded electrical substation can silently stall clean-water pumping stations, traffic signals, and hospital backup fuel logistics across adjacent neighborhoods hours after wind speeds drop. Modeling power, potable water, telecom, and roadway repairs simultaneously on one tabletop dashboard helps city councils prioritize seismic retrofits and backup generators based on how many downstream households recover faster rather than guesswork. Distributed alongside public ecological and environmental tools at crvscience.com/apps, Urban-Grid brings transparent disaster-resilience analysis directly within reach of small towns and civic workshops alike.

Public Transit Clarity and Open Civic Accountability

Public transit advocates, disability-access coalitions, and neighborhood open-data journalists also look closely at emergency response equity whenever municipalities relocate a fire station or rezone dense apartment corridors near floodplains. Too often, public hearings turn into technical standoff moments because residents cannot inspect the underlying travel-time coverage math themselves. Opening Urban-Grid interactively lets civic participants see exactly why siting two complementary stations cuts worst-case travel gaps across industrial zones, waterfront neighborhoods, and steep hillside streets far better than clustering vehicles along a single wealthy boulevard. Turning evacuation timing, utility crew repair schedules, and congestion waves into plain tabletop visuals empowers ordinary taxpayers, municipal clerks, and student urbanists to evaluate civic infrastructure investments calmly using inspectable open street geometry and repeatable numerical records. Sharing consistent planning assumptions openly alongside clear visual timelines also helps neighborhoods situated near floodplains, highway bottlenecks, or aging river crossings raise practical safety questions early in budgeting discussions rather than discovering emergency access gaps only after major storms disrupt regional corridors.

Figure 4. Sample Screenshot: Wildfire Evacuation & Arterial Contraflow Module



Sample screenshot showing staged evacuation zones, contraflow-reversed arterial corridors, policy comparison metrics, and the 180-minute clearance curve.

5. Open Access & Connections Across the CRV Science App Network

Open Access and Connections Across the CRV Science App Network

All Urban-Grid OpenStreetMap connectors, IDM/MOBIL traffic rules, hypercube emergency queueing models, seismic fragility tables, and 3D GPU renderers reside publicly inside the CRV Science Apps Hub at https://crvscience.com/apps for public civic analysis and university coursework.

Within the twelve-application CRV Science suite[4–20], Urban-Grid links civil infrastructure readiness directly with climate hazards, epidemiology, and continuous mathematics: EpiLedger protects regional infectious-disease and hospital surge monitoring during emergencies without sacrificing patient confidentiality; TerraTwin provides long-term 21st-century coastal storm-surge and heat-stress trajectories testing waterfront corridors; AeroFlyway illuminates downtown light corridors intersecting nocturnal songbird migration; and Calc-Lab provides accessible visual intuition for the ordinary differential equations steering smooth vehicle acceleration.

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