Module 01
Course Roadmap and Infrastructure Systems

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CE 4240/5240 — Intro to Infrastructure Systems Engineering

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VANDERBILT UNIVERSITY

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Course Instructor: Background & Interests

Background

- Born and raised in Beirut, Lebanon
- Finished my Ph.D. in ECE from Purdue University in August 2015
- Undergraduate education: American University of Beirut — Class of 2011, B.E., ECE
- Assistant Professor, ECE Department @ UTSA, August 2015—August 2021
- Associate Professor, CEE Department @ Vanderbilt, August 2021—present

What do professors do? What does my lab work on?

We study how complex infrastructure systems operate, then use that understanding to build tools and algorithms for system-level engineering challenges.

Teaching, Service, Impact, Funding

- **Teaching**: a well-rounded program on dynamic network science for critical infrastructure
  - Focus on applications and the theoretical fundamentals behind them
  - Theory matters because it tells us what is possible, reliable, and scalable
  - Modern infrastructure operates with small margins, so we need advanced engineering and mathematics
- **Impact**: infrastructure-specific algorithms for critical and timely engineering problems
  - Can these algorithms move from papers to practice?
  - Long-term goal: connect new theory to real systems and operational decisions
- **Funding:** mostly by the National Science Foundation (NSF)
- **Team:** excellent graduate students and collaborators

Examples From My Group's Recent Research

- Energy systems, climate change, and the transition away from fossil-fuel-based systems
- Water systems: distribution, drinking water, stormwater, flood control, and related networks
- Traffic control and monitoring, electrifying transportation
- Cybersecurity and resilience of infrastructure
- Foundational theory motivated by practical infrastructure problems

Module 01 Outline

1. Introductions: your background, interests, goals, and what brought you here
2. Course syllabus, expectations, and workflow
3. Course roadmap: what we will cover and why it matters
4. The fun stuff starts — infrastructure systems engineering and the scope of this class

Part I — Your Turn to Introduce Yourselves! ☺

Part II — Course Syllabus and Outline

Course Webpage & Communication

Course Page:

- Vanderbilt Brightspace: https://brightspace.vanderbilt.edu
- Course materials will be posted on Brightspace; additional material may also be posted on my webpage
- *Email is the best way to reach me*

Office Hours:

- Tuesdays and Thursdays, 12:30 – 14:00, in my office
- By appointment, in person or on Zoom: https://vanderbilt.zoom.us/my/ahmadtaha89

TA Info:

- I am the instructor, TA, and grader for this course

Course Description

A systems-level approach to the infrastructure of the built environment. Topics include elements of systems engineering, case studies of infrastructure under stress, smart infrastructure, transportation systems, building systems, water and wastewater supply and distribution systems, infrastructure interdependencies, smart-city concepts, and applications to infrastructure system design.

Main References

- No textbook is required for the class
- Lecture notes will be provided as handouts or presentation slides
- Research papers and supplemental lecture notes will be provided

Course Objectives & Expected Outcomes

This course is an introduction to infrastructure systems engineering from a system-level perspective. We will study specific infrastructure domains, including water, transportation, energy, and power systems, while also building the theoretical foundation needed to reason about them, including mathematical modeling, optimization, and control.

- Build mathematical models of infrastructure systems
- Improve programming and data-analysis skills
- Apply linear, nonlinear, and multi-objective optimization methods to infrastructure design and operation
- Use economic, social, and technical metrics to evaluate engineering decisions
- Develop a working introduction to control theory
- Understand contemporary problems in transportation, water, energy, and power systems
- Improve written and oral scientific communication
- Work across disciplines to address complex civil and environmental engineering problems

Prerequisites

An undergraduate-level understanding of:

- Multivariable calculus
- Basic linear algebra
- Basic programming; you may use your preferred language, but we will mostly use MATLAB
- Willingness to practice, debug, and ask questions

Grading Policy

- **Homework assignments** (15%)
- **Exam, Friday November 20, 2026** (40%)
- **Research paper** / **course project** (40%) divided into:
  - project proposal (5%)
  - progress report (10%)
  - final report (20%)
  - presentation (5%)
- **Attendance and instructor evaluation** (5%). Attendance is mandatory; students may not miss more than two classes.

Course Grade Cutoffs

- A-, A, A+: 90–100
- B-, B, B+: 80–90
- C-, C, C+: 70–80
- D-, D, D+: 60–70
- F: < 60

Programming Tools

- MATLAB or Python will be required for homework assignments and course projects
- Students can obtain the discounted student version of MATLAB
- All homework assignments must be typed. No handwritten homework will be accepted.
- You are strongly encouraged to use LaTeX for homework assignments and course projects
- CVX and YALMIP will be used for optimization modeling; install them early

Class Policies

- Regular attendance and active participation
- Email communication
- Arriving on time
- Smartphone and laptop etiquette
- Homework collaboration and individual responsibility
- Use of AI/LLM tools
- Homework feedback and revision expectations
- Late submission policy
- Changes to the syllabus

Tentative Class Schedule

Tentative Course Outline:

Module I — Class Overview & Background .... ≈ 1 class
- Course introduction & syllabus, major applications, course overview

Module II — Introduction to System Optimization .... ≈ 5-6 classes
- Crash course on mathematical optimization (linear/quadratic/convex optimization)

Module III — Introduction to Energy Systems and Climate Change .... ≈ 2-3 classes
- Intro to the most stressing problem of our time

Module IV — Introduction to Dynamic Systems and Control Theory ..... ≈ 5–6 classes
- Crash course on control theory for infrastructure

Module V — Introduction to Water Systems .... ≈ 2–3 classes
- Intro to various aspects of water systems

Module VI — Dynamic Models of Infrastructure .... ≈ 3–4 classes
- Demonstrating dynamic system models in infrastructure

Module VII — Introduction to Transportation Systems and Mobility ...... ≈ 3–4 classes
- Introduction to contemporary problems in transportation

Module VIII — Real-time Control and Optimization of Infrastructure ..... ≈ 3–4 classes
- In-depth discussion of how infrastructure are controlled in real-life.

Module IX— Advanced problems in infrastructure .... ≈ 3–4 classes
- Sensor placement, driver node selection, advanced mobility, flood control, renewables adaptation, etc...

Homework #1

- Install LaTeX or start learning how to use it on Overleaf
- Install CVX, MATLAB, and YALMIP—tools we will use throughout the course
- Deadline: Monday, August 31st, 11:59:59pm.

Part III — Why Infrastructure Systems Engineering?

Infrastructure Is More Than Physical Stuff

Working definition

Infrastructure is the set of physical, digital, institutional, and operational systems that make modern life possible.

- Roads, bridges, pipes, wires, plants, pumps, sensors, operators, policies
- The public experiences infrastructure as a **service**: mobility, water, energy, communication, safety
- The engineering question is not only *what do we build?* but *how should the system behave?*

Table 1 Infrastructure service sectors

SECTOR / SERVICE	TYPICAL PHYSICAL WORKS
URBAN	Public buildings; Streets; Street lighting; Leisure facilities
SOCIAL	Universities; Schools; Hospitals; Social housing; Prisons
WATER	Irrigation canals; Water supply networks; Dams; Drainage; Flood defences
TRANSPORT	Roads; Bridges; Tunnels; Ports; Canals; Railways; Tramways; Airports
COMMUNICATIONS	Telegraph; Telephone; Wireless; TV; Internet; Broadband
ENERGY	Gas; Electricity; Oil; Nuclear; Renewables
ENVIRONMENTAL	Wastewater treatment; Waste disposal; Green infrastructure

One possible sector-based view: urban, social, water, transport, communications, energy, environmental.

Infrastructure and Prosperity Co-Evolve

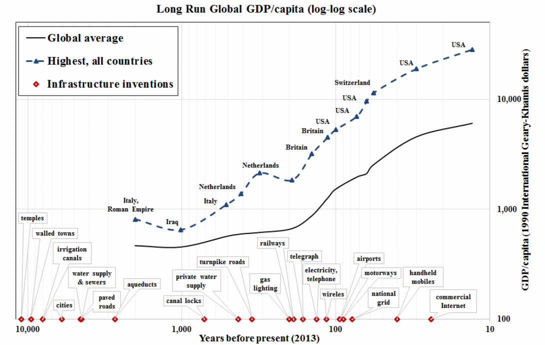
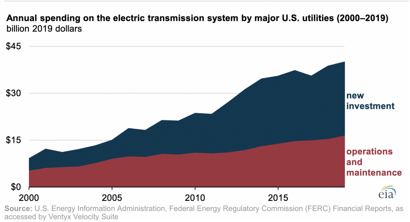


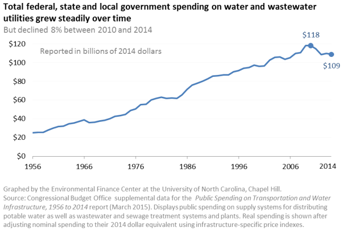
Figure 1. Time line of infrastructure innovations and economic growth
Source: Author's own elaboration for infrastructure invention dates (see text). GDP/capita data from Maddison (2007) - country maximum values exclude small oil states after 1920.

- Infrastructure innovations shape economic growth, urbanization, and public health
- Each era adds a new operating layer: canals, railways, electricity, telecommunication, Internet
- Today's layer is **intelligence**: sensing, prediction, optimization, control, and coordination

The Next Buildout Is Already Underway



Transmission spending rose sharply between 2000 and 2019.



Water and wastewater spending grew for decades, then softened after 2010.

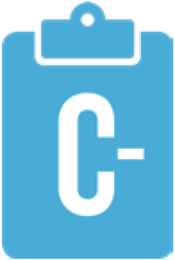
- Infrastructure systems are capital-intensive, long-lived, and hard to modify after deployment
- Better algorithms can change how we plan, operate, maintain, and prioritize these investments

The Pressure on Infrastructure Is Changing

- Climate, water quality, congestion, electrification, and reliability are coupled problems
- The public sees failures as headlines; engineers see interacting systems under constraints

Condition Is Only Part of the Story

ASCE Infrastructure Report Card, 2021



For the first time in 20 years, our infrastructure GPA is a C-, up from a D+ in 2017.

- A grade tells us something about condition, but not enough about **operation**
- Two systems with the same physical assets can perform very differently
- Performance depends on decisions:
  - when to repair, replace, dispatch, pump, route, store, curtail, or evacuate
  - how to balance cost, risk, equity, emissions, reliability, and resilience
- This is where infrastructure becomes a systems engineering problem

Why Money Alone Is Not Enough

Policy

Defines goals, constraints, standards, and accountability

Investment

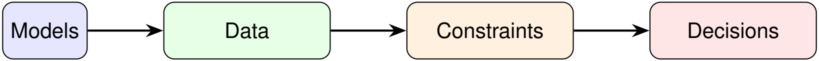
Builds, renews, and maintains physical assets

Incentives

Shapes behavior through prices, tolls, demand response

Algorithms

Turn models and data into operational decisions



- Investment creates capacity; algorithms decide how that capacity is used
- The strongest infrastructure strategies combine assets, policy, incentives, and computation

Class Focus and Application Areas

Class Focus

Creating computational algorithms for urban infrastructure systems

- **What we will balance**
  - new foundations and theory
  - real infrastructure applications
  - uncertainty, scale, nonlinearities, performance guarantees

1. Climate-aware power and energy systems
2. Drinking-water hydraulics and quality
3. Stormwater, flooding, reuse, and related water problems
4. Mobility and transportation systems
5. Multi-infrastructure coupling
6. Cybersecurity and resilience

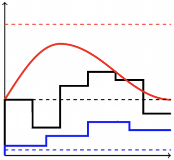
Technical Challenges

Lack of mathematical frameworks

…that couples the operation of dynamic infrastructure components

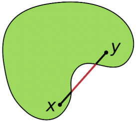
Significant time-scales discrepancy

…between interdependent infrastructure



Nonconvexity and nonlinearity

…in dynamic models, constraints, objectives



Rampant uncertainty

…from human-centered conditions, weather conditions, poor forecasts, parameters

- These four themes will keep reappearing: coupling, time scales, nonlinearity, and uncertainty
- The course tools are chosen because they help us reason about these themes mathematically

Core Sciences Behind Infrastructure Systems

1. Control Systems

- Study how dynamic systems respond to inputs, disturbances, and feedback
- Models can come from data,

$$\{u(t), y(t)\} \implies y(t) = \mathcal{F}(u(t)),$$

or physics,

$$y(t) = f(u(t), \dot{u}(t), \ldots)$$

- Key question: how do we make systems smoother, cheaper, safer, and more reliable?

2. Optimization

- Choose decisions that do the most good under limited resources
- Reduce cost, improve performance, manage risk, and satisfy constraints
- Examples: power dispatch, pump scheduling, traffic routing, sensor placement, flood control
- Career objective: bring control and optimization theory to infrastructure problems

Dynamic Models in Infrastructure

- Critical infrastructures rely on **physics-based models**
- A useful modeling evolution:
  1. Static algebraic models
  2. ODEs for lumped dynamics
  3. PDEs for distributed flows/densities
  4. Hybrid PDE-ODE for modern infrastructures
- Purpose: predict, optimize, and control under uncertainty
- We will learn these models in this class
- Data and AI are powerful, but they do not replace physical laws; they work best when we understand both

Water Distribution & Hydraulics

- **Early**: steady-state hydraulic equations

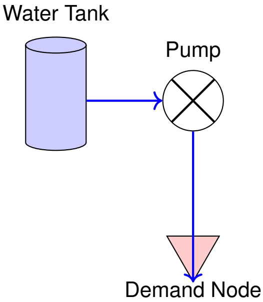
$$\sum Q_{in} = \sum Q_{out}, \quad h_i - h_j = R_{ij} Q_{ij}^2$$

- **Transient PDEs** (Saint-Venant):

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A} + p\right) = -gA\frac{\partial h}{\partial x}$$

  - $Q(x,t)$: volumetric flow rate along the pipe; $A(x,t)$: cross-sectional area; $p(x,t)$: pressure term
  - $h(x,t)$: hydraulic head, g: gravitational acceleration; PDE captures unsteady flow in pipes and channels
  - LHS: rate of change + momentum flux; RHS: pressure gradient and gravity driving the flow

- **Modern**: PDE + ODE coupling for tanks, pumps, valves, demand, and water quality



Transportation & Traffic Flow

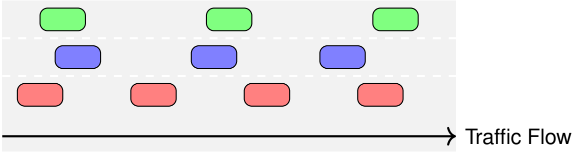
- **Microscopic ODEs**: car-following

$$\dot{v}_i(t) = f(v_i, d_{i-1,i}), \quad \dot{x}_i = v_i$$

- **Transient PDEs** (Saint-Venant):

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0, \qquad q(x,t) = \rho(x,t)v(x,t)$$

- This PDE models traffic-density conservation on a highway stretch where q is the traffic flow rate and ρ is the traffic density, v is the average vehicle speed
- **Modern**: PDE traffic density + ODE vehicle dynamics + network control

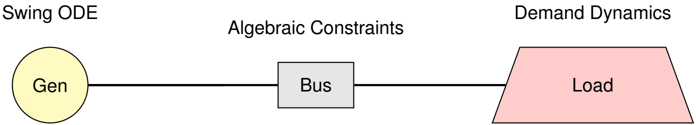


Power Systems Dynamics

- Early: algebraic load-flow equations
- ODE models: **swing equations** for synchronous machines

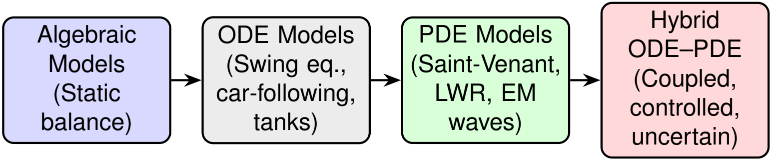
$$M\ddot{\delta} + D\dot{\delta} = P_m - P_e(\delta)$$

- PDEs: electromagnetic transients, distributed lines, inverter dynamics
- Current: nonlinear differential-algebraic equations (NDAEs)



Evolution and Comparison Across Infrastructures

- Evolution of models: *from static* → *ODE* → *PDE* → *hybrid ODE–PDE*



System	**ODE Models**	**PDE Models**
Water	Tank levels, pump dynamics	Saint-Venant, contaminant transport
Traffic	Car-following, signal ODEs	LWR conservation law, continuum flow
Power	Swing eq., inverter ODEs	EM propagation, inverter fields

Future Directions in Infrastructure Modeling

- **Digital twins**: real-time PDE/ODE simulations integrated with sensor data
- **AI + physics**: machine-learning surrogates constrained by PDE/ODE laws
- **Uncertainty quantification**: stochastic PDE/ODEs for resilience against extreme events
- **Multi-infrastructure coupling**: water-power-transport co-simulation using hybrid models
- **Control & optimization**: scalable algorithms for real-time predictive control of networks

What's next?

- Optimization and dynamic systems theory form the foundation for understanding infrastructure systems
- Much of this integration is still new
- Many infrastructure systems are still monitored and controlled using legacy algorithms
- Future systems will require algorithms that are scalable, resilient, and physically meaningful
- Next module: mathematical introduction to optimization, motivated by engineering problems

Questions

Thank You!