Module 01
Course Syllabus, Scope, and Intro

Dr. Ahmad F. Taha

Email: ahmad.taha@vanderbilt.edu

Webpage: http://lab.vanderbilt.edu/taha

CE 4240/5240 — Intro to Infrastructure Systems Engineering

VANDERBILT UNIVERSITY

August 22, 2024

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 @ Vandy, August 2021—currently

What do professors do and my lab's objective

Understand how complex systems operate and utilize this knowledge to create tools & algorithms to solve system-level challenges

- Hobbies, interests, likes, ...

Teaching, service, impact, funding

- **Teaching**: a well-rounded program on dynamic network sciences for critical infrastructure
  - Focus on the application + theoretical fundamentals
  - In today's world, theory is king
  - In a world where tiny margins matter, need to push systems through advanced engineering + math
- **Impact**: a library of infrastructure-specific algorithms to solve critical and timely engineering problems
  - Will these algorithms ever be implemented?
  - Future plan re: applying new theory to actual systems
- **Funding:** mostly by the National Science Foundation (NSF)
- **Team:** awesome group of grad students who make all of this possible

Examples on my group's recent research

- Energy systems, climate change, and transitioning to fossil fuels-free systems
- Everything water: distribution, drinking, stormwater, flood control, etc...
- Traffic control and monitoring, electrifying transportation
- Cyber-security of infrastructure
- Some theoretical questions

Module 01 Outline

1. You will tell me about yourselves: careers, objectives, education
2. Course syllabus and expectations
3. Homework 1
4. Course outline
5. The fun stuff starts — we will introduce infrastructure systems engineering and define the class scope

Part I — Your Turn to Introduce Yourselves! ☺

Part II — Course Syllabus and Outline

Course webpage & Communication

Course Page:

- Vanderbilt Brightspace: https://brightspace.vanderbilt.edu
- I might add the course content to my webpage—we'll see
- *Email is the best form of communication!*

Office Hours:

- Tuesdays and Thursdays, 12:30 – 14:00
- Or by appointment

TA Info:

- No TA

Course Description

Systems-level approach to the infrastructure of the built environment. Elements of systems engineering. Case studies of infrastructure under duress. Smart infrastructure. Transportation, building, and water and wastewater supply and distribution systems. Infrastructure interdependencies and concepts of smart cities. 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

The course presents an introduction to infrastructure systems engineering. In particular, the course takes a system-level perspective on what infrastructure systems engineering is all about. In particular, the class focuses on both specific infrastructure problems (i.e., water, transportation, energy, and power systems) as well as a generic theoretic foundations for infrastructure (i.e., control theory, mathematical optimization, etc..).

- mathematically model infrastructure systems
- improve programming and data analysis skills
- learn how to apply multi-objective linear and nonlinear optimization methods to design civil infrastructure systems using economic, social, and technical metrics
- learn a basic introduction to control theory
- gain knowledge about various contemporary engineering problems in transportation, water, and energy systems
- improve written and oral scientific presentation skills
- work in interdisciplinary teams to address complex problems across multiple civil and environmental domains

Prerequisites

An undergraduate-level understanding of:

- Multi-variable calculus
- Basic linear algebra
- Basic programming language (you pick your language but mostly Matlab)
- Some effort

Grading Policy

- Homework assignments/labs (30%), divided unequally
- Midterm 1 (30%)
- Midterm 2 (30%), right before thanksgiving
- Attendance and instructor evaluation (10%)

Course Grade Cutoffs

- A−, A, A+: 85–100
- B−, B, B+: 70–84
- C−, C, C+: 55–69
- D−, D, D+: 40–54
- F: ≤ 39

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. It's encouraged to use LaTeX for homework assignments and course projects (honestly, there's no good reason not to!).
- CVX, a toolbox in Matlab/Python, will also be required. Install it soon.

Class Policies

- Regular attendance
- Emailing me
- Showing up early
- Smartphone breaks
- On the homework
- 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...

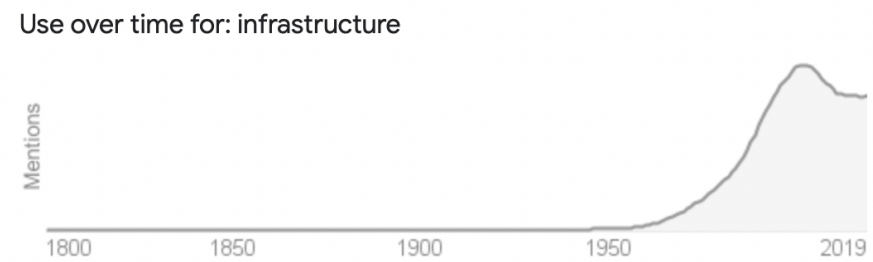
Homework #1

- Make a video about US infrastructure, download LaTeX
- Deadline: Monday, September 2nd, 23:59:59

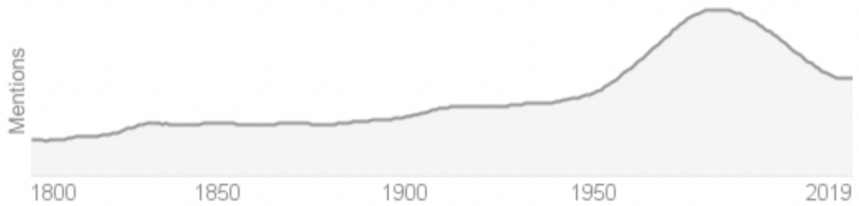
Part III — Introducing Infrastructure Systems

Nerding on words

- INFRASTRUCTURE
  - *infra*: word-forming element meaning “below, beneath,” from Latin *infra*
  - *structure*: action or process of building or construction from Latin *structura* “a fitting together”
  - *infrastructure*: the installations that form the basis for any operation or system, originally in a military sense [originally French, 1887]
  - Usage over time:



- SYSTEM
  - “the whole creation, the universe,” from Late Latin *systema* “an arrangement”
  - Linked words: *syn* (jointly), *sta* (make or be firm)
  - First use in the French literature, *système* [1610s]
  - Usage over time:



Modern uses

- Till today, no commonly accepted definition of infrastructure
- Proceedings of the Institution of Civil Engineers, published since 1826, has a first citation in 1933
- Categorization of infra:[1]

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

- Impossible to study all...so we focus on the more important ones

[1] *The Long-Run Evolution of Infrastructure Services* by Hugh Goldsmith.

Historical context

- Infra inventions and GDP

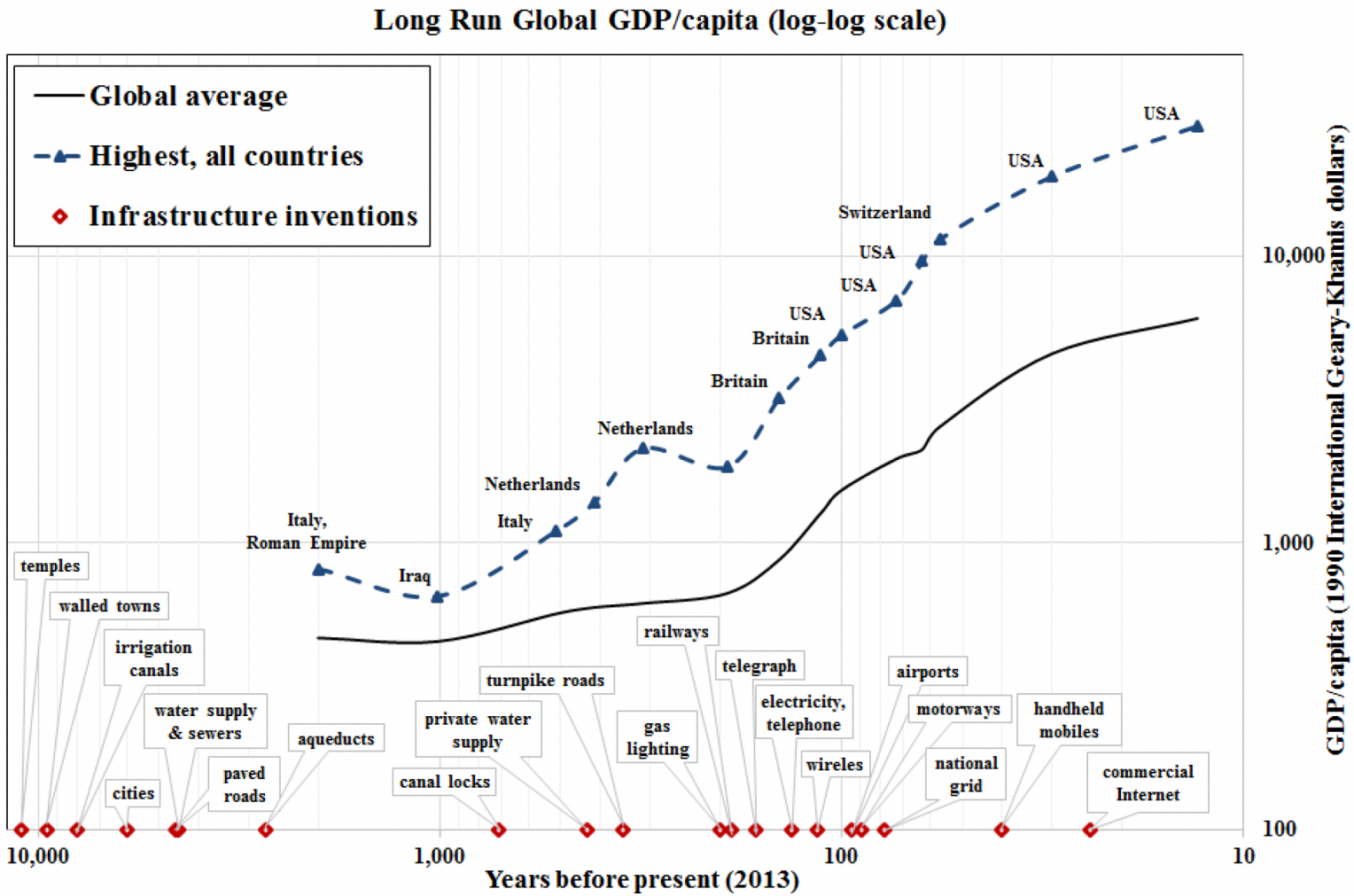


Figure 1. Time line of infrastructure innovations and economic growth

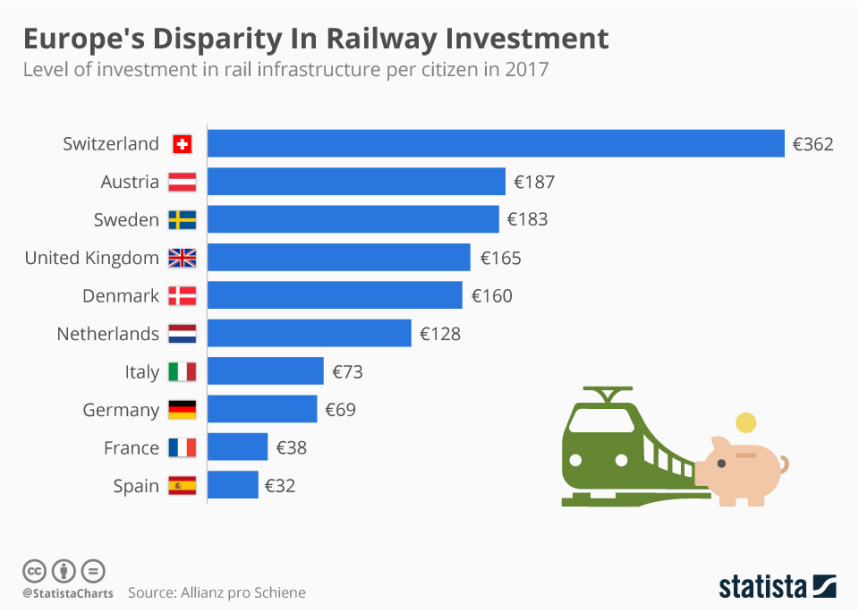
Source: Author's own elaboration for infrastructure invention dates (see text). GDP/capita data from Maddison (2007) - country maximum values exclude small oil states after 1920.

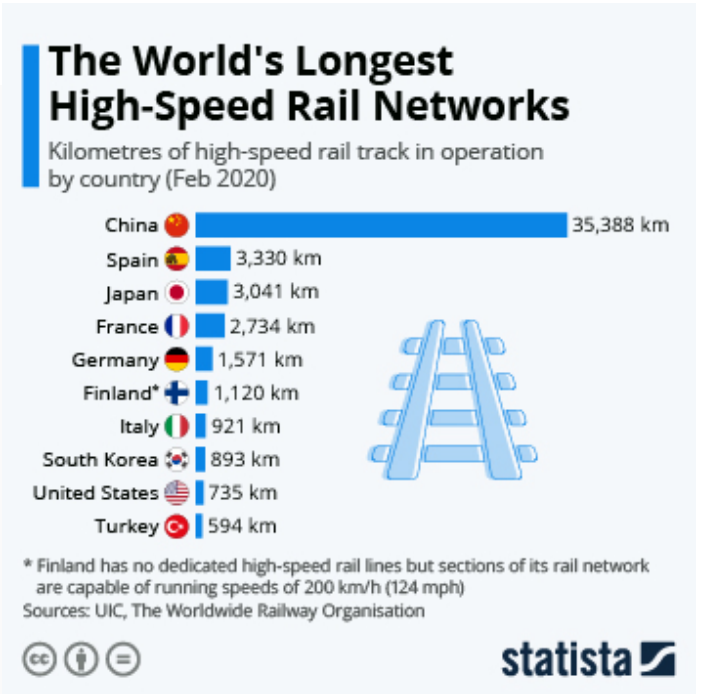
World's largest cities?

- Who can name 5 of the 10 largest cities in the world by population size?

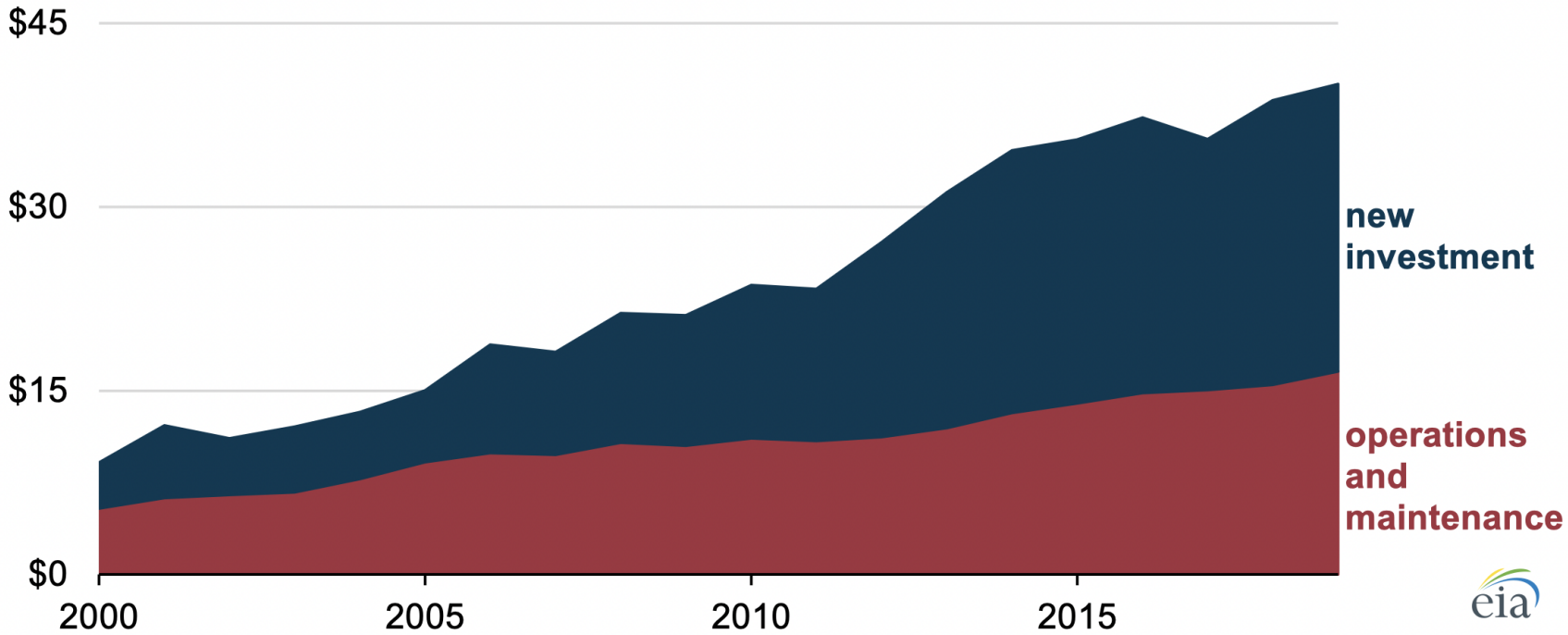
World's largest cities?

Disparity in railway infrastructure investment





Increase in power systems investments

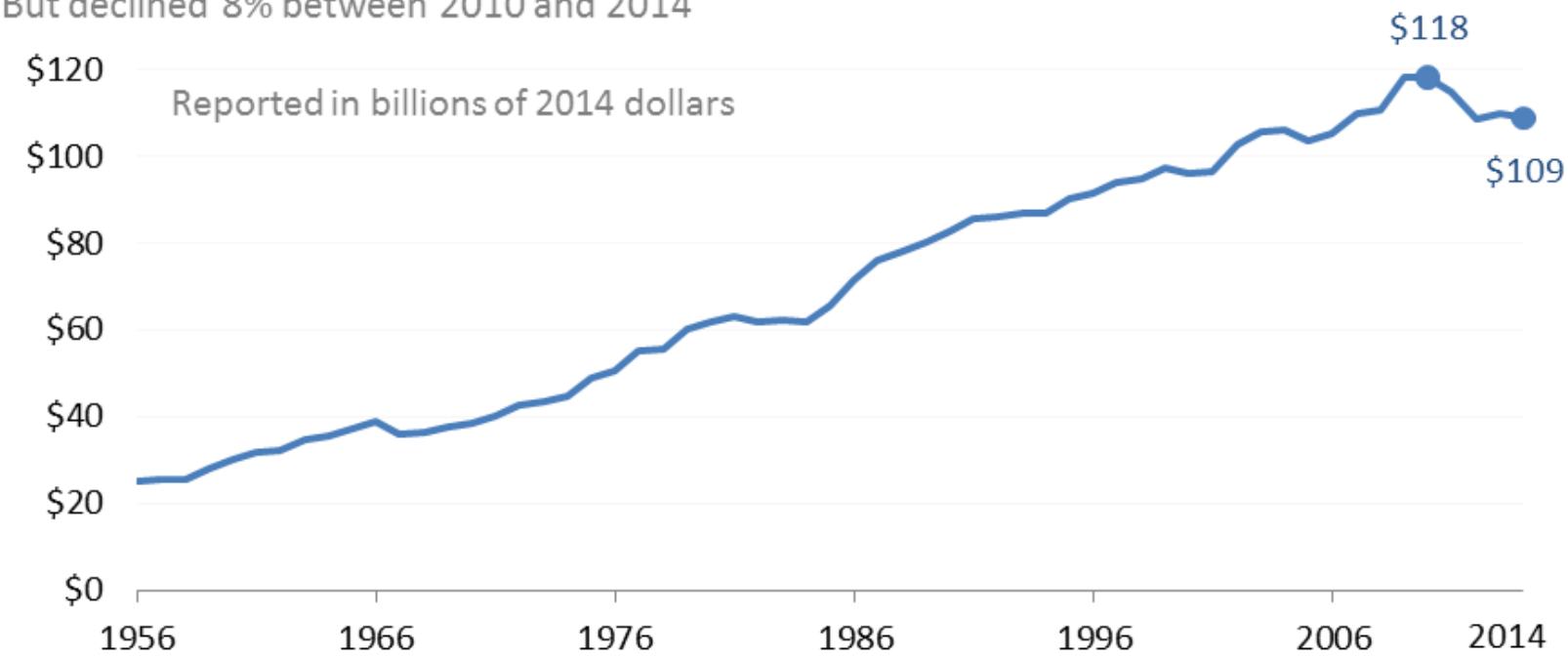


Source: U.S. Energy Information Administration, Federal Energy Regulatory Commission (FERC) Financial Reports, as accessed by Ventyx Velocity Suite

Increase in water systems investments

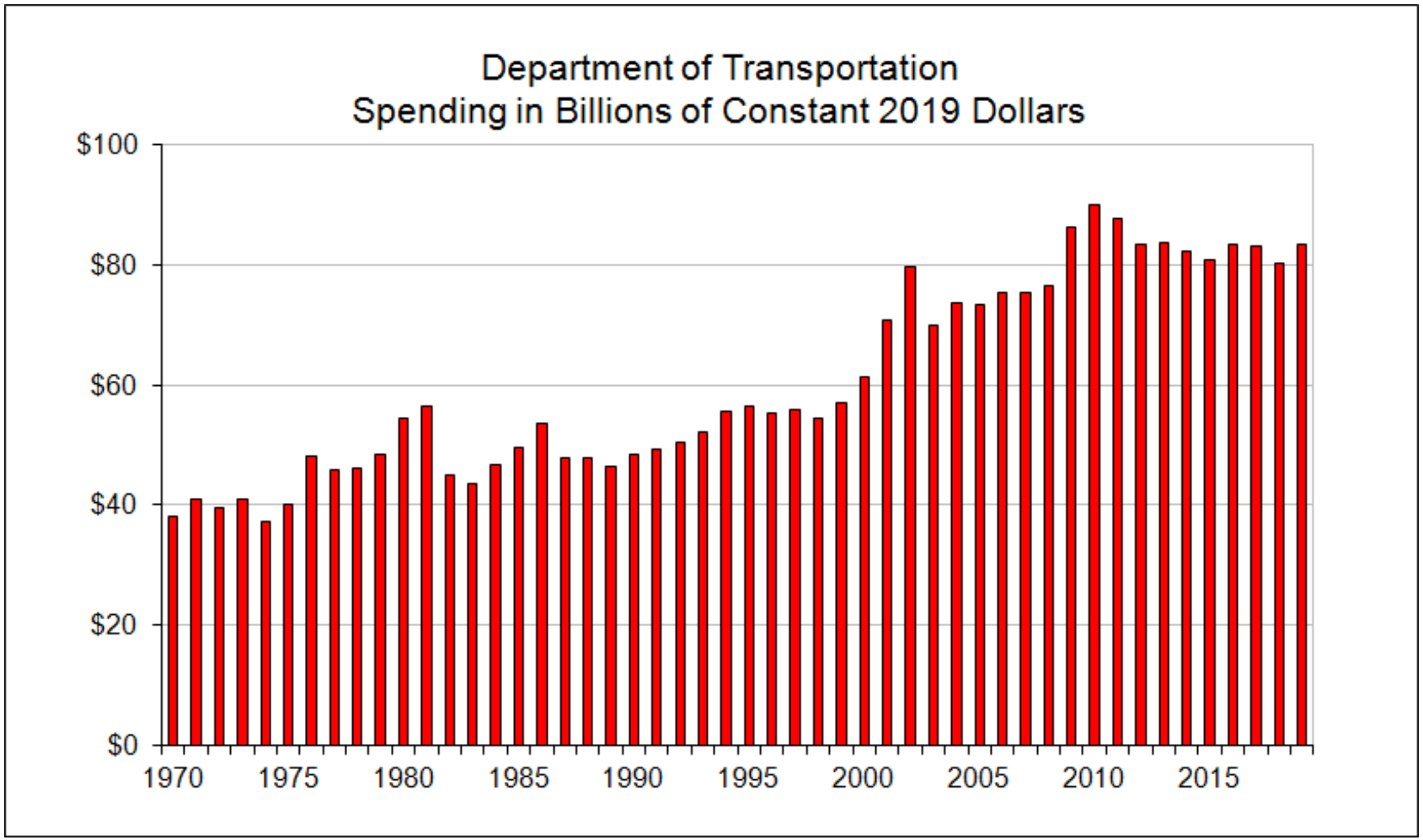
Total federal, state and local government spending on water and wastewater utilities grew steadily over time

But declined 8% between 2010 and 2014



Graphed by the Environmental Finance Center at the University of North Carolina, Chapel Hill.
Source: Congressional Budget Office supplemental data for the *Public Spending on Transportation and Water Infrastructure, 1956 to 2014* report (March 2015). Displays public spending on supply systems for distributing potable water as well as wastewater and sewage treatment systems and plants. Real spending is shown after adjusting nominal spending to their 2014 dollar equivalent using infrastructure-specific price indexes.

Increase in transportation systems investments

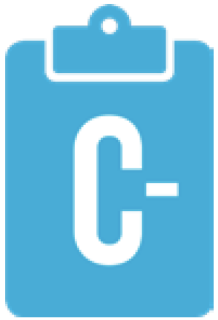


Future infrastructure

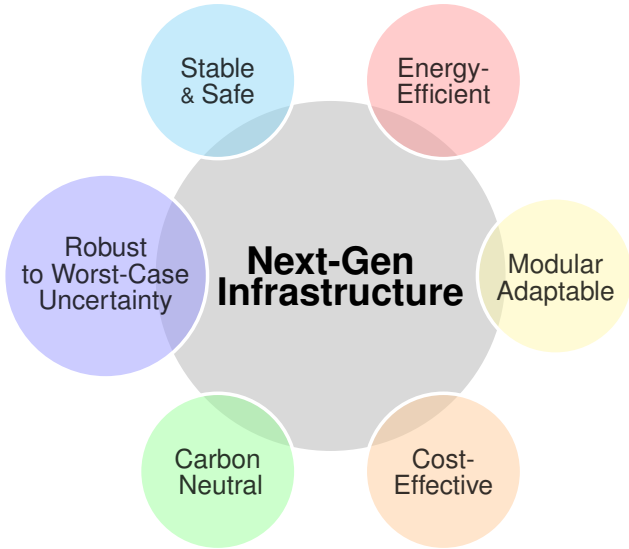
- Future infrastructure will be difficult to manage
  - uncertain, carbon-free, resilient
  - **2021 ASCE US infra rating**: C-
- World invests ∼$3T/year on major infra—not enough
- Inflation Reduction Act

- Urban population growth requires:
  - more integration between infra
  - advanced + applied theory
- Characteristics of future infra $\Longrightarrow$

ASCE Infrastructure Report, March 2021



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



Current US infrastructure state

Climate Change / Clean Energy

Climate change means the US must start building big things again

Sorry if it blocks your views.

by **James Temple**

Climate Change Jan 16

The latest numbers on renewable investments are in, and they aren't great

HOME NEWS WEATHER TALKERS TRAFFIC

Study finds 'phantom traffic jams' strain the economy

A new study found that traffic jams cost the U.S. economy a grand total of $179 billion each year.

Thursday, December 26th 2019, 4:49 AM EST
Updated: Thursday, December 26th 2019, 4:51 AM EST

Carbon Dioxide in the the Past 800,0

Ice core data from: Lüthi et al. 2008. Nature.
Current data from Mauna Loa - January 2020.

from full data record.

800.0 700.0 600.0 500.0 400.0 300.0 200.0 100.0 0.0 0

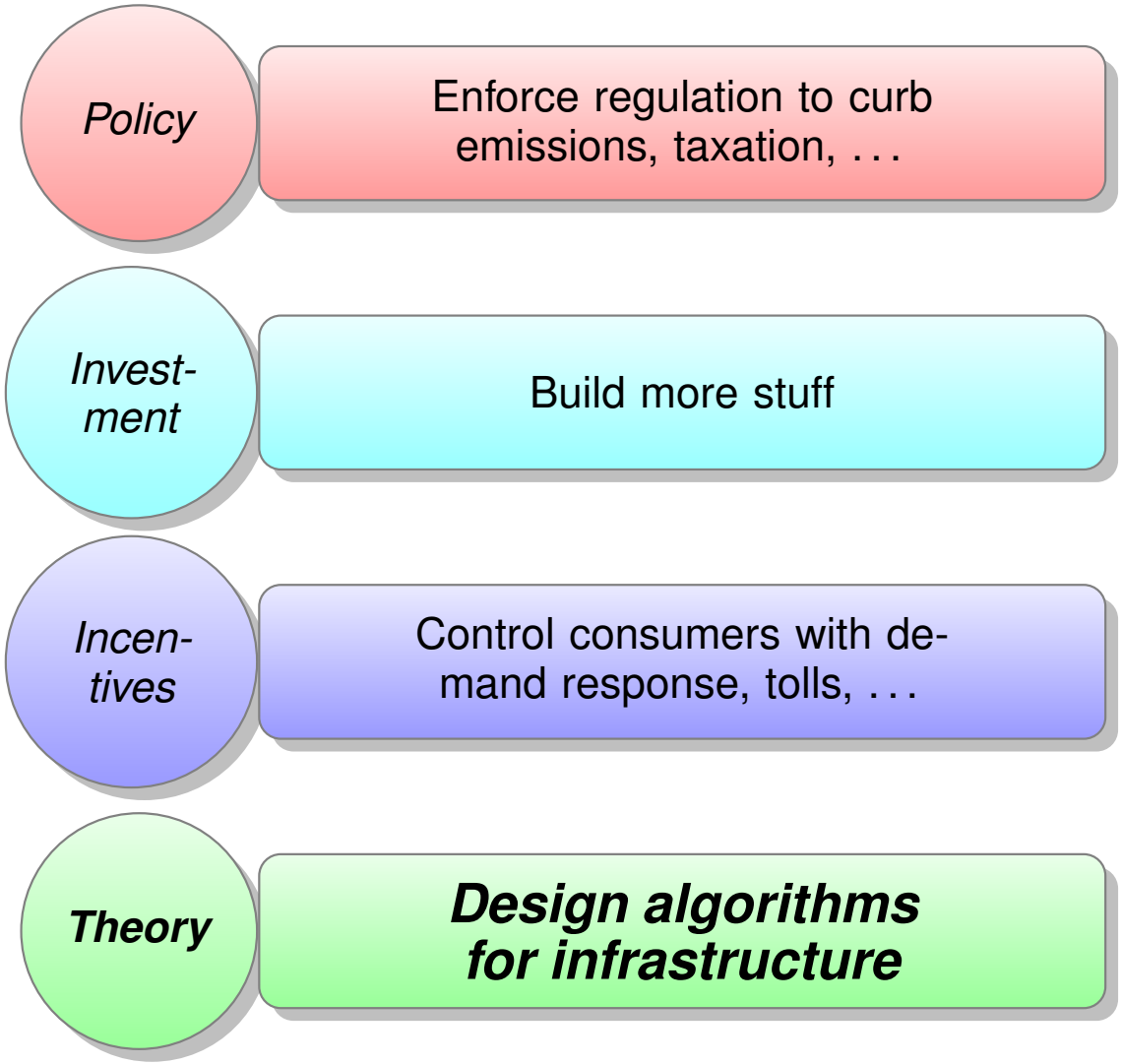
Thousand years before present (BP)

Leave a comment

Share

'Forever chemicals' found in drinking water in dozens of cities

Optimism: contemporary solutions



- $1 in infras. investment ⇒ $3 in GDP growth [UMD Study, 2014]
- Not all $'s are created equal! ***All strategies important, complementary***

Class's focus and application areas

Class focus

Creating computational algorithms for urban infrastructure

- *Balancing* the development of new foundations/theory with applications
- **Focus on:** uncertainty, nonlinearity, scale, performance guarantees
- **Application areas**:
  1. Climate change-aware algorithms for power/energy systems: *the old stuff doesn't work anymore*
  2. Contemporary problems in drinking water systems: *somewhere between quality and hydraulics*
  3. Other problems in water systems: *I don't know much about these but I'm learning*
  4. Mobility and transportation systems problem: *too many people, not enough roads*
  5. Multi-infrastructure problems: *the coupling is real*
  6. Cyber-security in infrastructure: *the bad guys are getting badder*

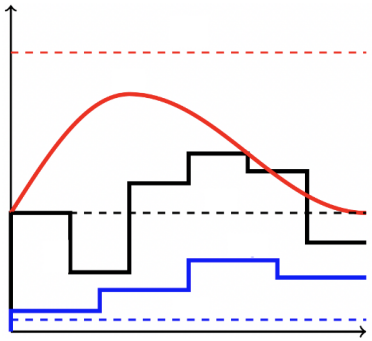
Technical challenges

Lack of mathematical frameworks

…that couples the operation of dynamic infrastructure components

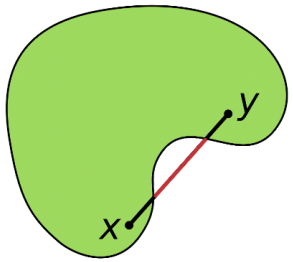
Significant time-scales discrepancy

…between interdependent infrastructure



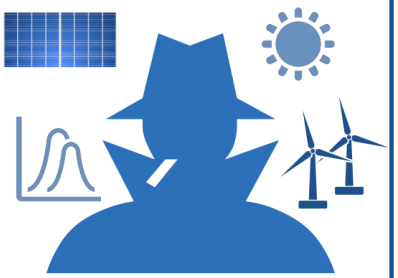
Nonconvexity and nonlinearity

…in dynamic models, constraints, objectives



Rampant uncertainty

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



Core sciences behind infrastructure science?

1. CONTROL SYSTEM THEORY
   - The study of **dynamic systems** modeled via
     - input-output mappings via data: $\{u(t), y(t)\} \Longrightarrow y(t) = \mathcal{F}(u(t))$
     - input-out mappings via differential equations/PDE $y(t) = f(u(t), \dot{u}(t), \ldots)$
   - **Fundamental questions**:
     - What is a good model? When should we use data-driven vs. physics-driven modeling?
     - When is the system well-behaved? Stability and beyond
     - How can we design better control $u(t)$ to make $y(t)$ smoother/cheaper/safer?
     - Theoretical questions, yes, but they are all applied to actual infra problems
2. OPTIMIZATION THEORY
   - Doing more with less
   - Reducing costs, optimizing system performance, hedging against risk, etc..
   - **Examples** in climate change, flood control, traffic reduction, etc...
   - **Career objective**: *bringing control and optimization theory to the marketplace of infrastructure problems*

Going back to tentative course schedule

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What's next?

- Because optimization and dynamic system theory form basis to understand infra, we need to cover these first
- Keep in mind, that all of this is basically new...
- ...most of today's infra are controlled and monitored using ancient algorithms that will not work in the future...
- ...hence, this class :))))
- This class is not going to be perfect, but y'all can make it better
- Next episode/module: thorough mathematical intro to optimization + motivation from different engineering problems

Questions

Thank You!

Please visit

https://lab.vanderbilt.edu/taha/

IFF you want to know more ☺