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NSF Smart and Connected Community (S&CC) Project
(NSF 1831140)

CTS STF Research Council Meeting

Project Overview and Highlights of Research Activities & Outcomes

Zhi-Li Zhang, University of Minnesota
&
Yanhua Li, Worcester Polytechnic Institute

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Outline

- Overview of Our NSF Project on Shared AVs
  - Motivation, Vision, Integrative Research Thrusts & Community Engagement & Pilot Projects
- Highlights of Major Research Activities in past 2 years
  - Theoretical & Economic Modeling, Design Issues
  - Social Challenges & Community Engagement
- Evaluation, Impacts and Data: Challenges
- Data-driven, AI-guided Approaches

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A Few Words about the Project

- $1.75 millions over 3 years, awarded by NSF Smart & Connected Community (S&CC) Program, starting 10/18
- Interdisciplinary team across multiple colleges at U.
  - Zhi-Li Zhang, Computer Science & Engineering, CSE
  - Saif Benjaafar, Industrial & Systems Engineering, CSE
  - Alireza Khani, Civil, Environmental & Geo-Engineering, CSE
  - Yingling Fan, Humphrey School of Pubic Policies
  - Frank Douma, Humphrey School of Pubic Policies
  - Tom Fisher, Design Center, College of Design
  - Yanhua Li, Data Science, Worchester Polytechnic Institute
- Consisting of two equally important tracks:

  i) Integrative Research & ii) Community Engagement

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A Few Words about the Project

- Community Partners
  - Minnesota Dept. of Transportation (MnDOT), including
    - ABC Ramp
  - Metropolitan Council (Met Council), including Metro Transit
  - Southwest Transit
  - Hourcar
  - Destination Medical Center (DMC)
  - SE MN Together
  - Greater MSP
  - Robert J. Jones Urban Research & Outreach-Engagement Center
  - Twin Cities Shared Mobility Initiative
  - Cities of Minneapolis/St. Paul
  - Hitch+Health
  - ……

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Driverless Cars are Coming!

- We've all heard it in the news!
  - Google Waymo, Uber, GM, Ford, …
- Whether like it or not, AVs will have huge impacts on many levels
  - car ownerships
  - transportation & mobility services
  - highways, urban streets, parking, land use, …
  - technology "haves vs. have-nots", businesses, …
  - social equity issues

- ➢ We believe autonomous vehicles (AVs) will transform how we move around in physical world!
  - Just as the Internet has transformed how we access information and interact w/ each other in cyberspace
- ➢ We better get ahead of it!

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This NSF S&CC Shared AV Project

Not about how to design AVs or make them feasible, but how to leverage *shared* AVs (SAVs) to

- ➢ envisage and design a *transformative* transportation & mobility service based SAVs for future smart cities, …
- ➢ bridge technology/geographical divides, bringing benefits to diverse communities
- ➢ work w/ stakeholders, policy makers & communities to identify & tackle various socio-economic challenges

❖ State of Minnesota and Twin Cities area have a reputation for forward-looking and have established a long tradition for planning for the future!

- partly why U. Minnesota were awarded two large NSF S&CC grants two years in a row!

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Our Vision

"Smart Cloud Commuting Service" via shared AVs

- Leveraging giant pools of shared AVs to provide a new kind of "mobility as a service" to bring benefits to citizens
  - aided by mobile, cloud computing, big data, AI & other technologies
- Targeting daily commutes, not merely ad hoc trips
  - peak demands, cause of traffic congestion, …
- "Economy of scales": maximize system efficiency gains
  - sharing AVs among users, smart trip scheduling, road efficiency, …

Goal: making SCCS as cheap as possible & as convenient as owning a personal car!

- bridging "spatial divide", serving diverse communities, enhancing economy, enabling smart communities, ……

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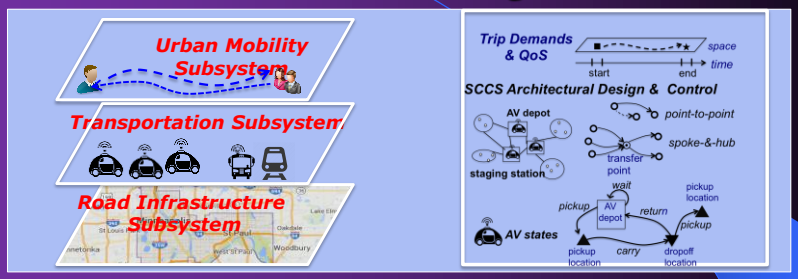
Our Vision
"Smart Cloud Commuting Service"



How do we go from here to there, realizing our vision?

- Integrative Research:
  i) modeling demands & quantifying efficiency gains; ii) economic issues; iii) SCCS architecture designs; iv) urban re-designs; .....
- Community Engagement & Broader Societal Impact
  - several (proposed) pilot projects

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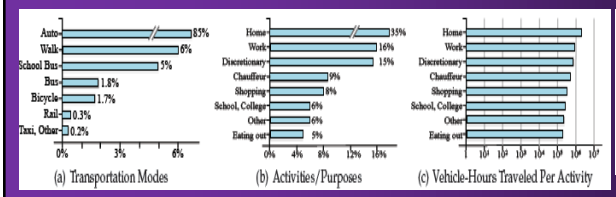
Integrative Research

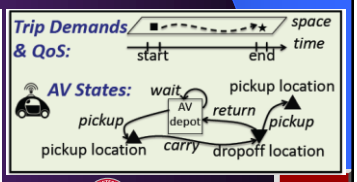
- Thrust 1. Data-Driven Demand Analysis: Quantifying Feasibility and Potential Gains of SCCS

  Basic Research Questions:

  1) How many shared AVs do we need to serve peak daily commute demands, say, in TC area, & meet user QoS?
  2) Will AVs change people's travel behaviors, increasing or reducing trip demands?

- Utilizing Met Council Travel Behavior Inventory surveys & other data sources; ABM & other demand models ?





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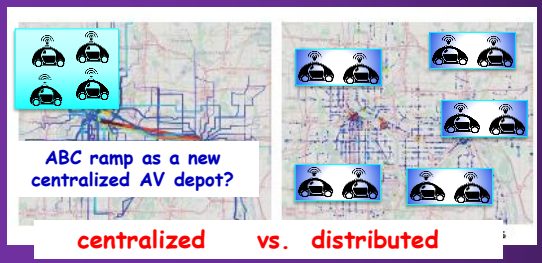
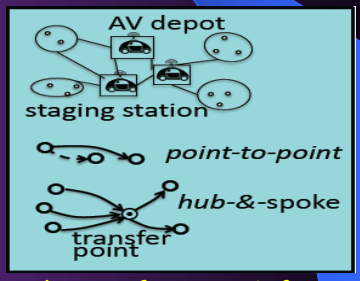
Integrative Research

- Thrust 2. Architectural Design & Operational Challenges

  Basic Research Questions:

  1) how should SCCS be architected? In particular, the physical architecture? e.g., where idle AVs be placed?
  2) what service models should be adopted?





- Building data-driven, simulation-based evaluation framework for tackling some of these design & operational challenges

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Integrative Research

- Thrust 3. Economic Viability: SCCS Business Models and Efficiency-Equity Trade-offs

  Basic Research Questions:

  1) AV ownerships, Business Models and Market Structure?

  e.g., i) individual AV ownership, "peer-to-peer" service?
  ii) multiple competing third-party service providers; or
  iii) a single regulated entity, e.g., public transit?

  2) Efficiency-Equity Trade-offs, Incentives and Policies?

  e.g., i) how can we accommodate user preferences/choices while lowering costs, ensuring no community left behind?
  ii) subscription services? iii) gov. regulations & policies?
  iv) what incentives can be provided, e.g., for ride-sharing, or taking an earlier or later ride? business subsidizing users?

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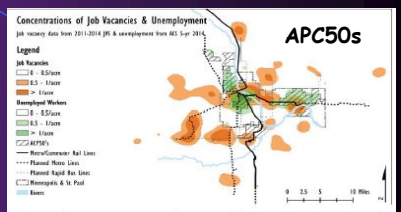
Integrative Research

- Thrust 4. Leveraging SCCS to Tackle Social Challenges
  - Thrust 4.1. Leveraging SCCS to bridge geographical disparities and reduce income inequalities?
  - Thrust 4.2. Urban and Street Re-Design, Land Use and Incremental Deployment



(a) Map showing severe spatial mismatch between concentrations of job opportunities and concentrations of poverty and unemployment in the Minneapolis-St. Paul metropolitan region. Transportation connections are much needed. ACP50s are areas of concentrated poverty where more than 50% of the residents are people of color.

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Community Engagement

- State of Minnesota, Regional & City Governments have a tradition of forward-looking & planning for the future
- U. of Minnesota, esp. CTS, UROC, have a long history of collaborating w/ various gov. entities & communities

Engaging Stakeholders at Various Levels

1) w/ Policy & Decision Makers and Urban Planners
2) w/ Infrastructure & Facility Providers and Service Providers
3) w/ User Communities (esp. Disadvantaged) and "Destinations"

Leveraging existing, ongoing & future related projects/activities

- MnDoT autobus pilot, MetCouncil AV Demand Survey/Planning
- ABC Ramp "Mobility Hub", Southwest Prime, HOURCAR, …
- Rochester/Mayo "DMC Project", Southeast MN Together, …

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Five "Envisioned" Pilot Projects

- P1. MnDoT Autonomous Bus Pilot and ABC Ramp Mobility Hub Initiative to explore SCCS architectural designs
- P2. SW Prime, APC50s, Businesses and Bridging Geographical Disparities for Equal Opportunities
- P3. Rethinking I94 Highway Corridor
- P4. America's City for Health
- P5. Southeast MN Together

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Highlights of Research Activities

Thrust 1. Feasibility Study & Demanding Modelings

- First Study of SCCS Feasibility using queueing theory model

Thrust 2. SCCS Architectural Design Issues

- Citylines: a "hub-&-spoke" model for transit
- Integrated Transit Systems

Trust 3. Economic & Operations of AVs

- AV ownership models, hybrid on-demand service platforms, operations

Trust 4. Social Challenges & Community Engagement

- Impacts of AV on future streets, community survey on AVs & spatial mismatch, addressing inequity issues, …

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Highlights of Research Activities

Thrust 1. A First Study of SCCS Feasibility using queueing theory model

- Basic Q: How many AVs do we need to serve a given peak daily commute demands?

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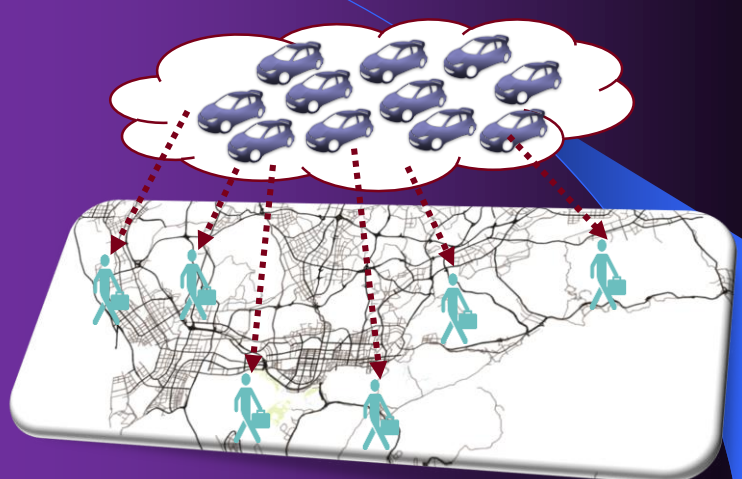
Smart Cloud Commuting System



Realize *economies of scale* via a giant pool of autonomous vehicles

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Key Questions to be Addressed

How many self-driving vehicles are needed in the system?

Where to deploy the vehicles?

- How to dispatch and route the self-driving vehicles?

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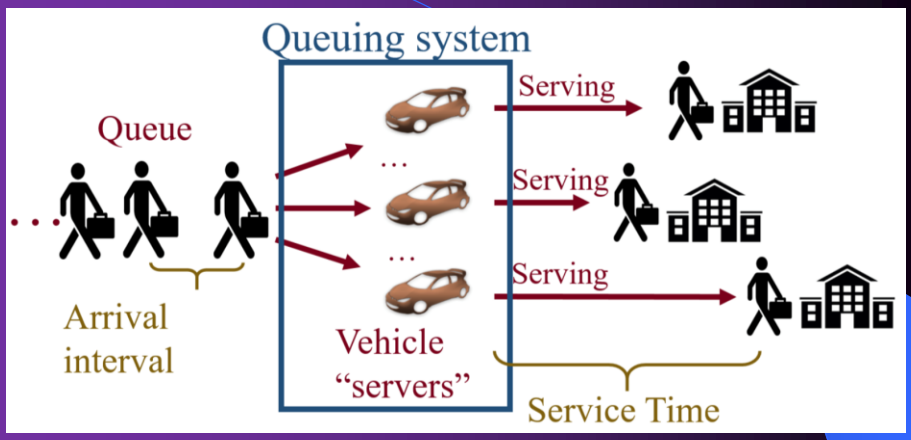
SCCS as a Queuing System



- Arrival rate λ: # arrivals / unit time.
- Service rate μ: # passengers served / unit time.
- Utilization: ρ = λ / μ, chance that a taxi server is busy

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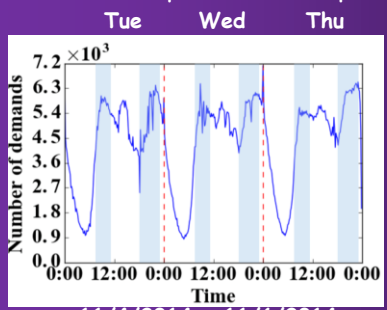
Trip Demand Modeling

- Using a city-wide taxi data as a proxy – understanding trip request arrival processes
  - 9,606 taxis in Shenzhen, China; 595,501 daily trip demands
  - A clear diurnal pattern of trip demands (in 10 mins intervals)



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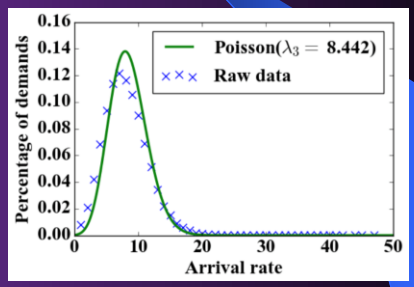

- Demand arrival rate (arrivals per hour) follows Poisson distribution ➔

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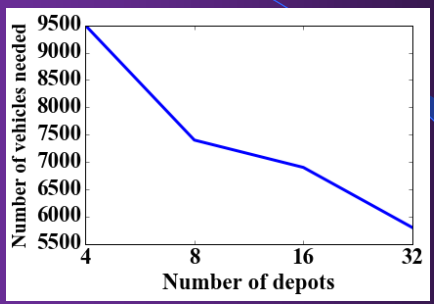
Takeaways: Number of AVs Needed



- # of AVs needed is reduced, as # of depots increases
  - → to provide the same average service time (40 min) of today
  - → compared w/ 9,606 taxis in deployment today
- Improve vehicle utilization
  - ➔ increase utilization rate from 42% of today to 90% (with 32 depots)

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Highlights of Research Activities & Key Outcomes

Thrust 2. SCCS Architectural Design Issues

- Citylines: a "hub-&-spoke" model for transit
  - an attempt to look at the architectural issues of SCCC
- Integrated Transit Systems

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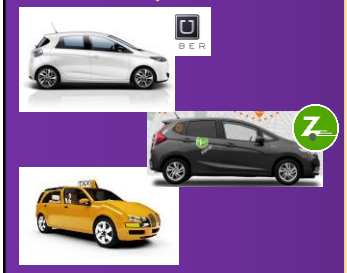
SCCS Architectural Design

Point-to-point mode



Pros:
- Short travel time

Cons:
- High Cost
- Service delay

fixed route mode

Pros:
- Affordable service

Cons:
- Fixed routes
- Fixed timetable
- Long travel time

Hub-and-spoke mode: ideal mode for SCCS

Dynamic services
- Meet real time trip demands

Short travel time
- As point-to-point mode

Low cost
- As fixed route mode

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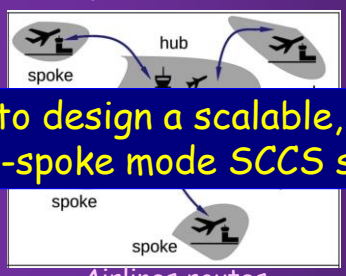
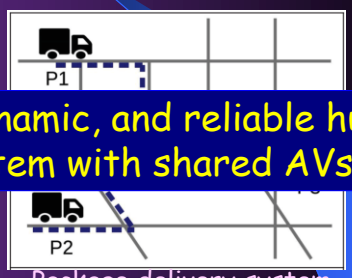
Hub-and-Spoke Mode for SCCS

- Having been used by many systems
  - Less operation cost;
  - Less stops/stations, thus lower transit time;



Airlines routes



Package delivery system

How to design a scalable, dynamic, and reliable hub-and-spoke mode SCCS system with shared AVs?

- Hub-and-Spoke mode design for SCCS
  - Hubs can be fixed or dynamic;
  - Hubs can be a point, e.g., bus stop, or area, e.g., (circular) shuttle services in downtown

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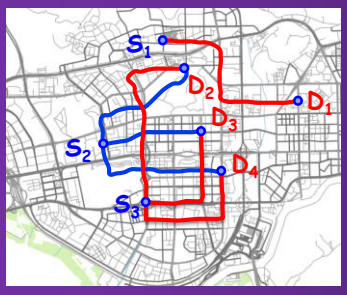
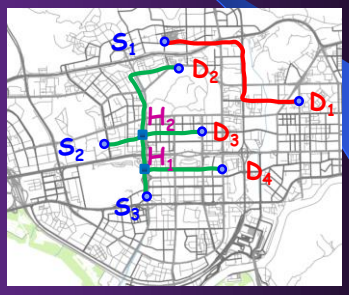
CityLines: Hub-and-Spoke Service

CityLines: a Hybrid Hub-and-Spoke mode for SCCS architectural design
- point-to-point mode: high demand source-destination pairs
- hub-and-spoke mode: low demand source-destination pairs



Point-to-point model



CityLines

Hybrid hub-and-spoke mode

AV	Routes
#1	S_1-D_1
#2	S_2-H_2-D_3
#3	S_3-H_1-H_2-D_2
#4	S_2-H_2-H_1-D_4

Reduce the number of AVs from 7 to 4

Reduce routes, thus operation cost

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CityLines: Hub-and-Spoke Service

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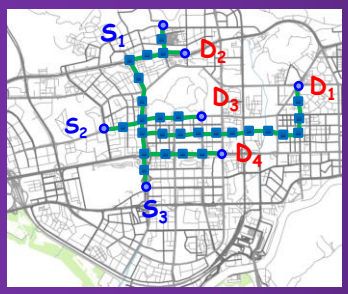

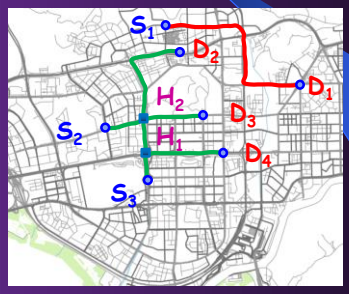

AV	Routes
#1	S_1-D_1
#2	S_2-H_2-D_3
#3	S_3-H_1-H_2-D_2
#4	S_2-H_2-H_1-D_4

Reduce the number of stops from 27 to 2, thus reducing the overall service time

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Integrated Transit Systems

(Research Conducted at UMN Transit Lab)

- It is believed that cities will still need high capacity, frequent, and reliable transit systems for core urban areas
- Integration with emerging technologies such as AVs and shared mobility can improve quality of service and cost-effectiveness
- Key questions are:
  - How to model the integrated system and estimate its demand?
  - How to plan for the infrastructure, e.g. transit routes and AV depots?
  - How to operate the integrated system?

Led by Prof. Alireza Khani and his research group

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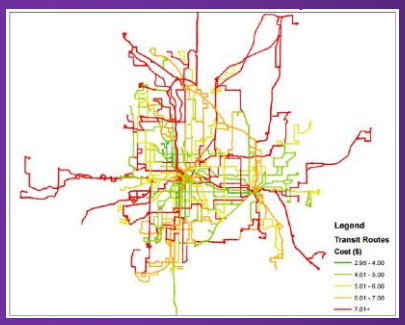
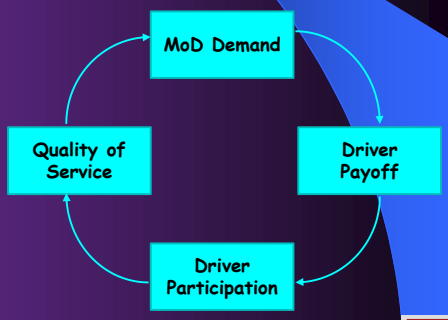
Integrated Transit System

- Sometime transit service may not be cost effective due to low demand
- MoD can serve as a cost-effective feeder
- Q: How to estimate demand and QoS for the integrated system?
- Application to the Twin Cities Transitways with destination to MSP





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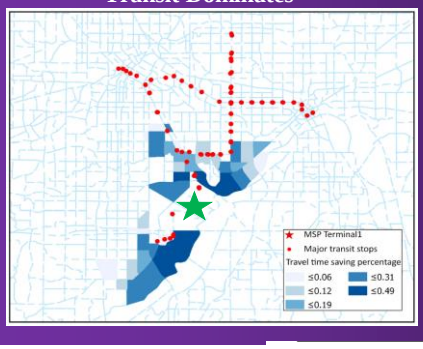
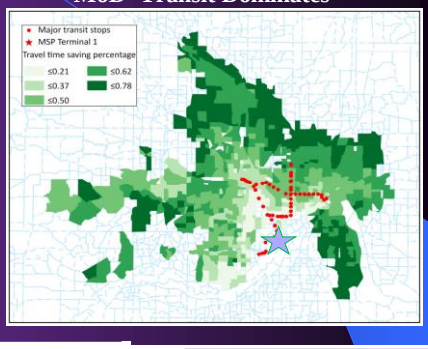
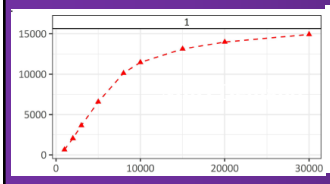
A1Integrated Transit System – Results

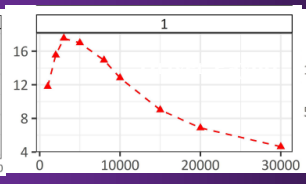
Transit Dominates

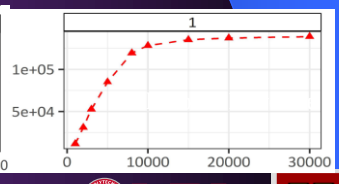


MoD+Transit Dominates









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Highlights of Research Activities

Economics & Operation of Automated Vehicles

- Key Research Questions
  - What are likely ownership scenarios and under what conditions (P2P, B2C, competitive/regulated monopoly, public/private)?
  - What are likely business models and their impact on welfare (pay per use, subscription models, dynamic pricing, differentiated service)?
  - What is the impact on ownership and usage?

Led by Prof. Saif Benjaafar and his research group

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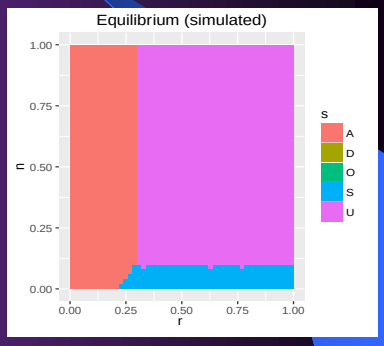
Equilibrium Modeling of AV Ownerships

- Equilibrium models that account for the strategic interactions between users (owners and non-owners), service providers, and regulators
- Analysis reveals that whether P2P or B2C emerges as the dominant equilibrium depends crucially on the ratio of ownership to usage cost
- A high ownership to usage cost makes B2C more likely while the reverse makes P2P more likely

B2C: AVs owned by service providers
P2P: owned by individual users, shared



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Equilibrium Modeling of AV Ownerships

- Introduction of AVs could lead to an increase in both ownership and usage
  - value enhancement through rental income
  - expanded access through short term rentals
  - new types of usage
- A role for government to induce desirable outcomes through regulation

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Hybrid On-Demand Service Platforms

In the short to medium term, conventional vehicles (CVs) and automated vehicles (AVs) will co-exist

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Hybrid On-Demand Service Platforms

- How should an on-demand service platform decide on the optimal mix of conventional and automated vehicles?
- Automated and conventional vehicles vary in the associated cost of capacity and the efficiency of this capacity
- Individuals vary in their preferences of conventional over automated vehicles

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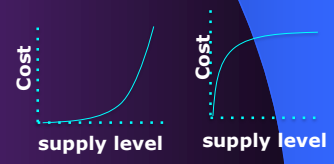
Hybrid On-Demand Service Platforms

Develop equilibrium and queue-theoretical models for studying the following questions:

- What are optimal mixes of AVs and CVs given a consumer profile of preferences and travel needs?
- How would a platform price its AV and CV services and how would it deploy them temporally and geographically
- How would the introduction of AVs impact consumers (price, service level) and workers (wages, utilization)



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Analytics for Design, Planning, and Operation

Key Questions (related to SCCS architecture design)

- How big should the service region be?
- How many and where to place vehicle hubs?
- How big should the fleet size be (given a service region and a target service level)
- Where should a vehicle go upon completing a drop off?
- How should the service be priced?

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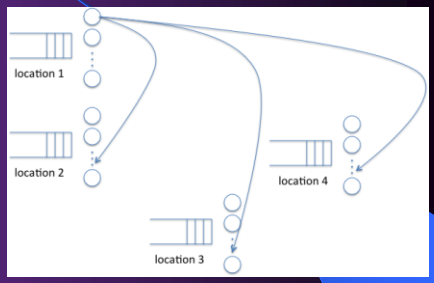
Optimal Fleet Sizing

- Tools (using queueing network analysis) to evaluate performance under varying conditions
- Analysis reveals that the optimal fleet size depends crucially on operational decisions (one way, round trip, return to hub, number of hubs)



Tension between inefficiency due to vehicle unbalance across locations and inefficiency due to empty travel

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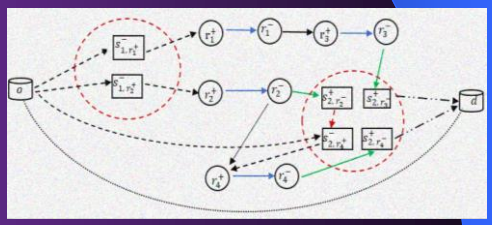
Optimal Depot Locations for AV-MoD

1. Customers request rides dynamically; a central dispatcher decides which customer to be served by which AV from which depot
2. After serving a customer, AVs can
   - **A) Go back** to depot
   - **B) Idle** until next request
   - **C) Park** on the street
3. Systems costs:
   - **A) Capital** cost of depots
   - **B) Operating** cost of AVs
   - **C) Users** travel cost
4. **Q: Where should depots be located to minimize total cost?**
   - Optimization model
   - Uncertain demand

Led by Prof. Alireza Khani and his research group



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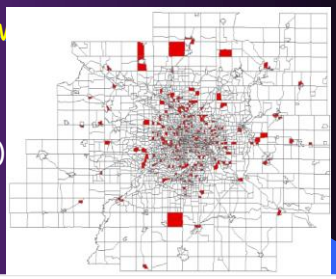
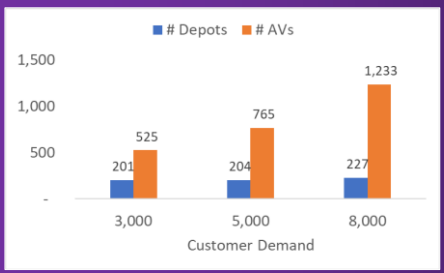
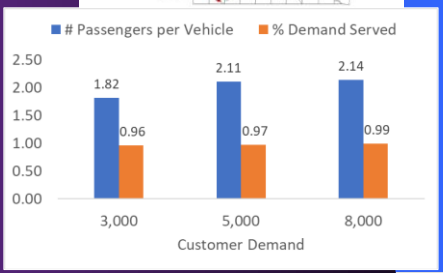
Optimal Depot Locations for AV-MoD

Application to the Twin Cities netw

- Three-hour peak period
- Demand scenarios from ABM
- One candidate depot per TAZ (~3000)







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Highlights of Research Activities & Key Outcomes

Impact of AVs on Physical Infrastructure, Tackling Social Challenges & Community Engagement

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Autonomous Vehicles & Future Streets

- Impacts of AVs, with their repetitive wear on road surfaces, on our street infrastructure
- Street/urban re-design and land reuse for healthy and better environments
  - re-design of road surfaces
    - likely having reinforced-concrete, grade-beam tracks for the vehicles' tires, with pervious paving or plantings on the remainder of the surface
  - allowing for storage of storm water in the road be
    - recharging acquifers,
    - reducing the heat-island effect of streets
  - increasing space of other habitat and human activities

Led by Prof. Tom Fisher and his group, working w/ community partners

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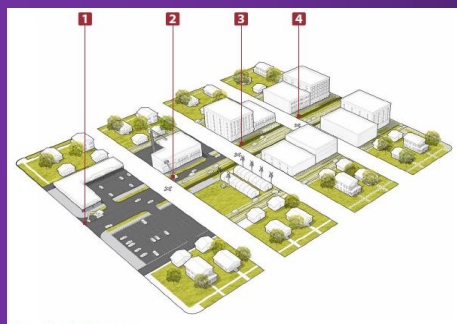
Autonomous Vehicles & Future Streets

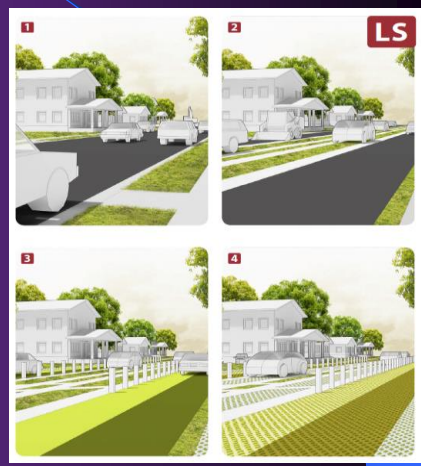
transition to conventional streets to AV-ready streets



COLLECTOR STREET

TRANSITION - COLLECTOR STREET TRACK

The transition of collector streets to an autonomous-vehicle infrastructure will gradual. Initially, it will involve the selective replacement of paved traffic lanes to allow for both driven vehicles and autonomous vehicles to share the right-of-way. That combination of technologies, though, will not last long, as it didn't when we transitioned from horses to cars over a century ago. Eventually, as driven vehicles become rare - or even not allowed in many jurisdictions - the streets will become completely AV ready. In the meantime, mobility services will lead to the adaptation of parking lots to urban agriculture or the infilling of lots with other needed development.



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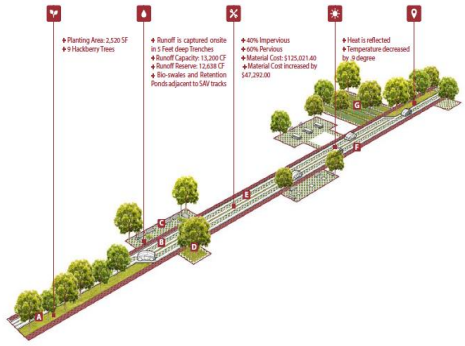
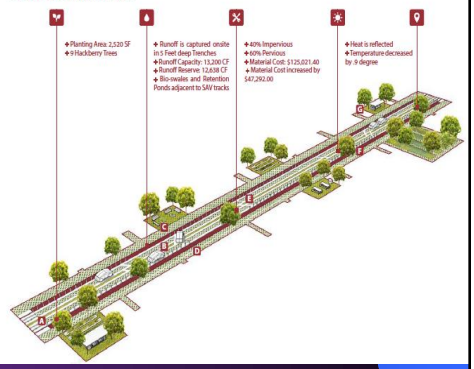
Future Local, Collector & Arterial Streets

SHARED AUTONOMOUS VEHICLE (SAV) DESIGN - ALLEY, TYPICAL



SHARED AUTONOMOUS VEHICLE (SAV) DESIGN - LOCAL, COLLECTOR, AND ARTERIAL, TYPICAL



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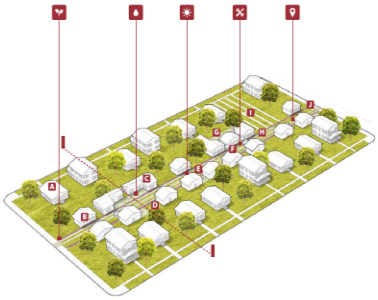
Future Alley Streets

FUTURE ALLEY STREET - AXONOMETRIC



FUTURE ALLEY STREET - GENERAL INFORMATION

Street Total Surface Area	12,000 Square Feet
Street Length	600 Feet
Street Width	20 Feet
Street Right-of-Way (ROW)	30 Feet
Street Speed Limit	10 Miles Per Hour
Surface Types - Surface Area	
Impervious	4,901 Square Feet (40%)
Pervious	7,099 Square Feet (60%)
Use	
Shared Green Street	
Access to Adaptive Reuse Structures	
Rear Parking and Entrance	

FUTURE ALLEY STREET - PLANTING

Street Planting Area	2,520 Square Feet
Planted Trees	9

FUTURE ALLEY STREET - MATERIAL COST

Street Total Surface Area	12,000 Square Feet
Materials	
Rock Base ($.65/SF)	$7,800.00
Permeable Paver ($5.00/SF)	$32,940.00
or Coarse Aggregate ($5.00/SF)	
Reinforced Concrete ($10.00/SF)	$48,010.00
Total Cost	$88,750.00
Total Cost (x 1.393 Inflation Rate)	$125,021.40

FUTURE ALLEY STREET - HEAT ISLAND INDEX

Heat is reflected; The Planting Area and Trees decreased the temperature by .9 degree.

FUTURE ALLEY STREET - STORMWATER RUNOFF

Street Total Surface Area	12,000 Square Feet
Impervious	4,901 Square Feet
Pervious	7,099 Square Feet
Average Rainfall (in Minnesota)	.104 FT/ 24HRS
Runoff Coefficient	.45
Volume of Runoff	562 Cubic Feet
Runoff Capacity	13,200 Cubic Feet
Runoff Reserve	12,638 Cubic Feet

- A Single Family Residential
- B Adaptive Reuse Structure
- C Adaptive Reuse Structure Expanded
- D Bio-Swale and Retention Pond - Runoff Reserve
- E Future Alley Street - Shared Green Street
- F Shared Autonomous Vehicle Tracks
- G Shared Community Space/ Public Courtyard
- H Shared Mixed Modes Permeable Sidewalks
- I Community Garden and Reclaimed Wet Land
- J Urban Forest Gateway - Green Plaza

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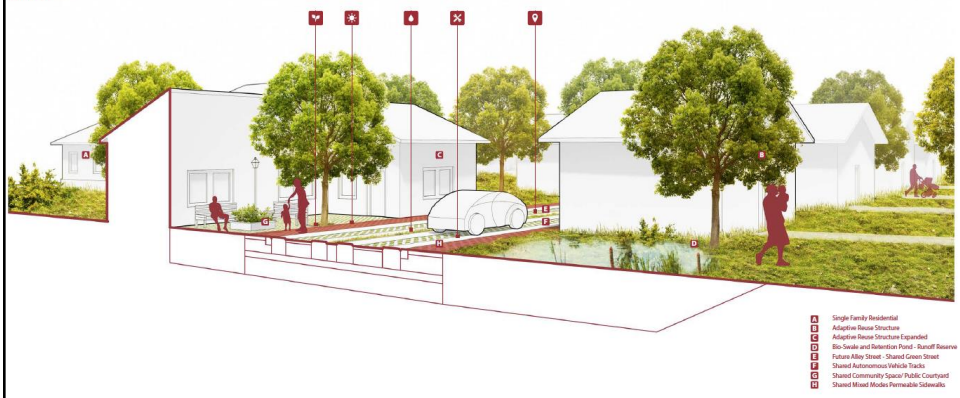
Future Alley Streets

FUTURE ALLEY STREET - AXONOMETRIC



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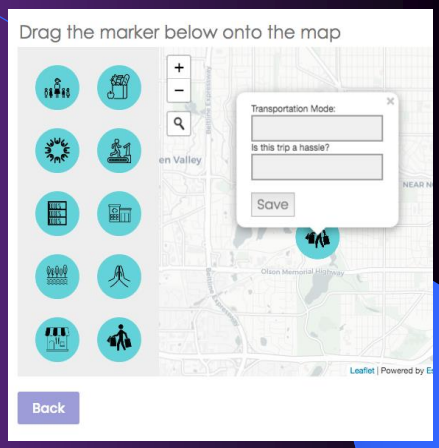
Community Survey

- Assess potential for AV's to address spatial mismatch
- Method
  - Seek representative sample
  - Tablet-based
  - Qualtrics platform
  - Mapping interface
- Questions:
  - Collect spatial info about current Destinations, Modes, and "hassles" encountered
  - Measure Spatial Mismatch: ask about difficultly commuting to hypothetical job locations in the Southwest Suburbs and Downtown St. Paul.



Led by Prof Yingling Fan & Frank Douma and their group

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Community Survey

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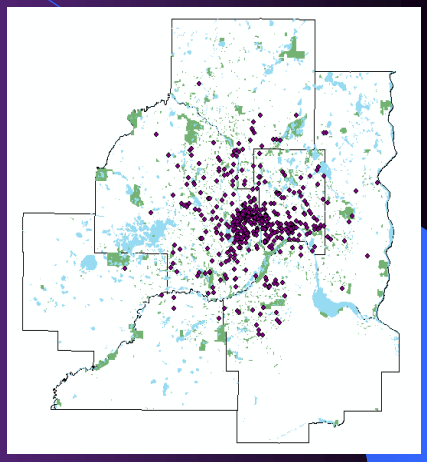

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Other Community Engagement Activities

- ABC Ramp Mobility Hub
- Analytics for one-way all electric vehicle sharing systems
- Improving access to healthcare through improved access to transportation

HOURCAR

HITCH+HEALTH

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Evaluation Framework & Impacts?

- Two sets of metrics:
  - quality-of-service (wait time, trip time, …)
  - cost-equity metrics (affordability, coverage, service options, …)
- Measured along multiple dimensions
  - Comprehensive Simulation Models, Tools and Platforms
  - Data- & Model-driven Feasibility Studies, Efficiency-Equity Tradeoff Analyses, Cost-Effectiveness, Case Studies, & Field Experiments
  - Policy Recommendations, Guidelines and White Papers on SCCS Design, Operational and Incremental Deployment Strategies
  - Community Engagement Pilot Projects
  - Annual Workshops and Broader Outreach

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Data, Data, Data!

- Transportation Demand
  - Regional travel demand model (activity-based model)
  - Traffic count and travel time (e.g. street light) data
  - Regional transit trips (automatically collected data)
  - Bikesharing and scooter usage data
  - Taxi and TNC trips
  - LEHD data
- Travel Behavior
  - Household travel survey
  - Transit onboard surveys (ridership, customer satisfaction)
  - Employees travel data (public agencies and large industries)
  - AV's stated preference surveys

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Data, Data, Data!

- Transportation Infrastructure
  - Current and planned highway network
  - Parking infrastructures
  - Transit network including fixed routes and demand responsive
  - Bikeshare and scooters systems
  - Employer shuttle and other services
  - Parking usage data
- Land Use Data
  - Current and planned population and job distributions
  - Residential developments plan
  - Planned jobs in the region
- Other Data
  - Community engagement / focus group surveys
  - Expert opinion surveys
  - Others

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Data-Driven, AI-Guided Approaches for Transportation Studies

- Learning Human Decision Strategies to Guide Future Mobility Services
- Machine Learning Approaches for Activity-based Models and Traffic Demand Forecasting

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Learning Human Decision Strategies

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Passenger-seeking trajectories

Food delivery service

Broken sharing bike recycling

Urban commuters' trip data

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Learning Human Decision Strategies

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assenger-seeking trajectories

Food delivery service

Urban commuters' trip data

Human-Generated
Spatial-Temporal Data (HSTD)

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Learning Human Decision Strategies

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assenger-seeking trajectories

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Urban commuters' trip data

Human-Generated
Spatial-Temporal Data (HSTD)

Spatial-Temporal Imitation Learning

Goal: Human Decision-Making Strategies

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Downstream Applications

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Spatial-Temporal Imitation Learning

Goal: Human Decision-Making Strategies

Downstream applications

Training self-driving car
Mimicking human

Human Agent Training
Understanding human

Transit Route
Planning

nd
More...

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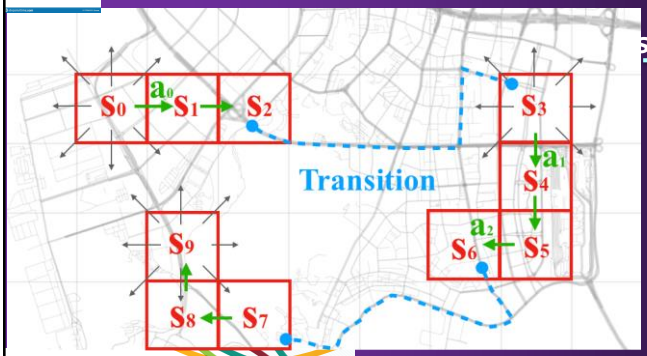
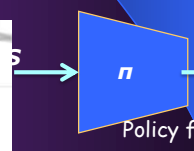
Learning Human Decision Strategies

- Modeling a Taxi Driver's Passenger-seeking Decisions with a Markov Decision Process

Decision Policy



Deep Neural Network to learn the decision policy



Policy function Huma

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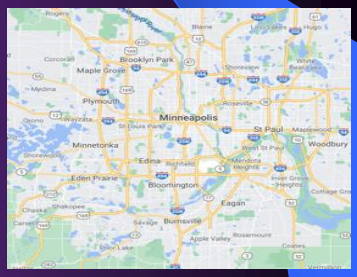
Travel Behavior Inventory (TBI)

- Trip data collected in Surveys by Metropolitan Council (MetCouncil) in 2019
  - data include 351k trips made by 16k people from 7.8k households
- Demand forecasting based on conventional activit—based models using stat. regression
- We are exploring ML & AI techniques (e.g., generative deep learning models) to augment ABM models using TBI data



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We need your advice!

- What are fundamental challenges for future mobility services based shared AVs?
- What are key technical and engineering problems?
- What are other plausible business models should we study?
- What are other drivers of ownership and usage should we consider?
- What regulatory policies should we consider?
- What are other metrics (beyond traditional measures of consumer surplus and social welfare) should we consider to account for inequity?

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THANK YOU!

Questions, comments, suggestions, ideas, …?

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