Smart, Sustainable Urban Transportation: A “Science of Cities” Approach

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Presentation Outline

- The “physics” of transportation systems.
- Smart transportation opportunities.
- Urban form and travel behaviour.
- Some implications for smart, sustainable transportation.
Throughout history the location, size, shape and economic & social functioning of cities has been fundamentally influenced by transportation technology, infrastructure and services. Transportation networks literally give spatial definition to land and, by making the land *accessible*, they make it useful. To date we have experienced 3 eras of transportation technology and, hence, urban form.
Pre-industrial cities were small, dense and extremely compact.

- Walking and animal-powered vehicles were the only options for intra-city travel:
  - To be accessible, everything had to be close at hand.
- Wind and animal-powered transport were the only inter-city options:
  - Cities were largely tied to rivers, lakes and ocean ports: water-based travel was so much faster and cost-effective than land travel.
  - Largely a person-based (individual) “supply” of transportation services.

1. The Pre-Industrial City
2. The Industrial City

• With the Industrial Revolution steam engines and, later, electrically-powered vehicles made mechanized transport possible for the first time, providing much higher speed and higher capacity transport services. This permitted the size of cities to expand dramatically, leading to:
  • Lower (but by modern standards still high) densities.
  • Vastly larger cities.
  • The ability to accommodate much larger populations (& economic activity).
3. The Automobile City

In the 20th Century, with its much higher speeds, flexibility of use and its provision of an affordable personal means of transportation, the auto again revolutionized transportation by freeing people from fixed-service public transit and freeing urban development to further spread out ("sprawl") in a dramatically increased, indeed explosive, way.

"Suburbs" first started to develop with the introduction of commuter railways and (even more so) electric urban street railways. But the private automobile made possible the development of the post-WWII low density "mass" suburbs that characterize much of current North American cities.
As cities have grown in size, however, we have discovered very clearly that large cities can not be served by roads/cars alone.
The 4th Era: Smart & Sustainable Transportation

- Modern Information & Communications Technology (ICT) is creating opportunities for:
  - Real-time operational control & user information systems.
  - New “smart mobility” services.
  - Autonomous vehicles.
  - Improved designs of urban form and urban systems.

- A “smart” transportation not only exploits ICT but involves “smart design” as well.

- Developing a smart, sustainable urban transportation system requires understanding how:
  - Transportation systems actually work: the “physics” of transportation.
  - Technology can be used to improve transportation system performance.
  - Transportation interacts with urban form and the urban economic system.
Traffic Physics: The Fundamental Flow Equation

\[
v = \text{average speed (km/hour)}
\]

\[
k = \text{average density (vehicles/km)}
\]

\[
q = \text{average flow (vehicles/hour)}
\]

\[
A = XT \text{ (km-hour)}
\]

\[
q = \frac{\sum_i x_i}{A}
\]

\[
k = \frac{\sum_i t_i}{A}
\]

\[
v = \frac{\sum_i x_i}{\sum_i t_i} = \frac{\left(\frac{\sum_i x_i}{A}\right)\left(\frac{\sum_i t_i}{A}\right)}{A} = \frac{q}{k}
\]

Or: \( q = vk \)

**Average Flow**

\[= \text{Average Speed} \times \text{Average Density} \]

This relationship holds for the movement of all vehicles.

It fundamentally constrains roadway capacity and achievable speeds.
A roadway’s capacity is an emergent outcome of vehicle interactions, given vehicle technology and roadway geometric design. Changes in technology & roadway design can change the parameters of this relationship but cannot change its fundamental nature.

One lane of highway can carry at most 2400 cars/hour under ideal conditions.

Mumbai roads do not operate under ideal conditions!
The Traffic Control Problem

The challenge of traffic control is to keep flow levels in the “undersaturated” regime, which maximizes both speeds and throughput.

As flow approaches capacity it becomes “turbulent” and “breaks down” into an “oversaturated” regime. Not only do speeds dramatically decline, but the maximum throughput (capacity) of the roadway actually decreases significantly as well.

Mumbai roads generally operate in this regime.
Physics, cont’d: the speed-density relationship

- Fundamental Theorem:
  \[ \text{Avg. flow (q)} = \text{Avg. speed (v)} \times \text{Avg. density (k)} \]

- Avg. speed (v) is a function of avg. density (k):
  \[ v = f(k) \]

- This speed-density relationship fundamentally determines roadway performance (capacity; achievable speeds and flows):
  - Vehicles take up space on the road.
  - Vehicles can only travel so closely together.
  - Vehicles slow down as density increases.
Vehicles (drivers) control their speed and spacing between vehicles for safe operations:

\[ \ddot{x}_{n+1}(t+\Delta t) = \lambda_0 \dot{x}_{n+1}(t)^M \left[ \dot{x}_n(t) - \dot{x}_{n+1}(t) \right] \frac{[x_n(t) - x_{n+1}(t)]^L}{[x_n(t) - x_{n+1}(t)]^L} \]

This second-by-second micro behaviour of each vehicle “averages out” to produce the macro relationship \( v = f(k) \) that describes roadway performance and capacity.

To increase roadway capacity one needs to change the operating behaviour of vehicles/drivers.
Smart Control Methods for (possibly) Improving Roadway Performance

- Dynamic, real-time, intelligent traffic control systems.
- Ramp metering.
- Road pricing.
- Dynamic speed control.
- Real-time Advanced Traveller Information Systems (ATIS).
- Autonomous (& connected?) vehicles.
Traffic Operation Control and ITS

Control Mechanisms
- Adaptive Traffic Control
- Telematics and Vehicle-Infrastructure Integration
- Dynamic Congestion Pricing
- ATIS
- ...
UofT Research Example (1): Adaptive Traffic Signal Control

MARLIN:
Traffic Lights that Learn

Reinforcement Learning
UofT Research Example (2): Dynamic Congestion Pricing

Optimization Algorithm
(E.g. minimization of total travel delay)

Discrete-Choice Module
(to capture change in route choice, mode choice, departure-time choice...etc in response to tolling)

Traffic-Network Simulator
(mesoscopic for large-scale applications and microscopic for small-scale applications)

Network Equilibrium Conditions
(Auto & Transit)
E.g. link flows, speeds, auto travel times, transit travel times...etc.

Historical Activity Schedules and Demand Profiles
(Departures and arrivals)

Toll Schedule
(Toll value for every tolled link and tolling-time interval)

Socio-economic Attributes
E.g. age, income, work location, home location...etc

Updated Activity Schedules

Real-Time (Online) Regulator
Optimum Tolling Schedule
Optimum Traffic Conditions

Real Traffic-Network
Closed-Loop (Online) Toll Regulator

Real-Time Tolling Structure
(Toll values across the network-priced links for the next time interval)

Measured Traffic Conditions
(Of the current time interval, e.g. link speeds and flows)

The triangular (Nonlinear) Pricing Structure

Open-Loop (Offline) Toll Optimizer Framework

$T_{\text{bottleneck model}}$
Nonlinear version of the triangular toll structure

$t^*$
Tolling intervals

$T$
Nonlinear version of the triangular toll structure

$T$
Tolling intervals

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Nonlinear version of the triangular toll structure

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Tolling intervals

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Nonlinear version of the triangular toll structure

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Tolling intervals

$T$
Nonlinear version of the triangular toll structure
Autonomous (& connected?) Vehicles

- Autonomous vehicles are certainly “coming”.
- Their impacts on roadway capacity & performance are very unclear (despite all the hype).
- But we definitely need to be planning for them.
- Possible roles/impacts in India?
Because of these fundamental limits of roadway capacity and performance, over & above environmental and land use impacts, roadways become very inefficient means of moving people as they become increasingly congested.
For short trips, walking & biking are by far the best way to move people. But in a large urban area, many trips are too long to be viable by walking or even bicycling.

In many Indian cities, the environment for walking & biking is challenging.
Public transit can be much more efficient in carrying large volumes of people than personal autos.

Mumbai’s Line 1 has a capacity of approx. 22,500 persons/hour at current operating frequencies. This is the equivalent of up to 10 lanes of highway!
An excellent transit system is an essential component of every great city: roads along cannot possibly carry the trip volumes.
Transit System “Physics” & Performance

- Walk times to/from transit depend on:
  - Stop spacing
  - Network density

- Wait & transfer times depend on service frequencies. Maximum achievable frequencies depend on:
  - Station dwell times
  - Control system
  - Vehicle technology

- In-vehicle travel times depend on:
  - Stop-to-stop speeds (vehicle technology)
  - Stop dwell times
  - Stop spacing (short spacing reduces average speeds)
  - Passenger boarding/alighting times

- Transit line capacity depends on:
  - Service frequency
  - Vehicle capacity

As with roads, there are fundamental limits to the speeds & capacities achievable with transit, as defined by transit vehicle and guideway technology and the route’s control system.

Capacities, however, can be much higher than for roads.
Transit Networks

In order to provide connectivity, coverage and high quality service levels, the transit network must be designed in a hierarchical fashion (high capacity trunk lines, feeder services; long-distance line-haul, local accessibility).

• Travellers need to be able to get to/from high-order services.
• “Door-to-door” service is required to compete with the auto.
• Transit is built line by line, but it is the network that makes it work.
Smart Control Methods for Improving Transit Performance

- Dynamic, real-time, intelligent transit priority systems.
- Real-time Advanced Traveller Information Systems (ATIS).
- Real-time operations management & enhanced business analytics.
- Autonomous (& connected?) vehicles
UofT Research Example (1): Transit Disruption Management System

- DSS for
  - short-term prediction of subway disruption effects
  - testing quick-response strategies

- Online response strategies
  - Dynamic vehicle dispatching
  - Information dissemination schemes
UofT Research Example (2): BI Analytics for measuring system performance & service quality
UofT Research Example (3): TSP-Advance

Bus detection → Request TSP → TSP Plans → TSP Plan library → Best TSP Plan → Mid-zone detection

Internal Simulation Model
Autonomous Vehicles & Transit

- Great potential exists for use of autonomous vehicles to:
  - Solve the “first/last mile” access/egress problem.
  - Possibly replace surface transit routes.

- If transit agencies are not aggressively pro-active in implementing new services & technology, however, they may find themselves “pre-empted” by private-sector mobility services that may compete with / cannabalize transit.

Uber launches Toronto commuting service on four routes

Drivers will take up to five passengers on UberHop service on fixed routes to and from downtown during rush hour for $5 a ride.
Emerging Mobility Services

- India has always had private “mobility services” (auto-rickshaws, etc.) to provide mobility options intermediate between the private car and public transit.
- ICT is enabling a wide range of new “smart” private sector services:
  - Car-, ride- & bike-sharing services.
  - “Re-invented” taxi services (Uber, Lyft, …)
  - Micro-transit.
  - Integrated services (transit + …)
- As autonomous vehicles come on-stream they will greatly accelerate this trend.

Implications in the Indian context?
Transit Usage

- Travel times and costs, among other factors affect trip-makers’ choice of travel mode.
- For transit, walk, wait and in-vehicle time all affect transit usage.
- The utility of each mode can be expressed as:

\[ V(\text{transit}) = \beta_1 + \beta_2 \times (\text{In-vehicle time}) \\
+ \beta_3 \times (\text{Wait time}) \\
+ \beta_4 \times (\text{Walk time}) \ldots \]

- And then the probability that a person takes transit for a given trip can be expressed as:

\[ P(\text{transit}) = e^{V(\text{transit})} / \sum_m e^{V(m)} \]
The challenge is to build a transit system that is sufficiently competitive with the automobile to provide an attractive alternative, in a cost-effective manner.
Unfortunately, a considerable majority of trips in most cities are made under conditions that are not transit-supportive.
The viability of transit is tied directly to urban form: how we build our urban region directly determines how much and what type of transit will be cost-effective.
Although difficult to do given the complexity of cities, we can systematically study the interactions between transportation and urban form, land use and socio-economic activity systems.

We can use this understanding to develop better land use designs that will enable:

- More efficient transportation.
- Improved economic productivity.
- Greater social equity & quality of life.


Key System Elements
T – transport system
A – activity system
F – flows & transport system performance

System Interactions/Feedbacks
I Market demand-supply interactions determine flows & system performance
II System performance (accessibility) influences activity system markets
III Gov’t, public & private service providers respond system demand & performance
Building the “Smart City”

Ultimately, a “smart city” is a well-designed one. ICT can improve the efficiency of any system, but “optimization” requires an integrated transportation & land use approach.
A good example of this integrated, multi-modal approach to smart city design is Pune.
Policy Implications (1)

- Information technology is having an increasing impact on both system performance and travel behaviour.
- We are entering an “age of disruption” within which a new “era” in mobility is emerging.
- Great opportunities, but also potentially great pitfalls, exist within a very uncertain future.
- But “smart technology” alone will not “solve all problems”. Limits will always exist as to what is physically possible to accomplish on our roads and our transit systems.
Policy Implications (2)

- Maximizing transportation system performance requires:
  - A multi-modal approach in which technologies and services are balanced with markets.
  - Integrating urban design/development with transportation system design.
Policy Implications (3)

- New transportation technology (notably autonomous, connected vehicles) will undoubtedly have significant impact, but will not be a “silver bullet”.
  - “Transit” applications need serious exploration (especially wrt the “first/last mile” problem).
  - Pro-active government policy will be essential to guide changes in socially beneficial directions.
  - Labour impacts of AVs could be very large.
Policy Implications (4)

- New service concepts (auto/bike-share, etc.) also can significantly change the urban mobility with respect to:
  - Affordability.
  - Vehicle ownership.
  - Parking needs & systems.
Policy Implications (5)

Big, successful cities will always be “congested”. The challenge is to find the “right” balance between modes and an urban form that is sustainable (as opposed to pathological) from a transportation perspective while also meeting a wide variety of social & economic goals.
A smart, sustainable urban transportation system must be built upon four pillars:

- Good governance
- Adequate & sustainable financing

which lead to:

- Sound infrastructure
- Good urban form and neighbourhood design.
THANK YOU.
QUESTIONS?