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# **Introduction to Traffic Flow Theory**

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# Traffic Flow Theory

*“Mathematics is the language with which God has written the universe.”*

*Galileo Galilei*

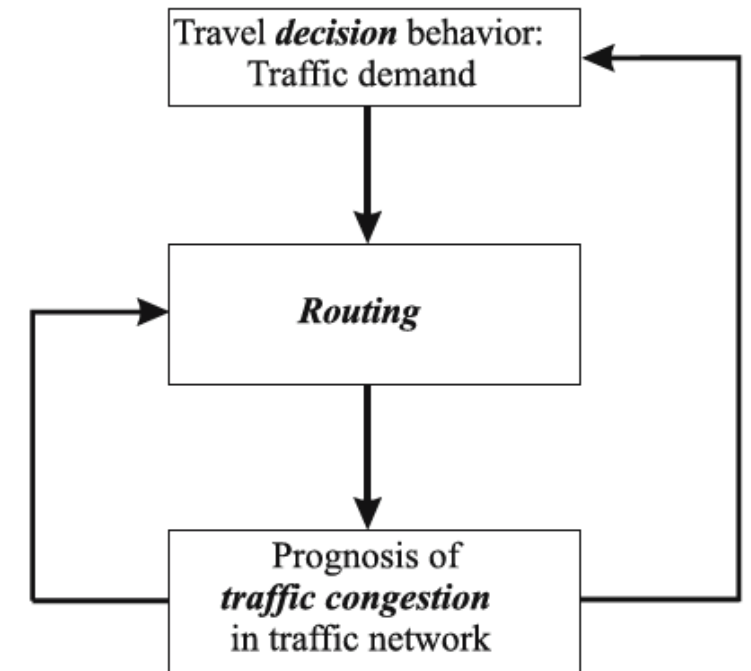
- Mathematical approaches have been widely used and eminently successful in the field of natural sciences
- Traffic flow theories describe the dynamics of vehicular traffic flow in terms of mathematical models.
  - ✓ They describe and predict traffic on roads.
  - ✓ They can model the number of vehicles on the road and their speeds.
  - ✓ They can predict travel times and congestion levels on the roads.

# Traffic Flow Theory

- Population growth and economic growth come with an increase in traffic demand and increased levels of congestion and accompanying delays, pollution and decrease in safety.
- There are several strategies to reduce congestion, keep cities livable, clean and safe and limit travel time increase:
  - to encourage people to travel using modes of transport that put less strain on the transportation network,
  - to encourage people to travel at different times or on different routes,
  - to apply traffic management to use roads in a more efficient way,
  - to improve transportation systems and to expand the road network.
- Therefore, it is important to know how traffic flow will actually look:
  - where and when will there be congestion,
  - what are the bottlenecks,
  - where is the road capacity already sufficient.

# Traffic Flow Theory

- Vehicular traffic is an extremely complex dynamic process associated with the spatiotemporal behavior of many-particle systems.
- The complexity of vehicular traffic is due to nonlinear interactions between the following three main dynamic processes :
  - Travel decision behavior, which determines traffic demand,
  - Routing of vehicles in a traffic network, and
  - Traffic congestion occurrence within the network.

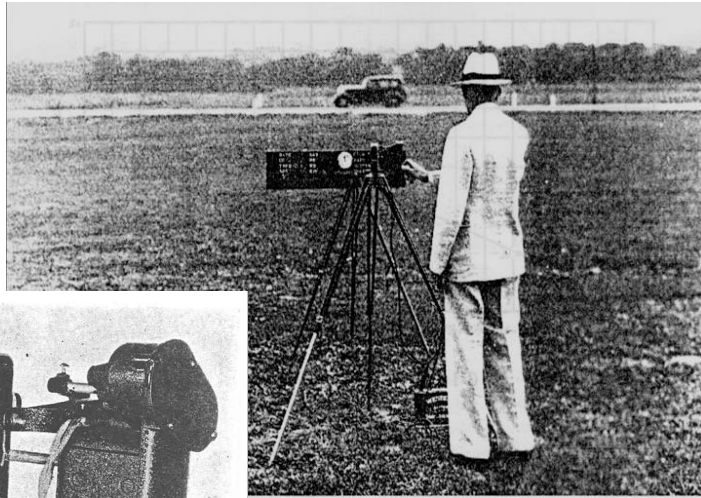


*The complex dynamic process of vehicular traffic*

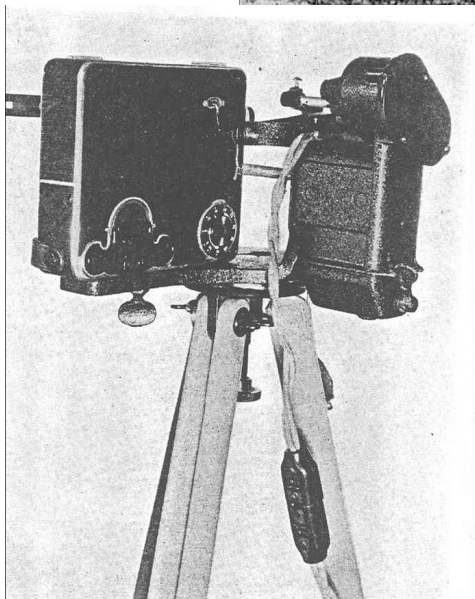
# Traffic Flow Theory

- The understanding of empirical traffic congestion is the key for effective traffic management, control, organization, and all other applications of transportation engineering.
- Traffic congestion observed in real measured traffic data is a spatiotemporal effect: The traffic congestion occurs in space and time in the form of spatiotemporal congested traffic patterns propagating within a traffic network. These empirical congested traffic patterns exhibit a variety of complex spatiotemporal features.
- The optimization of transportation systems should ensure either the dissolution of traffic congestion or, if this is not possible to achieve, the minimization of the influence of traffic congestion on travel costs

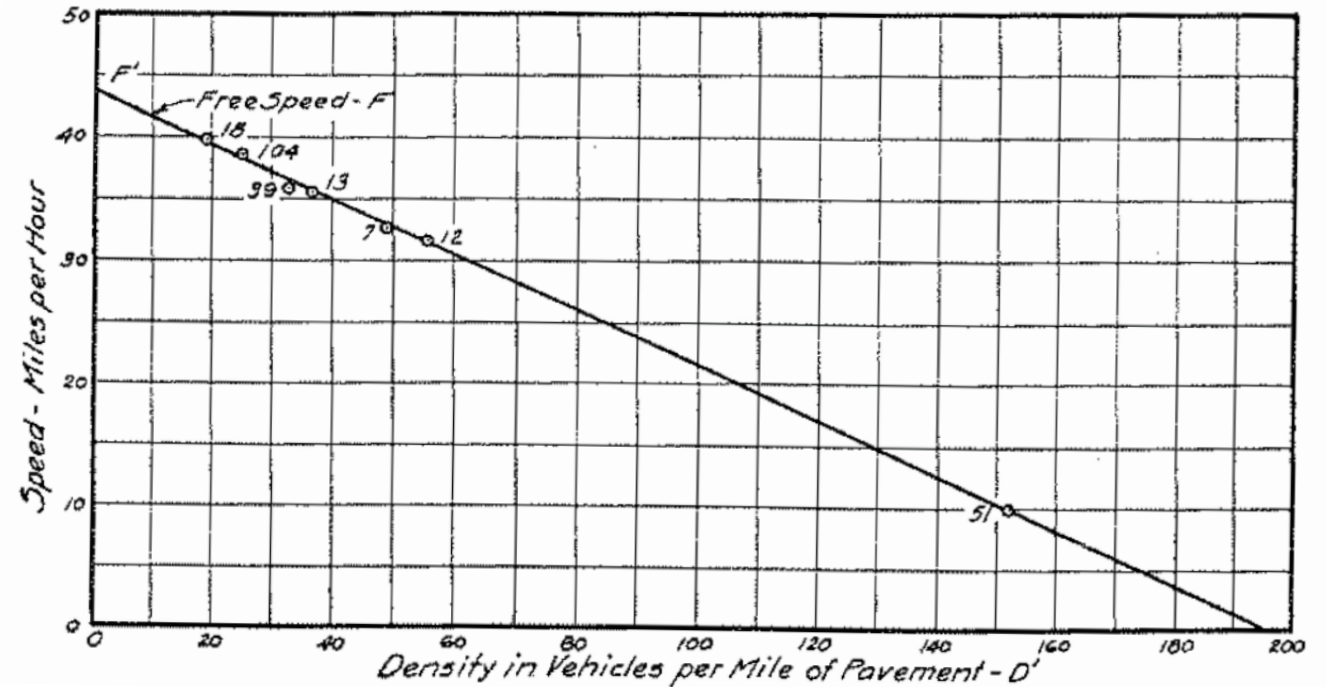
# Traffic Flow Theory



Greenshields measurement set up (1930s)



Camera with motor attachment used by Greenshields (1930s)

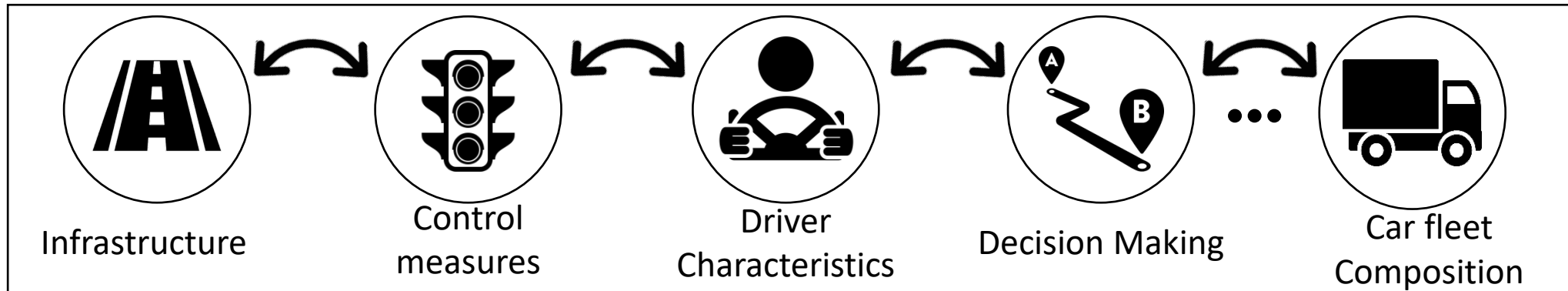


Greenshields' fundamental diagram (1935), showing a linear relation between density and speed

# Traffic Flow System

## Traffic flow System / Model?

Interconnected, complex, and functionally related components



### Traffic Flow System

A complex unity formed of diverse parts, joined in regular interaction or interdependence, subject to a common plan or serving a common purpose.

### Traffic Flow Model

A mathematical representation of the traffic flow system, which is used to study the effect of various components on traffic flow dynamics.

# Traffic Flow Simulation

## What is traffic flow Simulation?

The implementation of traffic flow models to create a device for describing and understanding how a traffic flow system works, behaves, and evolves over time is called traffic flow simulation.

## What is the purpose of traffic flow Simulation?

This device is used for predicting the output from a real system, under various conditions that are specified by the input data, without actually using the real system to make this prediction.

## What are the applications traffic flow Simulation?

In general simulation models are used as tools to solve problems in complex systems, when system components interact. Traffic flow simulation models are principally used to assess the impact of a new infrastructure, a new road design or a new traffic management measure on traffic flow dynamics.



Source: <http://www.tatweer-co.ae/t-project/mobile-speed-radar/>



# Travel Demand Modelling

## Four-Step Travel Demand Modelling

- First step – Trip Generation: How many trips are generated?
  - The goal of trip generation step is to estimate the number of trips that are produced or originate in each Traffic Analysis Zone (TAZ)
- Second step – Trip Distribution : Where do the generated trips go?
  - In this step matches between origins and destinations are developed. Trip ends are linked to create complete trips.
- Third step – Mode Choice: What travel mode is used for each trip?
  - Mode choice predicts the choices that individuals or groups make in selecting their transportation modes. For instance, an important objective is to predict the share of trips attracted to public transportation.
- Fourth step – Trip Assignment: What is the route of each trip?
  - The final step is to determine the routes travelers choose to reach their destinations.

# Mathematical Models

## Different Approaches

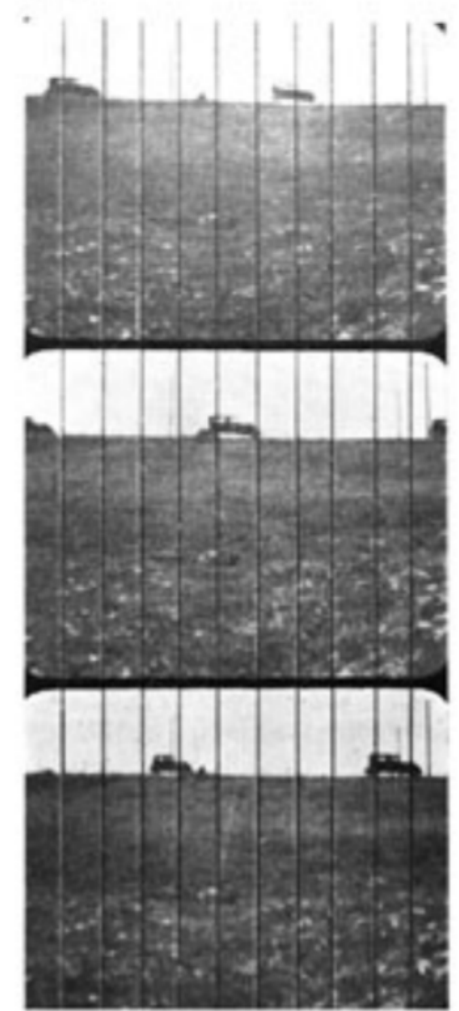
General mathematical models aimed at describing observed phenomena in traffic flow include the following approaches:

- Purely deductive approaches, where widely accepted and accurate physical laws are applied to describe the phenomena (ex: conservation law).
- Purely inductive approaches, where available data from real systems (i.e., real-world observations) are used to fit generic mathematical structures (ex. ARIMA models, neural networks).
- Intermediate approaches, where basic mathematical model-structures are developed in the first step, then calibrated using real-world observations in the second step.

# Mathematical Models

## Different Approaches

- Traffic flow modelling is a largely inductive process
- Traffic observations are used to build a theory about the behavior of individual drivers and vehicles or about traffic flow in general.
- Subsequently, that theory is used to build a model, discretize it and apply it in simulations.
- A simple example is the observations by Greenshields of vehicles passing his camera in the 1930s.
- Plotting the distance between the vehicles (spacing) and their change in position in consecutive photographs leads to a theory that spacing and speed are related
- Subsequently, this leads to a model with a linear relationship between spacing and speed.

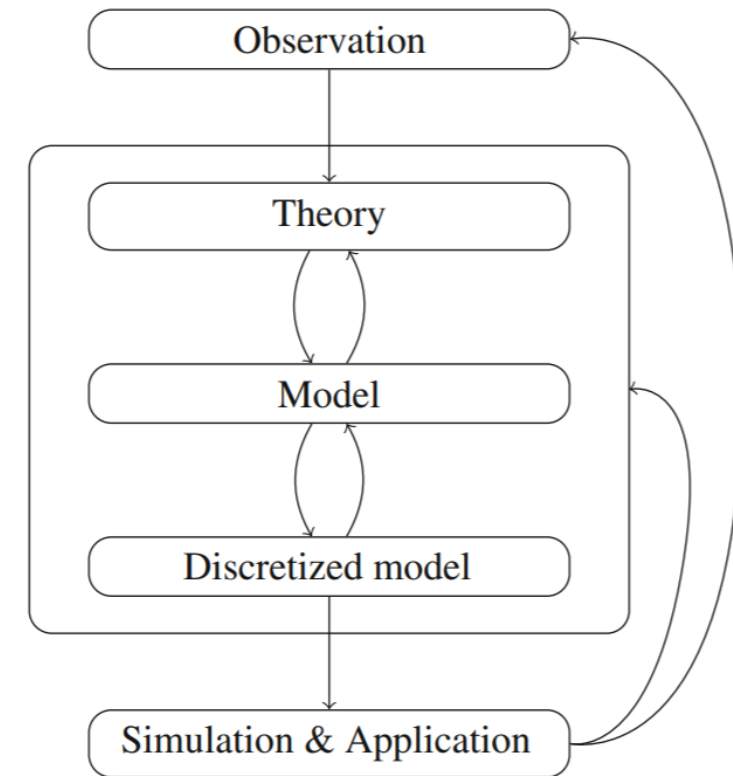


*Greenshields field observations*

# Mathematical Models

## Different Approaches

- The development and application of traffic flow models is schematized.
- As a first step, data is collected.
- This can be done using, for example, loop detectors, cameras or GPS devices that many vehicles have on-board, such as navigation systems or mobile phones.
- Alternatively, data is collected using lab experiments for example with a driving simulator.
- These observations are analyzed and phenomena that characterize traffic flow are recognized.

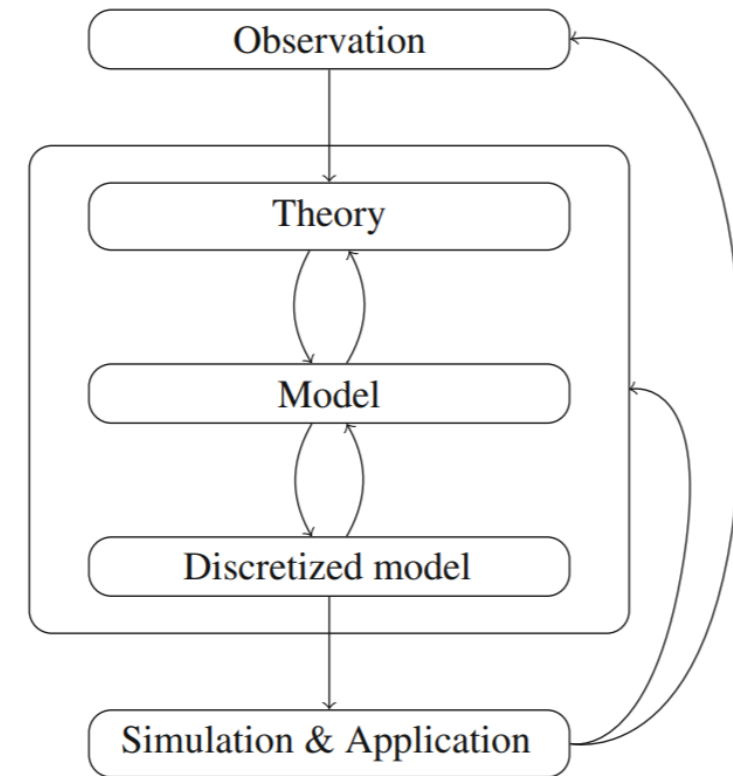


*Traffic flow modeling cycle*

# Mathematical Models

## Different Approaches

- In the second step, observations are used to build a theoretical framework.
- The theoretical framework consists of (mainly qualitative) statements and (behavioral) assumptions.
- For example, it is assumed that drivers perceive short space headways as more dangerous at high velocities than at low velocities.
- This is assumed to be the reason why at low velocities shorter headways are maintained.
- Another assumption is that drivers only react to their leaders and not to their followers.

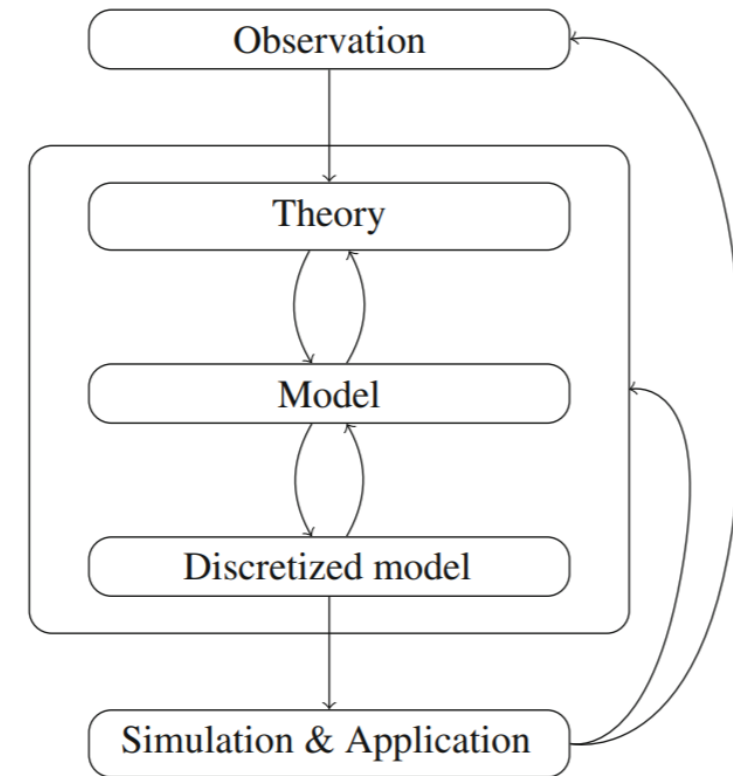


*Traffic flow modeling cycle*

# Mathematical Models

## Different Approaches

- In the third step, the theoretical framework is used to build a traffic flow model.
- The model consists of a set of equations, sometimes supplemented with a set of (behavioral) rules.
- For example, the theory about short headways at low velocities and long headways at high velocities is quantified in a fundamental diagram.
- It expresses the average vehicle velocity as a function of the average headway.
- Alternatively, a car-following model is developed that describes how a following vehicle reacts to its leader(s), at which distance the leading vehicle is followed, and how the distance depends on the speeds of both leading and following vehicle.

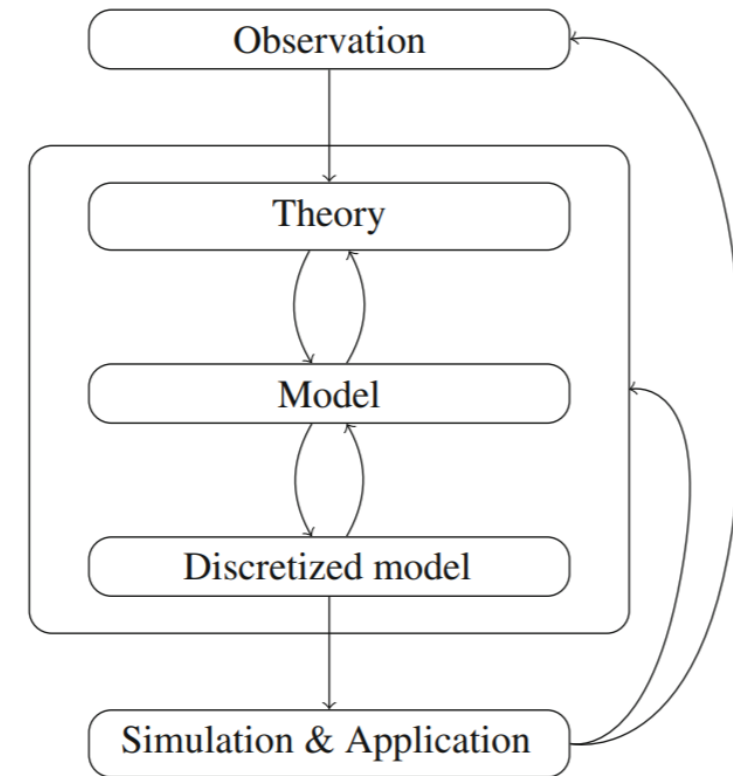


*Traffic flow modeling cycle*

# Mathematical Models

## Different Approaches

- The models can not be used directly in applications using computer simulation.
- Therefore, discretization is applied in the fourth step.
- In most simulation tools, time is divided into discrete time steps
- Furthermore, depending on the model, also space or other continuous variables are discretized.
- Numerical methods are applied to approximate the new traffic state each time step.
- This results in a discrete traffic flow model.

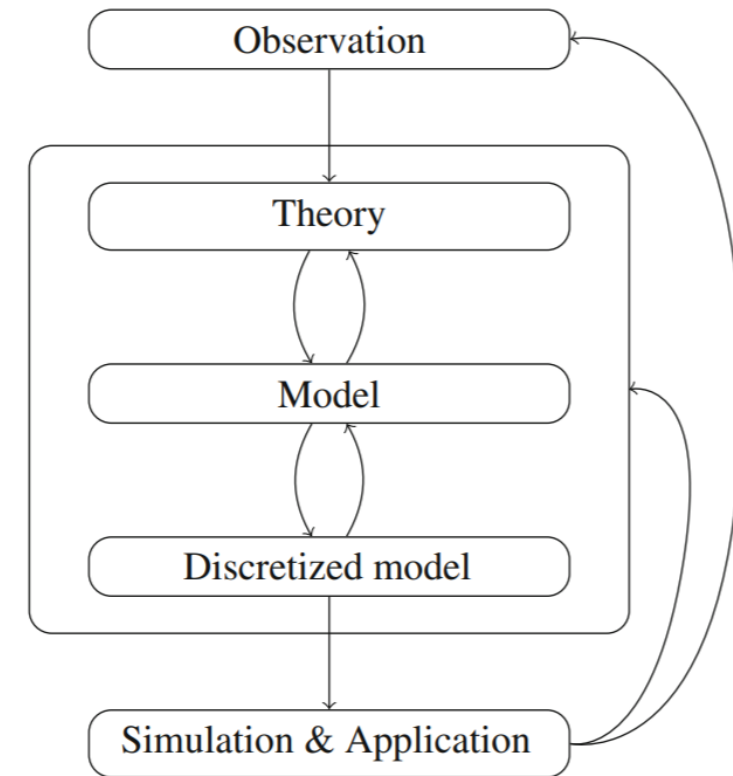


*Traffic flow modeling cycle*

# Mathematical Models

## Different Approaches

- Finally, the discrete traffic flow model is implemented in a computer program, resulting in a simulation tool.
- By applying this tool and combining it with inputs, such as data from traffic sensors, traffic state estimation and predictions can be made.
- Simulation results are compared to observations to calibrate the parameters and to validate the simulation tool.



*Traffic flow modeling cycle*



# Mathematical Models

## Desired Characteristics

### 1. Tractable

Roughly speaking, a tractable model uses simple and robust methods.

### 2. Parsimonious

Simple models with great explanatory power with as few predictor variables as possible.  
We should mostly compromise between the model's ability to explain and its complexity.

### 3. Predicting

A good model leads to useful forecasts.  
The most useful forecasts are not always produced by the most accurate model

**Buisson, C. (2010).**  
Comprendre, quantifier et réduire  
la congestion autoroutière.  
Technical report, ENTPE.

# Traffic Flow Models

## Unique model of a system

- Traffic flow models have many applications, for different purposes
  - State estimation & short-term predictions to inform travelers
  - State estimation & short-term predictions for traffic management (ex. variable message signs or ramp metering)
  - Decision support for autonomous vehicles
  - Optimizing the operation of traffic lights
  - Long term assessment of development plans, e.g. the (re)design of a transportation network
  - Assessment of the impact of traffic on safety and emissions
  - Design of evacuation plans
- It should be pointed out that in traffic flow simulation there exists no such thing as “the model of a system”, i.e. a unique model of the traffic flow system.
- A model depends to:
  - the objectives of the study,
  - the problem that the model builder tries to solve, and
  - the beliefs and understanding that he has of the modeled system.



*An isolated intersection*



*Trips originating from Laval  
with a destination in Montreal*

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