Review of system identification and control algorithms used for smart motorways applications

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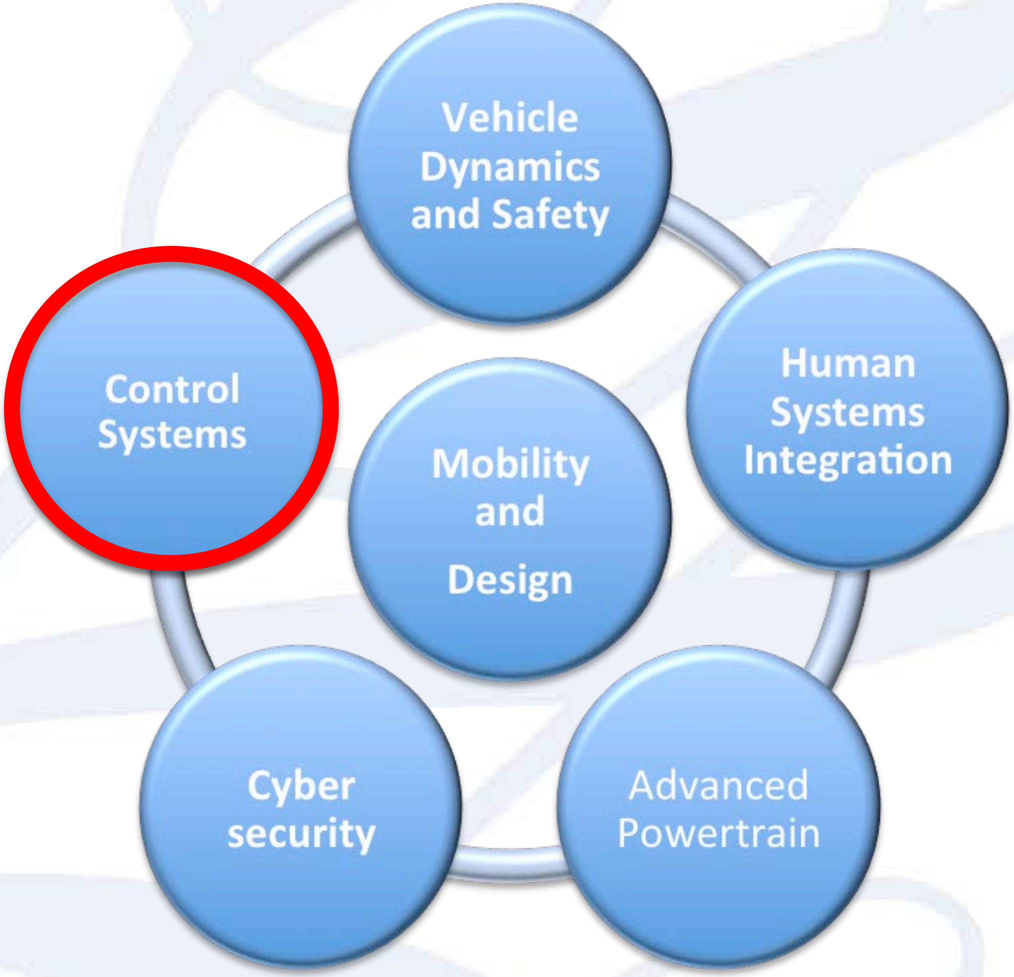
Content

- The control group in Coventry Univeristy
- What is control, system ID, parameter estimation
- The variable speed limit control problem
- Problem formulation
- Approaches to date
- Models required by model based controllers
- traffic state estimation algorithms
- Use of simulation
  - Aimsun, Vissim, SUMO

The Centre for Mobility and Transport



6 key groups impacting:

Energy use: Low carbon vehicle technologies, light weighting, behavioural change

User experience: Mobility, comfort, inclusiveness, human factors

Safety: Traffic accidents and fatalities, ADAS, sensing

Security: Connected Autonomous Vehicles, Assurance

Future vehicles design: Future mobility, materials & manufacturing product evaluation

The Control Group vision

Control combines engineering with computer science.

Control solutions involve system modelling, control engineering, optimization, artificial intelligence, data analytics and big data.

Modern controllers need to be able to learn whilst still meeting industry standards for systems safety in a system of system framework.

http://www.emergemag.co.uk/research/areas-of-research/mobility-transport/control-systems/

iVMS @ Coventry University

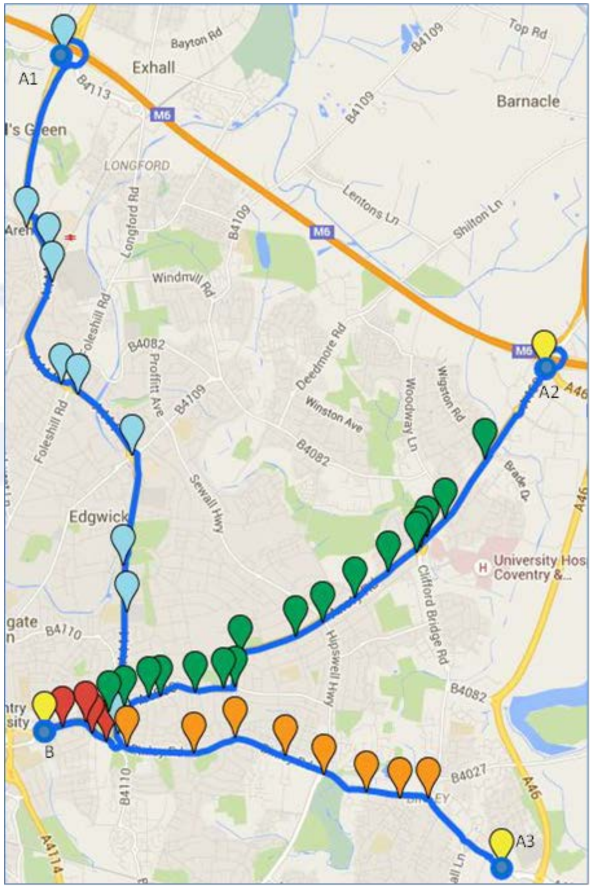
WP2 Research, Modelling, Interface Definition

- Develop realistic traffic simulation
- Be responsible for driver behavioural modelling
- Scenario simulation to support the business case

WP5 Test Platforms

- Support Horiba-MIRA for Human factors lab / track testing

WP7 Trial Phase



Can we reduce traffic congestion through coordinated traffic management and individualized re-routing strategies?

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WP8: Driver Interface Testing

- Identify best practice and latest design recommendation for V2X interface design
- Evaluate the driver response using driving simulator and field tests
- Carry out driver's behavioural analysis following on road trials

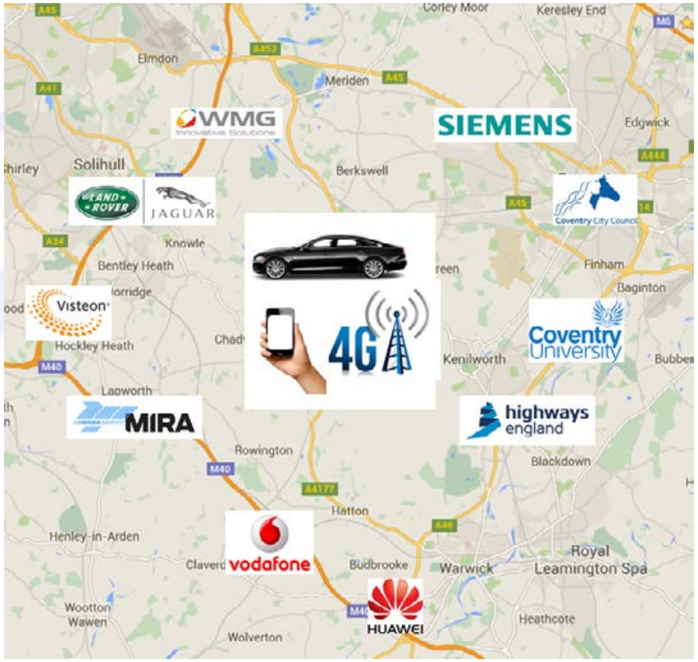
WP9: Simulation and modelling

<u>Support Horiba-MIRA to</u>:

- Evaluate state of the art in traffic simulation
- Develop realistic traffic simulation

<u>Be responsible for driver modelling</u>

- For purpose of traffic simulation
- To capture/integrate human factors



Can we improve the accuracy of traffic simulation by building into it human factors?

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Smart Motorway control problems

- **Two inter-related control problems**
- Queue protection (takes precedence)
  - Increase safety
- Congestion management
  - Increase safety, Smooth flow, delay onset of jam, increase throughput or flow and hence reduce pollution.
- **Control methods**
  - Variable speed limit
  - Ramp meeting: manage in-flows
  - Use of hard shoulder: ↑ capacity
  - Driver education

Queue protection - Current solutions

- Detects slow-moving traffic, and then sets speed limits upstream of the event in order to protect the back of the queue.
- Can react quickly (3s) but slow to change (4 minimum on-time)
- HIOCC2 (2002)
  - rule based watchdog
  - use speed data where possible, and revert to occupancy if speed not available.
- Challenges/opportunities
  - Use occupancy then convert to speed => Leads to variability.
  - Opportunity = floating vehicle data, not yet sufficiently consistent
  - 40mph QP settings take priority over 50mph CM settings in queues

VSL - Current solutions

- If flows approaches the road capacity, reduced speed limits become active to smooth the flow, reduce lane changing and delay the onset of flow breakdown
- Originally highly responsive, now heavily smoothed
- Smart Motorways Calibration and Optimisation (SMCALO)
  - Determine the road capacity and ON & OFF flow thresholds for 60mph and 50mph limits.
  - Built in hysteresis to prevent frequent changes in speed settings
- Problems / opportunities
  - Capacity changes with AM and PM peaks as well as weather
  - QP takes precedence => changed 50mph to 40mph speed limit (M42)
  - Use floating vehicle data = identify congestion and bottlenecks

Ramp Metering - Current solutions

- Sets traffic light signals on the entry slip road to control the entry of traffic onto the motorway.
  - Uses upstream flow and downstream speed to calculate the spare motorway capacity.
  - Modifies the green time to allow an appropriate amount of slip road traffic through. The remaining traffic queues on the slip road.
- Challenges:
  - Once the slip road is full of queueing traffic, a queue override mechanism switches the slip road signal to green, to avoid queueing traffic affecting the all-purpose network.
  - Long entry slip roads desirable

Control Approach

- Understand the problem
- Model the system
- Identify control variables, measurable and non measurable signals
- Design control strategy
- Evaluate control strategy using simulation
- Implement in real life taking into account constraints and practicalities

Motorway traffic modelling

- Microscopic
  - SUMO, Paramics, AIMSUN, CORSIM, VISSIM, etc.) essentially multi-class.
  - For solution validation
- Macroscopic: for on-line model-based control
  - First order models (Cell Transmission Models, (Daganzo, 1994))
  - Asymmetric Cell Transmission Model (ACTM)
  - Link-Node Cell Transmission Model (LN-CTM)
  - METANET familly
- Mesoscopic

Link model

- Aggregated behaviour inspired from fluid based on flow density
- PDE + conservative law
- Lighthill–Whitham–Richards (LWR): first-order model

$$\partial_t \rho_e(x,t) + \partial_x f_e(\rho_e(x,t),t) = 0 \quad \forall e \in E,\ x \in (0, L_e),\ t \in [0,T]$$

Time t
Vehicle position x
Density ρ
Average speed $v = V(\rho)$
Flow $q = \rho V(\rho) = Q(\rho)$
Speed density V
Flow density Q

$$f_e^{\max}(t) = f_e(\rho_e^c, t) \quad \text{with } \rho_e^c = \rho_e^{\max}/2$$

$$f_e(\rho,t) = \rho\, v_e^{\max}(t)\left(1 - \frac{\rho}{\rho_e^{\max}}\right)$$

- Discretise LWR model:
  - Cell Transmission Model (CTM) (Daganzo, 1995, Lovisari et al., 2015).

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METANET (1/2)

- Describe physical relation between state variables
- Describes conservation of vehicles
- Characterizes the evolution of the speed,
  - Relaxation: drivers try to achieve a desired speed V(r) ,
  - convection term expresses speed change caused by vehicles inflow
  - anticipation term: speed change as drivers experience a downstream density change

$$\rho_j(l+1) = \rho_j(l) + \frac{\Delta T_{\text{sim}}}{n_j l_j}[q_{\text{in},j}(l) - q_{\text{out},j}(l)]$$

$$v_j(l+1) = v_j(l)$$

$$+\frac{\Delta T_{\text{sim}}}{\tau}[V[\rho_j(l)] - v_j(l)] \quad \text{Relaxation}$$

$$+\frac{\Delta T_{\text{sim}}}{l_j} v_j(l)[v_{j-1}(l) - v_j(l)] \quad \text{Convection}$$

$$-\frac{\nu \Delta T_{\text{sim}}[\rho_{j+1}(l) - \rho_j(l)]}{\tau l_j[\rho_j(l) + \kappa]}, \quad \text{Anticipation}$$

METANET (2/2)

- Links
  - motorway stretches,
  - divided into homogenous segments.
- Nodes
  - on-ramps, off-ramps, changes in geometry.
- Additions/extensions:
  - Extra merging terms (for on-ramps)
  - weaving terms (reduction in number of lanes).
  - Node equations to model connections between links (joins and splits).
  - Multi-class (Liu et al 2017) different vehicle classes
  - …

System identification (Seo *et al* 2017)

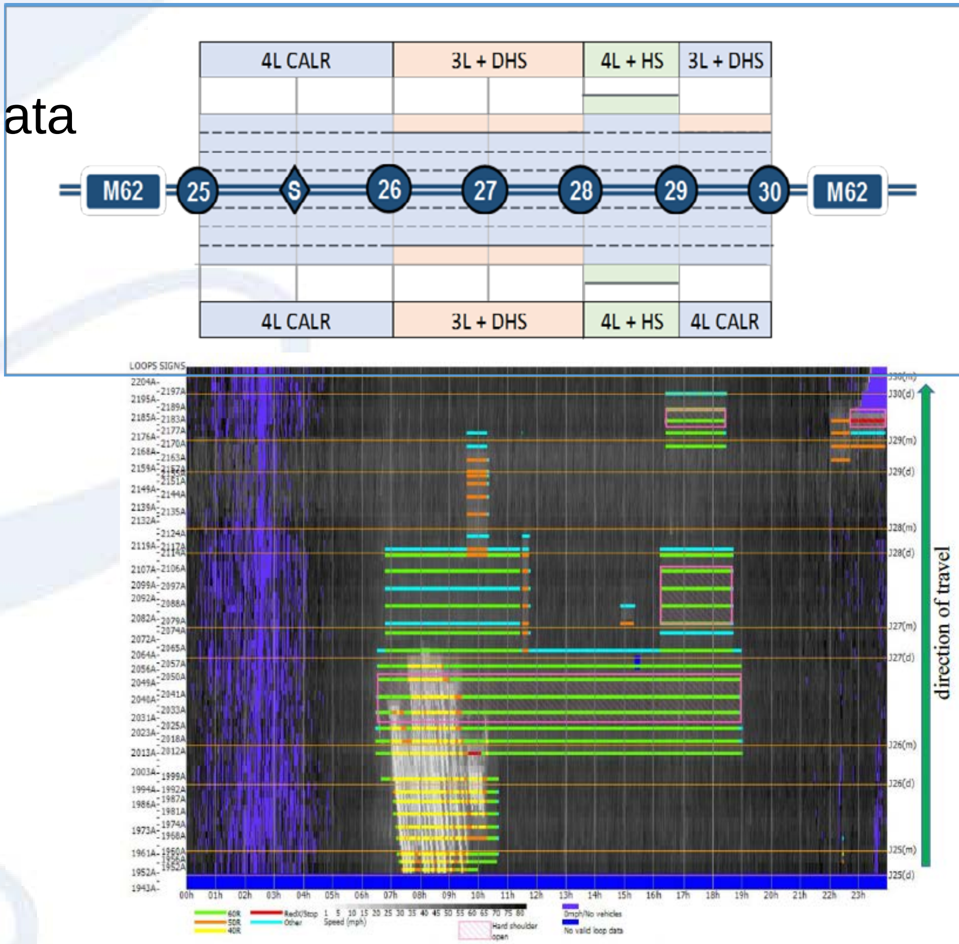
- Identify the traffic states in terms of fixed or time varying parameters
- Methods
  - Model driven (METANET, LWR)
  - Data driven
  - Streaming data driven (real time)
- Algorithms:
  - Kalman Filter (extended, unscented, +Monte Carlo), Bayesian statistics, Fuzzy, deep learning ANN)
  - Observer (for real time)

Validation of results using simulation

- Use a macroscopic model to determine the control actions
- Validate the approach using microscopic traffic simulation using software such as Vissim, Aimsun and SUMO
- Microscopic models calibration
  - Similarly to macroscopic models:
    - Obtain all required data to determine appropriate in/out flow and origin destination
  - Adapt the models parameters using optimisation
    - Car following (driver model)
    - lane changing
    - Driver behaviour
    - Traffic light behaviour

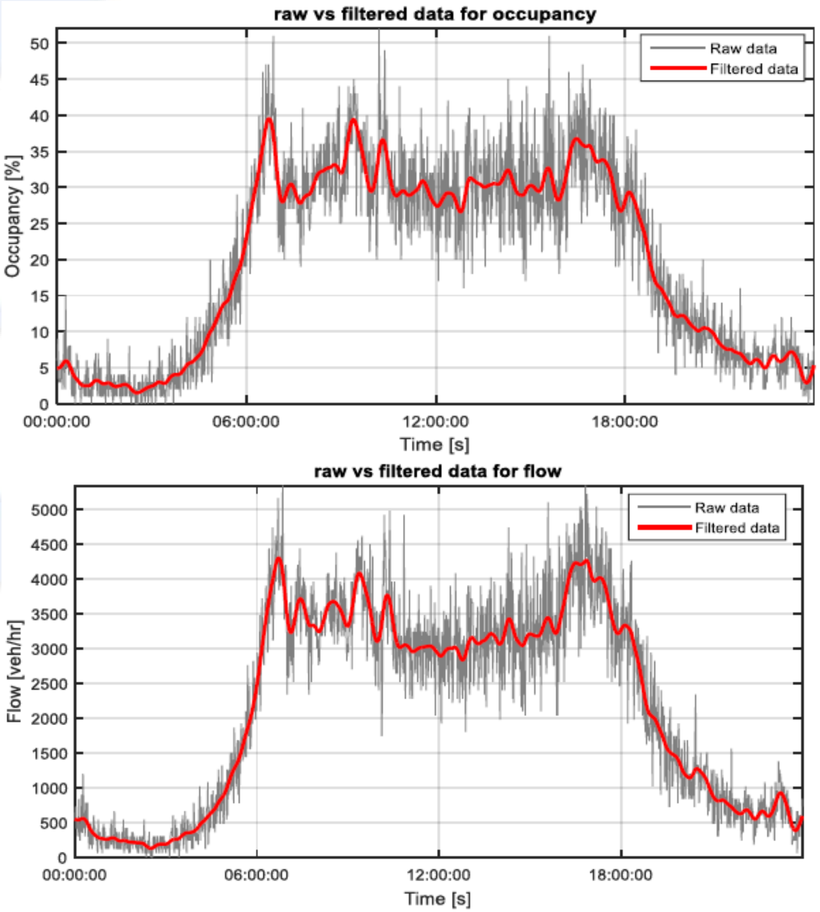
Example of data used for modelling

- Traffic data: minutely averaged data collected from loop detectors: occupancy, flow, velocity.
- Data consistency verified and converted to SI units.
- Issues with the data:
  - Missing samples due to low vehicle numbers at night
  - noisy



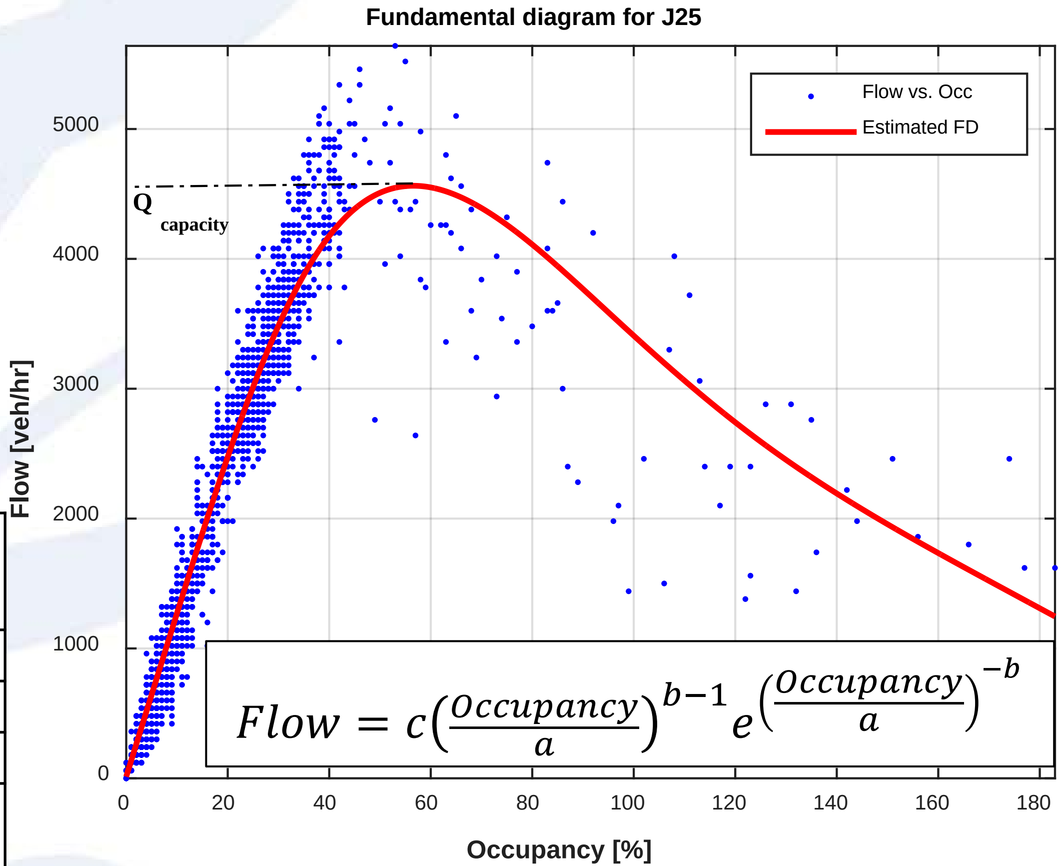
Non causal filtering of the data

- Remove missing data samples
- Remove instances of 0
- Use an Integrated Random Walk (IRW) filter (Young 1998), CAPTAIN toolbox (Young et al. 2010) to extract a smooth time series from the data sets.
  - Filter parameter: noise variance ratio = 0.001.



Build fundamental diagram

- Obtain the fundamental diagram for each road section



$$Flow = c\left(\frac{Occupancy}{a}\right)^{b-1} e^{\left(\frac{Occupancy}{a}\right)^{-b}}$$

Ramp metering setting	J25	J26	J27
Flow [veh/h]	1100	2000	2800
Min Flow [veh/h]	400	930	1565
Max Flow [veh/h]	1149	3470	3130
Desired downstream occupancy	24	20	19

Control algorithms

- **Feedforward:** Percent occupancy scheme, look-up tables

- **Feedback – reactive**
  - Proportional, Integral (ALINEA), Proportional + Integral, METALINE, mainline virtual metering, control, CORDIN, VSL-1, VSL-2 (Lin et al 2004), VSL-GA

- **Self tuning and adaptive (model based)**
  - state dependent parameter (ramp metering)
  - Iterative learning control(ramp metering)

- **Model predictive controller (MPC)**

Example of VSL algorithm implemented

If Flow > Threshold

- $V_{N-1}(k) = V_{N-1}(k-1) + K_{(\hat{O},V,H)}\left(O - \hat{O}(k-1)\right)$
- $V_{N-1-m}(k) = V_{N-1-(m-1)}(k) + \Delta V_{max}$
- round V_{N-1-m} to be within +/- 10mph

end

$V_{N-1}(k)$ the VSL equation of section *N-1*

$V_{N-1}(k-1)$ previous speed limit,

O constant representing the desired occupancy to be maintained

$\hat{O}(k-1)$ is the measured occupancy, at time $k-1$

$K_{(O,V,h)}$ is a variable controller gain based on the current Occupancy $\hat{O}(k-1)$, speed $V_{N-1}(k-1)$ and time headway $H(k-1)$

Model Based Predictive Control

- Use a prediction model to obtain the trajectories of system variables
- Optimize an objective function, subject to constraints to determine the best sequence of control actions for the system.
- Apply the first control action in sequence (rolling horizon)
- Objectives:
  - Total travel time (TTT), total travel distance, mean speed, time to collision,
- Constraints
  - Discrete set of possible speed limits values (☐)
  - Reduce VSL rate of changes
  - Reduce speed difference between adjacent segments
  - Driver compliance
- Challenges
  - Non linear problem, different sampling time, discrete speed values, model accuracy, expertise, …

Fuzzy

- Mostly focused on modelling
- Fuzzy rules used to describe the operation of variable speed limit based on
- Current limitations:
  - Fuzzy naturally good for continuously varying speed limit => need to be adapted to provide discrete values
  - Local knowledge and specificity need to be accounted for in rule development
  - Only evaluated on simulation with simplified model.
- Need to take into account weather, incidents, roadwork, driver compliance and behaviour.

Conclusions

- Advanced motorway traffic management is a gold mine for research!
- Mobility and Transport research Centre
  - Advanced distributed control techniques
  - Model predictive control
  - Multi-objective optimisation
  - Deep learning to model system based on data
  - Combined with fuzzy to add adaption
  - ADAS + CAV
  - Human factors (driver), Human Machine Interface