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SAFFRON: Store-And-Forward model toolbox For urban ROad Network signal control in MATLAB

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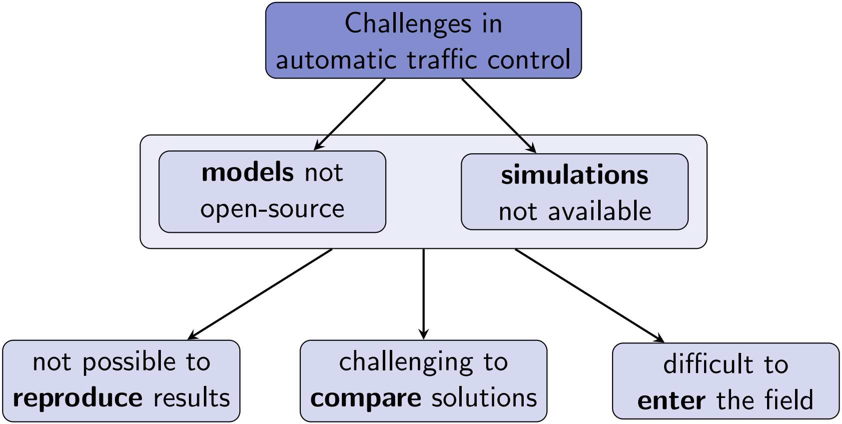
Outline

Introduction
Motivation



Introduction

Idea

SAFFRON toolbox:

MATLAB

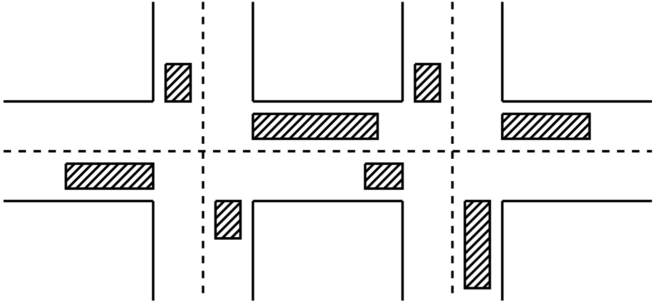
- open-source **tools** for **store-and-forward** models
- traffic network **model** of **Chania**, Greece
- implementation **source-code** of signal control strategies
  - **TUC** [Diakaki, 1999]
  - **DTUC** and **D2TUC** [Pedroso and Batista, 2021]

GitHub `https://github.com/decenter2021/SAFFRON`

Outline

Store-and-forward model

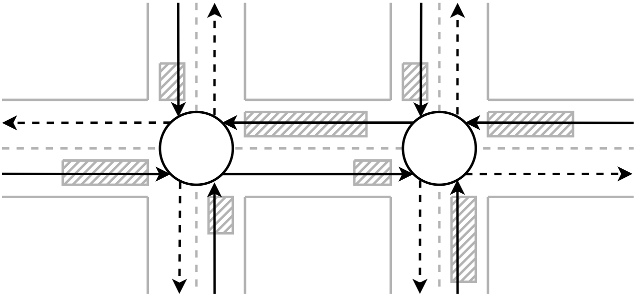
Modeling: Traffic network



Z links, J signalized junctions

Store-and-forward model

Modeling: Network graph

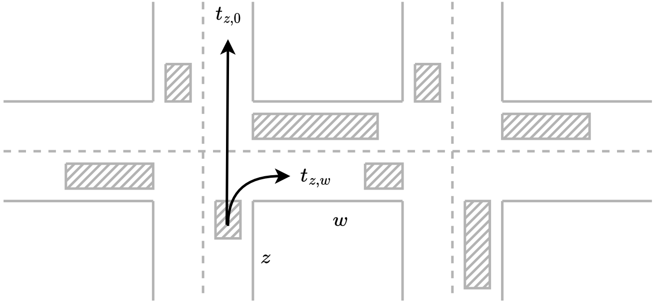


Directed graph $\mathcal{G} := (\mathcal{V}_\mathcal{G}, \mathcal{E}_\mathcal{G})$:

- Each **junction** is a **vertex**
- Each **link** is an **edge**

Store-and-forward model

Modeling: Link characterization



Each link z is characterized by:

- Saturation flow, S_z
- Turning rates, $\mathbf{T} : [\mathbf{T}]_{z,w} := t_{w,z}$
- Exit rates, $\mathbf{t_0} := [t_{1,0} \ \dots \ t_{Z,0}]^T$

Store-and-forward model

Modeling: Traffic network characterization

A traffic network topology is defined by the triplet $(\mathcal{G}, \mathbf{T}, \mathbf{t_0})$.

Definition (Open traffic network)

A traffic network characterized by $(\mathcal{G}, \mathbf{T}, \mathbf{t_0})$ is said to be open if, for every edge of the network $e_z \in \mathcal{E}_\mathcal{G}$, there is a directed walk starting at e_z which a vehicle may follow to exit the network with non-zero probability.

Definition (Feasible traffic network)

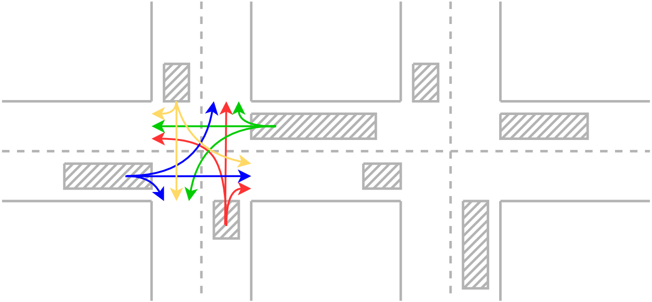
A traffic network characterized by $(\mathcal{G}, \mathbf{T}, \mathbf{t_0})$ is said to be feasible if

1. $\mathcal{E}_\mathcal{G}$ and $\mathcal{V}_\mathcal{G}$ are finite sets;
2. $(\mathcal{G}, \mathbf{T}, \mathbf{t_0})$ is open.

For more details: [Pedroso and Batista, 2021]

Store-and-forward model

Modeling: Stages



Signal control strategy:

- **Cycle** of duration C
- For each junction j there is a set of **stages** $s \in \mathcal{F}_j$
- For each **stages** there is a set of links that have **right of way**

Store-and-forward model

Modeling: Stages

Green time g_s of stage s:

- **Minimum** constraint

$$g_s \geq g_{s,\min} \;, s \in \{1, \ldots, S\}$$

- **Cycle** duration constraint

$$\sum_{s \in \mathcal{F}_j} g_s + L_j = C \;, \quad j \in \{1, \ldots, J\}$$

where L_j is the **inter-green** time.

Stage matrix **S**:

$$[\mathbf{S}]_{zs} := \begin{cases} 1 \;, & \text{if link } z \text{ has r.o.w. at stage } s \\ 0 \;, & \text{otherwise} \end{cases} \quad .$$

Store-and-forward model

Modeling: Stages

Definition (Minimum complete stage strategy)

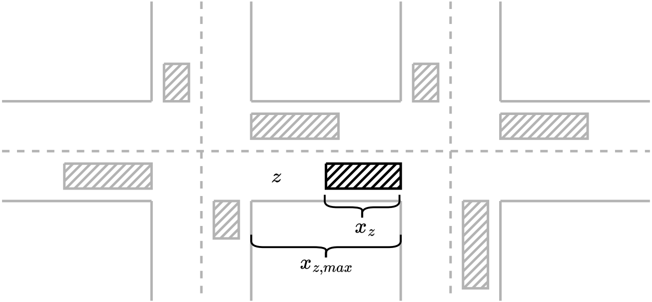
A stage strategy characterized by the stage matrix $\mathbf{S}$ is said to be a minimum complete stage strategy if

1. $\forall s \in \{1, \dots, S\} \ \exists z : [\mathbf{S}]_{zs} = 1$;
2. $\forall z \in \{1, \dots, Z\} \ \exists s : [\mathbf{S}]_{zs} = 1$;
3. $\forall j \in \{1, \dots, J\} \, \forall s \in \mathcal{F}_j \ \forall z \in \{1, \dots, Z\}$
   $[\mathbf{S}]_{zs} = 1 \implies e_z \in \mathcal{E}_j^-$;
4. $\forall j \in \{1, \dots, J\} \, \forall s_1, s_2 \in \mathcal{F}_j \ s_1 \neq s_2 \implies \nexists k \in \mathbb{R} : [\mathbf{S}]_{s_1} = k[\mathbf{S}]_{s_2}$,
   where $[\mathbf{S}]_s$ denotes the s-th column of $\mathbf{S}$.

For more details: [Pedroso and Batista, 2021]

Store-and-forward model

Modeling: Link occupancy

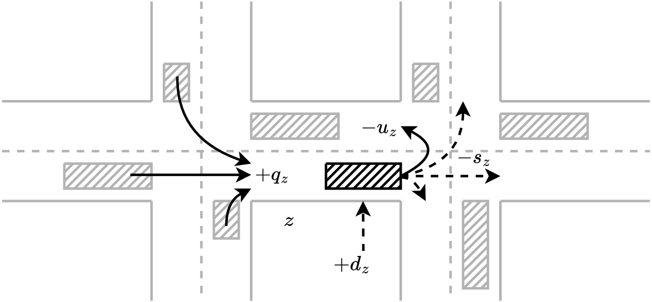


$x_z(k)$: number of **vehicles** in link z

$$0 \leq x_z(k) \leq x_{z,\mathrm{max}}$$

Store-and-forward model

Modeling: Vehicle dynamics



$$x_z(k+1) = x_z(k) + C\left(q_z(k) - u_z(k) + d_z(k) - s_z(k)\right)$$

- outflow: $u_z(k)$
- inflow: $q_z(k) = \sum_{w \in I_z} t_{wz} u_w(k)$
- demand: $d_z(k)$
- exit flow: $s_z(k) = t_{z,0} q_z(k)$

Store-and-forward model

Modeling: Approximation of traffic flow

Store-and-forward Traffic flow approximation

Models **green-red switchings** within a whole cycle as a **continuous flow** of vehicles

$$u_z(k) = S_z G_z(k)/C \ , \quad z \in \{1, \ldots, Z\}$$

- $G_z(k)$: **total green time** of link z

$$G_z(k) = \sum_{s:[\mathbf{S}]_{zs} \neq 0} g_s(k)$$

Store-and-forward model

Modeling: Approximation of traffic flow

Store-and-forward Traffic flow approximation

Models **green-red switchings** within a whole cycle as a **continuous flow** of vehicles

$$u_z(k) = S_z G_z(k)/C \ , \quad z \in \{1, \ldots, Z\}$$

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B_G}\mathbf{G}(k) + C\mathbf{d}(k) \ , \tag{1}$$

- $\mathbf{G}(k) := \mathrm{col}(G_1(k), ..., G_Z(k)) \in \mathbb{R}^Z$
- $\mathbf{B_G} = ((\mathbf{I}_Z - \mathrm{diag}(\mathbf{t_0}))\,\mathbf{T} - \mathbf{I}_Z)\,\mathrm{diag}(S_1, \ldots, S_Z)$

LTI system: but the green time $G_z(k)$ cannot be freely selected

Store-and-forward model

Modeling: LTI system

$$G_z(k) = \sum_{s:[\mathbf{S}]_{zs}\neq 0} g_s(k)$$

$$\downarrow$$

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B_g}\mathbf{g}(k) + C\mathbf{d}(k) \tag{2}$$

- $\mathbf{g}(k) := \mathrm{col}(g_1(k), ..., g_S(k)) \in \mathbb{R}^S$
- $\mathbf{B_g} = \mathbf{B_G}\mathbf{S}$

LTI system: the green time of a stage $\mathbf{g}(k)$ can be freely selected using a **signal control strategy**

Store-and-forward model

Modeling: Controllability

Proposition (Controllability)

Consider a feasible traffic network characterized by $(\mathcal{G}, \mathbf{T}, \mathbf{t_0})$ and a minimum complete stage strategy characterized by a stage matrix $\mathbf{S}$. Let $\mathcal{C}$ be the controllability matrix of the store-and-forward LTI system (2). Then, $\mathrm{rank}(\mathcal{C}) = S \leq Z$.

Proposition (Controllability)

Consider a feasible traffic network characterized by $(\mathcal{G}, \mathbf{T}, \mathbf{t_0})$. Then, the store-and-forward LTI system (1) is controllable.

For more details: [Pedroso and Batista, 2021]

Store-and-forward model
Simulation

For **simulation** purposes

$$\mathbf{x}(k_T+1) = \mathbf{A}\mathbf{x}(k_T) + \frac{T}{C}\mathbf{B_u}\mathbf{u_{nl}}(k_T) + T\mathbf{d}(k_T)$$

- $T \ll C$: simulation sampling time
- $\mathbf{u_{nl}}(k_T) := \mathrm{col}(u_{nl,1}(k_T), ..., u_{nl,Z}(k_T))$

$$u_{nl,z}(k_T) = \begin{cases} 0, & \exists w \in O_z : t_{z,w} \neq 0 \wedge x_w(k_T) > c_{ug}x_{w,\max} \\ \min\{x_z(k_T)/T, u_z(k = \lfloor k_T T/C \rfloor)\}, & \text{otherwise} \end{cases}$$

- $c_{ug} \in]0,1[$: sensitivity of **upstream gating**
- Follows the queue length constraint

Store-and-forward model

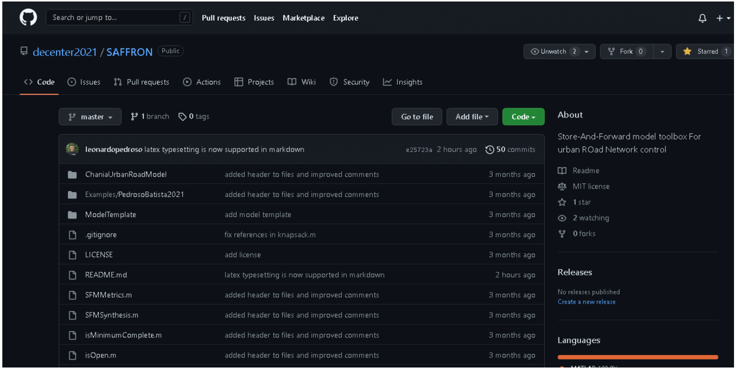
This brief store-and-forward model description is based on:

- [Gazis and Potts, 1963]
- [Aboudolas et al., 2009]
- [Pedroso and Batista, 2021]

For more details see the references above.

Outline

SAFFRON toolbox



GitHub https://github.com/decenter2021/SAFFRON

SAFFRON toolbox

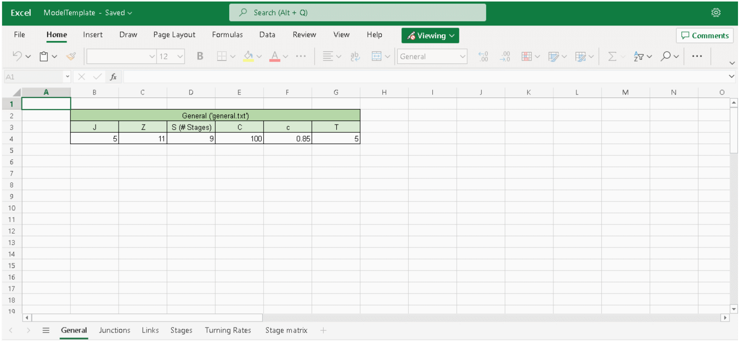
Model Synthesis

Input into a **provided custom spreadsheet**:

- J, L, S, C, T, c_{ug}
- $\mathbf{S}$,$\mathbf{T}$, $\mathbf{t_0}$
- **each junction**: L_j and number of stages
- **each link**: $x_{z,max}$, S_z, number of lanes, initial number of vehicles, and demand flow
- **each stage**: $g_{s,min}$ and historic green times

SAFFRON toolbox

Model Synthesis




```
>> model = SFMSynthesis("directory")
```

- `directory`: **path** of the spreadsheet's enclosing folder
- `model`: *MATLAB* **struct**

SAFFRON toolbox

Model Synthesis

`model` **struct**

Field	Description
`J`	J
`Z`	Z
`nStages`	S
`C`	C
`c`	c
`Tsim`	T
`lostTime`	$\mathrm{col}(L_1, \ldots, L_J)$
`nStagesJunction`	$\mathrm{col}(\lvert\mathcal{F}_1\rvert, \ldots, \lvert\mathcal{F}_S\rvert)$
`capacity`	$\mathrm{col}(x_{1,\mathrm{max}}, \ldots, x_{Z,\mathrm{max}})$
`saturation`	$\mathrm{col}(S_1, \ldots, S_Z)$
`x0`	$\mathbf{x}(0)$
`d`	$\mathrm{col}(d_1, \ldots, d_Z)$

SAFFRON toolbox

Model Synthesis

`model` **struct**

Field	Description
`gmin`	$\mathrm{col}(g_{1,min}, \ldots, g_{S,min})$
`gN`	$\mathbf{g_N}$
`T`	$\mathbf{T}$
`t0`	$\mathbf{t_0}$
`S`	$\mathbf{S}$
`junctions`	See online documentation
`links`	Ordered array of edges of the network graph
`A`	$\mathbf{A}$
`Bu`	$\mathbf{B_u}$
`BG`	$\mathbf{B_G}$
`Bg`	$\mathbf{B_g}$
⋮	⋮

SAFFRON toolbox

Utilities: Model characteristics

Check if `model` is **open**

```
>> flag = isOpen(model)
```

Check if a stage strategy is **minimum complete**

```
>> flag = isMinimumComplete(model)
```

Recall

These are conditions for **controllability guarantees**

SAFFRON toolbox

Utilities: Performance metrics

Total time spent (TTS)

$$\mathrm{TTS} := C \sum_{k} \sum_{z=1}^{Z} x_z(k)$$

Relative queue balance (RQB)

$$\mathrm{RQB} := \sum_{k} \sum_{z=1}^{Z} \frac{x_z^2(k)}{x_{z,max}}$$

```
>> [TTS,RQB] = SFMMetrics(model,xNL)
```

SAFFRON toolbox

Utilities: Quadratic Continuous Knapsack Problem

$$\begin{aligned} \underset{\mathbf{x}\in\mathbb{R}^n}{\text{minimize}} \quad & \frac{1}{2}\mathbf{x}^T \operatorname{diag}(\mathbf{d})\mathbf{x} - \mathbf{a}^T\mathbf{x} \\ \text{subject to} \quad & \mathbf{0} \leq \mathbf{x} \leq \mathbf{b} \\ & \mathbf{1}^T\mathbf{x} = c \ , \end{aligned}$$

```
>> x = knapsack(a,b,c,d)
```

Remark

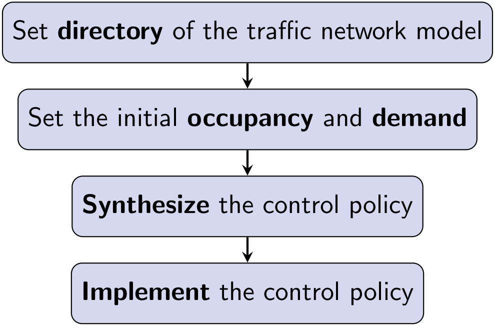
It arises oftentimes in a **post-processing** step of a signal control strategy (*e.g.* TUC)

Algorithm in [Helgason et al., 1980]: takes, **at most**, n iterations

SAFFRON toolbox

Simulation script

Template: simulation with **upstream gating**.



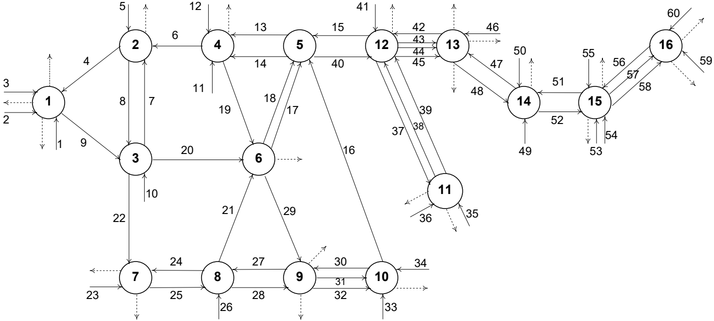
Script: `simulation_template.m`

SAFFRON toolbox

Chania urban road network

Chania urban traffic network

- $J = 16$ signalized junctions
- $L = 60$ links



SAFFRON toolbox

Chania urban road network

```
>> model = SFMSynthesis('ChaniaUrbanRoadModel');
>> model = load('ChaniaUrbanRoadModel/data.mat');
```

Chania urban traffic network:

- validate **high-impact** traffic control strategies ([Aboudolas et al., 2009, Diakaki, 1999, Dinopoulou et al., 2006],...)
- validate **recent innovative** solutions ([Pedroso and Batista, 2021, Baldi et al., 2019])
- now **available** to the community

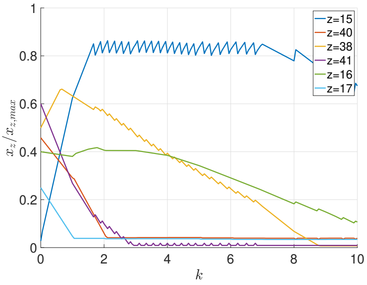
SAFFRON toolbox

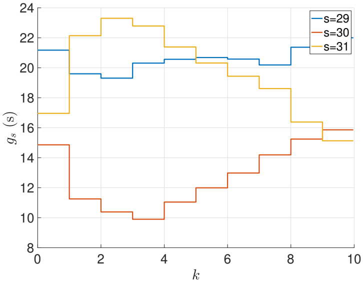
Example

Source code of application example:

- **TUC** strategy [Diakaki, 1999]
- **DTUC** and **D2TUC** strategies [Pedroso and Batista, 2021]

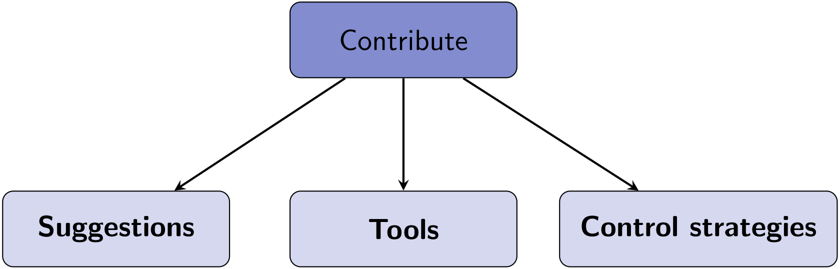
Illustrative simulation of **D2TUC**:





Outline

Contribute to SAFFRON



Refer to the **online repository** for more details

Outline

Conclusion

SAFFRON features:

- open-source **tools** for **store-and-forward** models
- traffic network **model** of **Chania**, Greece
- implementation **source-code** of signal control strategies

With **SAFFRON** new strategies can be:

- seamlessly **simulated**
- applied to a **open-source meaningful reproducible** model
- **compared** with other strategies with ease

Outline

References I

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