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Freeway Ramp Metering Control Made Easy and Efficient

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Abstract: "Model-free" control and the related "intelligent" proportional-integral (PI) controllers are successfully applied to freeway ramp metering control. Implementing moreover the corresponding control strategy is straightforward. Numerical simulations on the other hand need the identification of quite complex quantities like the free flow speed and the critical density. This is achieved thanks to new estimation techniques where the differentiation of noisy signals plays a key rôle. Several excellent computer simulations are provided and analyzed.

Keywords: Traffic control, ramp metering, congestion, fundamental diagram, free flow speed, critical density, model-free control, intelligent PI controllers, identification, estimation, numerical differentiation.

1. INTRODUCTION

This plenary lecture aims at presenting in a clear and unified manner recent advances due to the same authors (Abouaïssa, Fliess, Iordanova & Join (2011a,b)) on two important subjects in intelligent transportation systems (see, *e.g.*, Ghosh & Li (2010), Kachroo & Osbay (2003), Mammar (2007), and the references therein):

(1) the control of freeway ramp metering,
(2) the estimation of the free-flow speed and of the critical density.

Freeway ramp metering control, which should alleviate congestions, is achieved via *model-free control* (Fliess & Join (2008, 2009)). It yields an *intelligent proportional-integral*, or *iPI*, controller which

- regulates the traffic flow in a most efficient way,
- is robust with respect to quite strong disturbances,
- is easy to tune and to implement,
- does not need any precise mathematical modeling.

Remark 1.1. Model-free control, although quite new, has already been successfully employed in many concrete situations: Andary, Chemori & Benoit (2012); d'Andréa-Novel, Boussard, Fliess, el Hamzaoui, Mounier & Steux (2010); Choi, d'Andréa-Novel, Fliess, Mounier & Villagra (2009); De Miras, Riachy, Fliess, Join & Bonnet (2012); Formentin, de Filippi, Tanelli & Savaresi (2010); Gédouin, Delaleau, Bourgeot, Join, Arab-Chirani & Calloch (2011); Join, Masse & Fliess (2007); Join, Robert & Fliess (2010); Michel, Join, Fliess, Sicard & Chériti (2010); Villagra, d'Andréa-Novel, Fliess & Mounier (2009); Villagra & Balaguer (2011); Wang, Mounier, Cela & Niculescu (2011).

Computer experiments show that our control strategy behaves better than *ALINEA*, [1] which was a most remarkable breakthrough when introduced more than twenty years ago (Hadj-Salem, Blosseville, Davée & Papageorgiou (1988); Hadj-Salem, Blosseville & Papageorgiou (1990); Papageorgiou, Hadj-Salem & Blosseville (1991)). [2] Despite a huge academic literature, which utilizes most of the existing methods of modern control theory, whether with lumped or with distributed parameter systems, ALINEA, which is exploited in France and in many other countries,

[1] *ALINEA* is an acronym of *Asservissement LINéaire d'Entrée Autoroutière*.
[2] See, *e.g.*, (Papageorgiou, Diakaki, Dinopoulou, Kostialos & Wang (2003); Smaragdis & Papageorgiou (2004)) for recent developments.

remains until today to the best of our knowledge the only feedback-control law for ramp metering that has been implemented in practice.

Computer simulations, on the other hand, need some kind of precise mathematical macroscopic modeling. They become therefore more subtle and complex than model-free control. This necessity yields a dichotomy which is analyzed in this paper for the first time. We utilize here ordinary differential equations, *i.e.*, a macroscopic model of order two, due to Payne (1971) and improved by Papageorgiou, Blosseville & Hadj-Salem (1990). The corresponding model properties are quite sensitive to parameter variations and uncertainties. The *free-flow speed* and the *critical density* are estimated here via the *fundamental diagram* due to May (1990) thanks to recent differentiation techniques of noisy signals (Fliess, Join & Sira-Ramírez (2008); Mboup, Join & Fliess (2009)). Most of the existing methods for achieving real-time estimation employ in one way or the other the Kalman filtering (see, *e.g.*, Mihaylova, Boel & Hegyi (2009); Wang & Papageorgiou (2005); Wang, Papageorgiou & Messmer (2008)). Their computational burden seems however quite higher than ours.

Our paper is organized as follows. Model-free control and intelligent PI controllers are presented in Section 2. [3] Section 3 studies the application to a concrete example of an isolated ramp metering. After reviewing the identification techniques which are connected to the fundamental diagram, important parameters corresponding to the same freeway are estimated in Section 4. Convincing computer simulations are also analyzed in Sections 3 and 4. Some concluding remarks are discussed in Section 5.

2. MODEL-FREE CONTROL: A SHORT REVIEW

2.1 Basics

We restrict ourselves for simplicity's sake to a SISO system $\mathfrak{S}$, with a single input u and a single output y. We do not know any global mathematical description of $\mathfrak{S}$. We replace it by a "phenomenological" model, which is

- valid during a short time lapse,
- said to be *ultra-local*,

$$\boxed{y^{(\nu)} = F + \alpha u} \qquad (1)$$

where

- the differentiation order ν of y, which is
  - · chosen by the practitioner,
  - · generally equal to 1,

  has no connection with the unknown differentiation order of y in $\mathfrak{S}$;
- the constant parameter α has no *a priori* precise numerical value. It is determined by the practitioner in such a way that the numerical values of αu and $y^{(\nu)}$ are of equivalent magnitude;
- F, which contains all the "structural" information, depends on all the system variables including the perturbations.

[3] See Fliess, Join & Riachy (2011) for a complete presentation.

2.2 Intelligent PI controllers

Assume that we have a "good" estimate [4] $[F]_e$ of F and, for simplicity's sake, that $\nu = 1$ in Equation (1). [5] The desired behavior is obtained via an *intelligent proportional-integral*, or *iPI*, controller

$$\boxed{u = -\frac{[F]_e - \dot{y}^\star + K_P e + K_I \int e}{\alpha}} \qquad (2)$$

where

- $y^\star$ is the output reference trajectory,
- $e = y - y^\star$ is the tracking error,
- K_P, K_I are the usual gains.

If $K_I = 0$, we have an *intelligent proportional*, or *iP*, controller:

$$\boxed{u = -\frac{[F]_e - \dot{y}^* + K_P e}{\alpha}} \qquad (3)$$

Remark 2.1. Contrary to the situations with classic PI controllers, controllers (2) and (3) are easy to tune: they stabilize a pure integrator.

Remark 2.2. See d'Andréa-Novel, Fliess, Join, Mounier & Steux (2010) for the explanation of the strange ubiquity of classic PIDs via the above viewpoint. [6]

2.3 Estimation of F

Estimation of $\dot{y}$ If $\nu = 1$ in Equation (1), $[F]_e$ may be obtained via the estimate of $\dot{y}$. Elementary differentiation filters do suffice in this situation where the sampling is rather crude.

Another technique Rewrite Equation (2) as

$$F = -\alpha u + \dot{y}^\star - K_P e - K_I \int e$$

Corrupting noises are attenuated by integrating both sides on a short time interval. [7] It yields:

$$F_{\text{approx}} = \frac{1}{\delta} \int_{T-\delta}^{T} \left(-\alpha u + \dot{y}^\star - K_P e - K_I \int e \right) d\tau \qquad (4)$$

where F_{approx} is a piecewise constant approximation of F. Equation (4) may be easily implemented as a discrete linear filter.

3. FREEWAY RAMP METERING PRINCIPLE

3.1 Generalities

Consider the simple example of the freeway section depicted in Fig. 1:

- q_r, in veh/h, is the ramp flow related to the control variable $r \in \{r_{min}, r_{max}\}$, [8] by $q_r = r\hat{q}_r$, where $\hat{q}_r = \min\left(d + \frac{w}{T_s}, Q_{sat} \min\left(r, \frac{\rho_{max}-\rho_s}{\rho_s-\rho_c}\right)\right)$ is the flow;

[4] See Section 2.3.

[5] $\nu = 1$ is an appropriate choice for most of the concrete examples. See Fliess, Join & Riachy (2011) for an explanation.

[6] See also Fliess, Join & Riachy (2011).

[7] See Fliess (2006) for a mathematical explanation.

[8] Just as in Hegyi, De Schutter & Hellendoor (2005), we set $r = 1$ for an unmetered on-ramp.

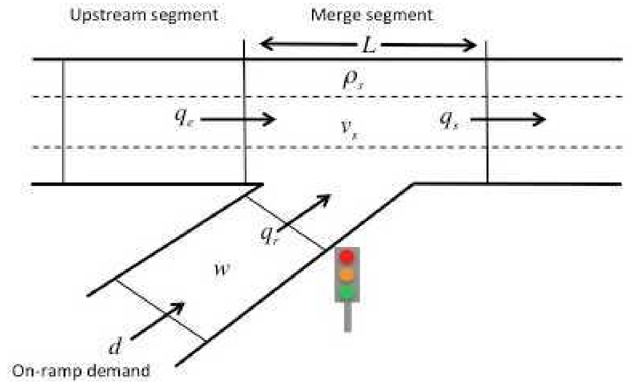


Figure 1. Freeway ramp metering principle

- w represents the queue length in vehicles,
- Q_{sat}, is the on-ramp capacity in veh/h,
- ρ_{max}, ρ_c are respectively the maximum and the critical density.

The *ramp metering*, or *admissible control*, consists to act on the traffic demand at the on-ramp origin in order to maintain the traffic flow in the mainstream section close to the critical density. [9]

Ramp metering strategies may be local (isolated ramp metering) or coordinated (Smaragdis & Papageorgiou (2004)). Isolated ramp metering makes use of real-time traffic measurements in the vicinity of each controlled on-ramp in order to calculate the corresponding suitable ramp metering flows. Coordinated ramp metering exploits the all available measurements of the considered portions of controlled freeway. We focus here on isolated ramp metering.

3.2 Model-free ramp metering

For the studied freeway section (see Fig. 1), Equation (1) becomes [10]

$$\boxed{\dot{\rho}_s(t) = F(t) - \alpha r(t)} \tag{5}$$

The control variable $r(t)$ is given *via* the intelligent controller iPI (2):

$$\boxed{r(t) = \frac{1}{\alpha}\left[-[F]_e + \dot{\rho}^\star + K_P e + K_I \int e\right]} \tag{6}$$

where

- $\rho^\star$ is the reference trajectory.
- $e = \rho_s - \rho^\star$ is the tracking error.

The estimation of F is provided thanks to the following expression:

$$\boxed{[F(k)]_e = [\dot{\rho}_s(k)]_e - \alpha r(k-1)]}$$

where

- k is the sampled time,
- $[\bullet]_e$ indicates an estimate of $\bullet$. [11]

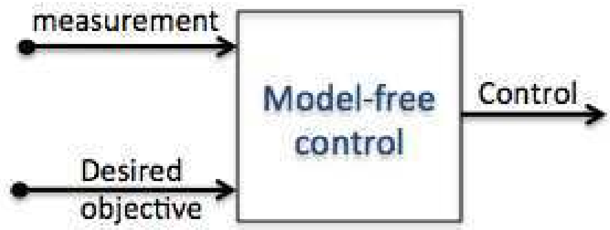


Figure 2. General scheme of the input/output control

3.3 Implementation issues

Implementing our model-free control and the related iPI controller is straightforward: [12]

- The gains K_P and K_I are easily tuned thanks to the first order ultra-local model (5).
- The remarkable robustness properties follow from the excellent estimation $[F]_e$ of F. [13]
- the generation of the desired trajectory (density) $\rho^\star$ is achieved thanks to the following algorithm:
  - · Let V_{filtered} be the filtered mean speed and $V_{\text{threshold}}$ the speed threshold. [14]
  - · ρ_{d0}, ρ_{inc}, ρ_{dec} denote respectively the initial density, the increment and decrement of the desired density.
  - · If $V_{\text{filtered}} > V_{\text{threshold}}$, then $\rho^\star = \rho_{\text{d0}} + \rho_{\text{inc}}$.
  - · If $V_{\text{filtered}} < V_{\text{threshold}}$, then $\rho^\star = \rho_{\text{d0}} - \rho_{\text{dec}}$.

3.4 Simulation results

Our computer simulations are based on numerical data which are collected from the French freeway *A4Y* with one on-ramp (see Fig. 3 and Fig. 4). The software *METANET* (Papageorgiou (1983)) is utilized. [15] Although the measurements, *i.e.*, the traffic volume in veh/h, are quite poor and noisy, the performances of our iPI controller (Fig. 7) are good. Congestions are alleviated as soon as they appear (Fig. 5 and Fig. 6).

4. TRAFFIC FLOW PARAMETRIC ESTIMATION

4.1 Generalities

The macroscopic models which are used for simulation purposes, are not only heuristic but also quite sensitive to parameter variations and uncertainties. The only available accurate physical law is the conservation equation. All other equations (speed equation and the fundamental diagrams, for instance), are based on empirical observations

[9] The traffic demand is assumed to be independent of any control actions (see, *e.g.*, Papageorgiou, Blosseville & Hadj-Salem (1990); Kostialos, Papageorgiou & Middelham (2001)).

[10] The traffic occupancy measurements are utilized for practical implementation.

[11] See Section 2.3.

[12] See Fig. 2 for a corresponding block diagram scheme representation.

[13] See Section 2.3.

[14] Concrete studies (see, *e.g.*, Cete Méditerranée - Les études (2006)) have demonstrated that the level of service is highly degraded and the congestion phenomenon is at its maximum, when the mean speed of individual vehicle is about 30 km/h. The threshold of discomfort is reached, when this speed is equal to 85 km/h (see e.g. Cete Méditerranée - Les études (2006)).

[15] It is based on a second order macroscopic model.

Figure 3. Aerial picture of the studied site (Source DiRIF)

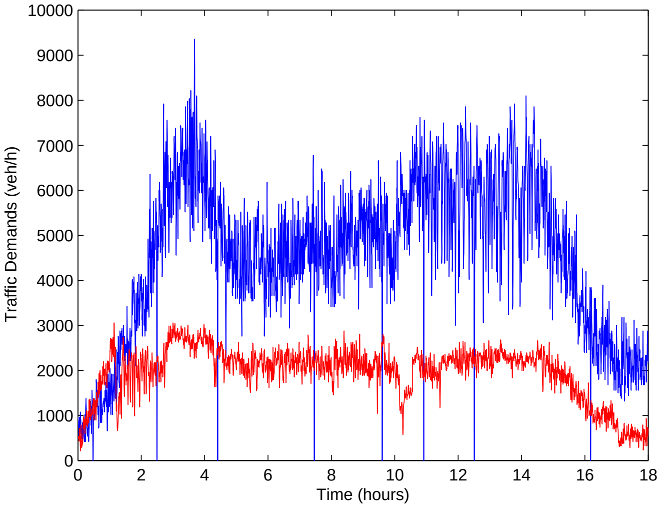


Figure 4. Traffic demands: (–) mainstream, (–) on-ramp

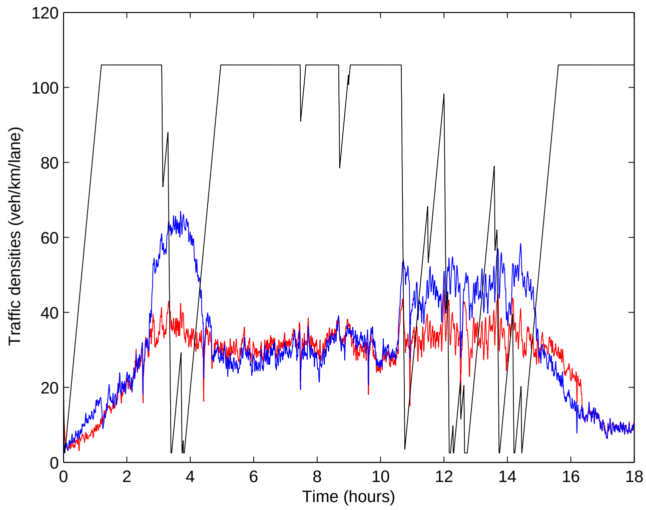


Figure 5. Traffic densities evolutions: (–) no-control case, (–) control case, (–) $\rho^\star$

and coarse approximations. The main parameters such as the critical density and the free-flow speed are moreover subject to variations.

4.2 Fundamental diagram

The *fundamental diagram* due to May (1990) is given by

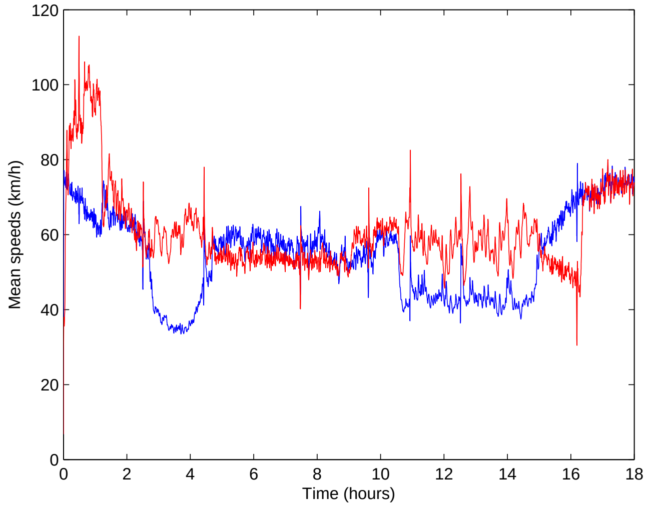


Figure 6. Mean speeds evolutions: (–) no-control case, (–) control case

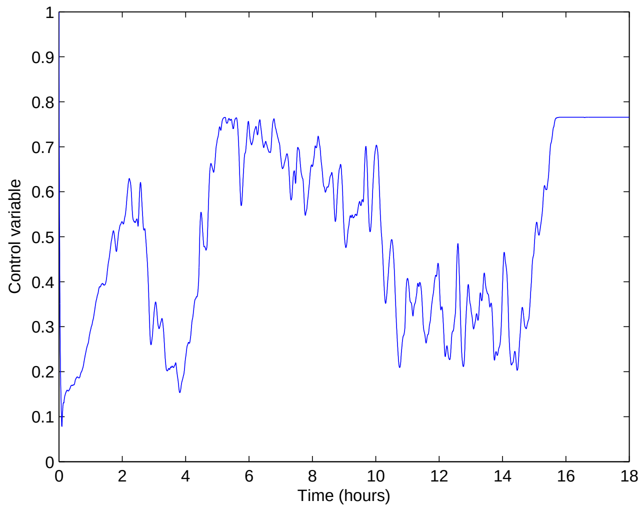


Figure 7. Control variable

$$\boxed{V(\rho_i) = v_f \exp\left(-\frac{1}{a}\left(\frac{\rho_i}{\rho_c}\right)^a\right)} \tag{7}$$

where

- ρ_i is the density of the segment i,
- V is the corresponding the mean speed,

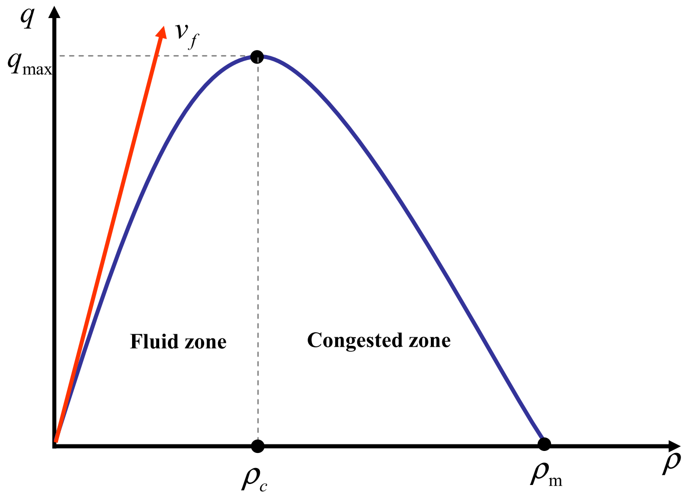


Figure 8. Fundamental diagram example

- v_f is the free-flow speed,
- ρ_c the critical density,
- a is a model parameter.

Although it is of heuristic nature (see Fig. 8), *i.e.*, not derived from physical laws, it provides important parameters for the macroscopic modeling which is used for the numerical simulations and to identify congestion and fluid zones.

4.3 Identification

The existing results in signal processing (see Fliess, Mboup, Mounier & Sira-Ramírez (2003); Fliess (2008); Mboup (2009)) should be extended to the arbitrary exponent a in Equation (7).

New setting Rewrite Equation (7) in the following form

$$V(\rho_i) = v_f \exp\left[-K\rho^a\right] \tag{8}$$

where $K = \frac{1}{a\rho_c^a}$. The equality

$$\rho_c = \sqrt[a]{\frac{K}{a}}$$

shows that ρ_c may be deduced at once from a and K.

Notation: If G is a function of ρ_i, write G_{ρ_i} its derivative with respect to ρ_i.

Write W the logarithmic derivative of V with respect to ρ_i:

$$W = \frac{V_{\rho_i}}{V} = -Ka\rho^{a-1} \tag{9}$$

Thus

$$\frac{W_{\rho_i}}{W} = \frac{a-1}{\rho_i}$$

The identifiability of a follows at once. Equation (9) provides K and Equation (8) v_f.

Remark 4.1. Note that the second order derivative $V_{\rho_i^2}$ of V is needed.

Derivation with respect to time Consider ρ_i and, then, V as functions of time t. The time derivatives are obtained using the following expression:

$$V_{\rho_i} = \frac{\dot{V}}{\dot{\rho}_i} \tag{10}$$

The numerical derivation of noisy signals, developed in (Fliess, Join & Sira-Ramírez (2008); Mboup, Join & Fliess (2009)), has been already successfully implemented in many concrete applications (see, for example in intelligent transportation systems, Menhour, d'Andréa-Novel, Boussard, Fliess & Mounier (2011); Menhour, d'Andréa-Novel, Fliess & Mounier (2012); Villagra, d'Andréa-Novel, Fliess & Mounier (2009, 2011)). In order to summarize the general principles, let us start with the first degree polynomial time function $p_1(t) = a_0 + a_1 t$, $t \geq 0$, $a_0, a_1 \in \mathbb{R}$. Rewrite it thanks to classic operational calculus (see, *e.g.*, Yosida (1984)) p_1 as $P_1 = \frac{a_0}{s} + \frac{a_1}{s^2}$. Multiply both sides by s^2:

$$s^2 P_1 = a_0 s + a_1 \tag{11}$$

Take the derivative of both sides with respect to s, which corresponds in the time domain to the multiplication by $-t$:

$$s^2 \frac{dP_1}{ds} + 2sP_1 = a_0 \tag{12}$$

The coefficients a_0, a_1 are obtained via the triangular system of equations (11)-(12). We get rid of the time derivatives, *i.e.*, of sP_1, s^2P_1, and $s^2\frac{dP_1}{ds}$, by multiplying both sides of Equations (11)-(12) by s^{-n}, $n \geq 2$. The corresponding iterated time integrals are low pass filters which attenuate the corrupting noises, which are viewed as highly fluctuating phenomena (Fliess (2006)). A quite short time window is sufficient for obtaining accurate values of a_0, a_1.

The extension to polynomial functions of higher degree is straightforward. For derivatives estimates up to some finite order of a given smooth function $f : [0, +\infty) \to \mathbb{R}$, take a suitable truncated Taylor expansion around a given time instant t_0, and apply the previous computations. Resetting and utilizing sliding time windows permit to estimate derivatives of various orders at any sampled time instant.

4.4 Computer experiments

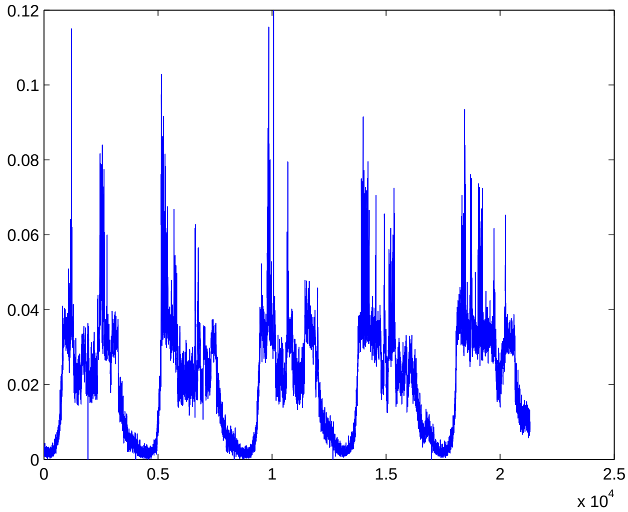
The measurements concern the evolution of the mean speed and of the traffic occupancy depicted in Fig. 9.[16] The data are

- provided during five days with a sampling period of 20 seconds,
- quite poor and noisy.

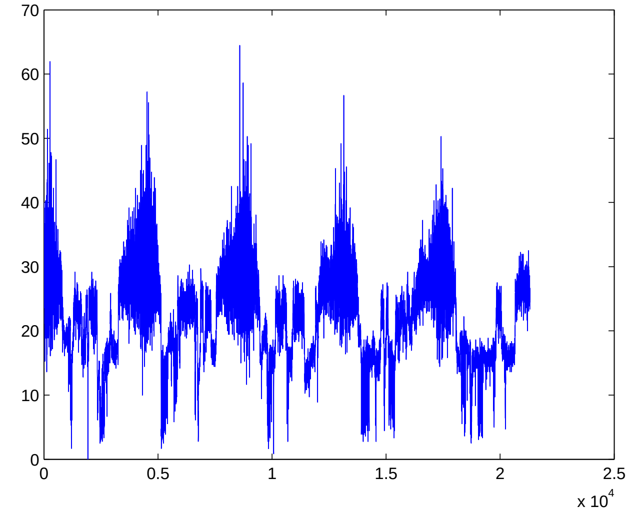
The modeling approximation,[17] and the numerical singularities, which are unavoidable in such a real-time setting, explain why our estimates do fluctuate to some extent. The results depicted in Fig. 10 do however show a satisfactory "practical" convergence towards values which are suitable for our simulation purposes.

[16] The occupancy measurements are transformed into traffic density for simulations purposes.

[17] As already stated in Section 4.2 the fundamental diagram is only heuristic.



(a) Density evolution ρ vs time in seconds



(b) Speed evolution v vs time in seconds

Figure 9. Measured variables

5. CONCLUSION

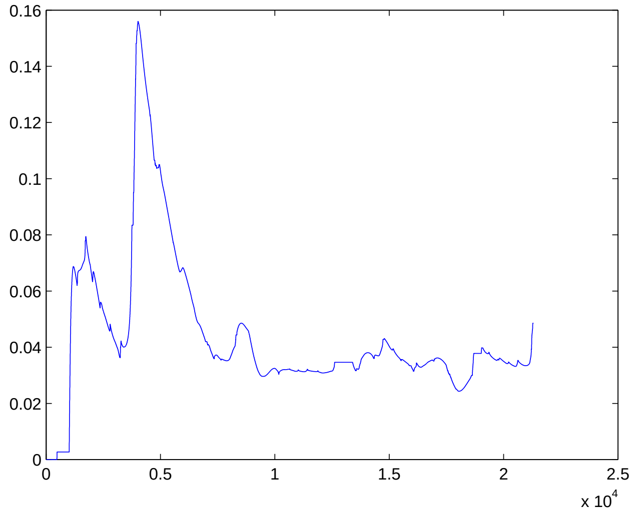
The control design described in this paper will soon be implemented in practice. The pending patent [18] prevents us unfortunately from discussing future developments in traffic control.

From a theoretical standpoint two major points might however be stressed:

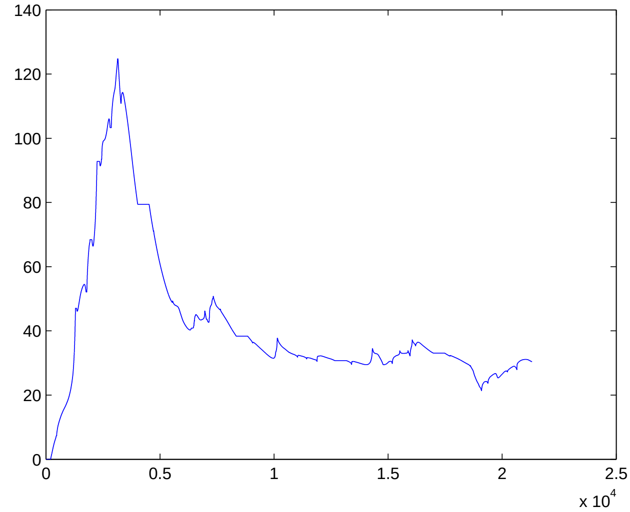
(1) The control of freeway ramp metering and of hydroelectric power plants is approached almost exclusively in the existing academic literature via a rather complex modeling where partial differential equations are often utilized. [19] The present work confirms what has already been obtained for hydroelectric power plants by Join, Robert & Fliess (2010), namely that an

[18] See the acknowledgement below.

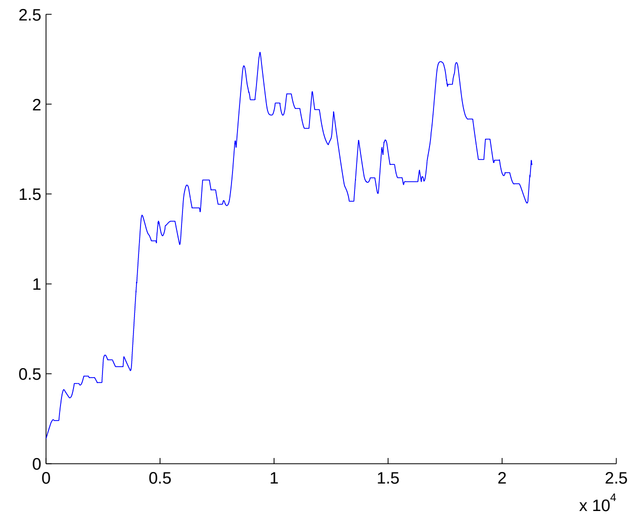
[19] See, *e.g.*, some references in Abouaïssa, Fliess, Iordanova & Join (2011b).



(a) Critical density estimation ρ_c vs time in seconds



(b) Free-flow speed estimation v vs time in seconds



(c) Estimation of a vs time in seconds

Figure 10. Estimated parameters

elementary model-free control is enough for obtaining excellent results.[20]

(2) Computer simulations do necessitate a quite realistic modeling which implies a more subtle mathematical setting than model-free control. This fact which is stressed here for the first time will be further studied in the future. It might lead to a profound epistemological revolution in applied mathematics and, more generally, in applied sciences, the consequences of which are not yet clear.

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[20] See the conclusion in (Fliess, Join & Riachy (2011)) for a more thorough analysis.

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