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快速路交通密度的自抗扰控制器设计及不同扰动情况下的性能评价

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摘要: 本文针对快速路主道交通密度的控制问题, 提出了一种新的自抗扰匝道调节方法. 该方法包括跟踪微分器(TD)、扩展状态观测器(ESO)和非线性输出误差反馈控制律(NLOEF)3个部分. 通过微分跟踪环节安排的过渡过程, 可有效降低系统的超调; 而系统外部不确定性可通过ESO估计, 并将估计信息用于NLOEF更新控制信号. 本文分别基于宏观MATLAB和微观PARAMICS平台进行了仿真研究, 验证了所提出方法抑制不同类型外部扰动的有效性.

关键词: 自抗扰控制; 快速路交通密度控制; 匝道调节; 控制性能分析

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Active disturbance rejection controller for freeway traffic density and performance assessment with different types of disturbances

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Abstract: An active disturbance rejection control approach (ADRC) is proposed for the traffic density control via ramp metering. This new traffic density ADRC approach consists of a tracking differentiator (TD), an extended state observer (ESO), together with a nonlinear output error feedback control law (NLOEF). The system overshoot can be reduced by the arranged transition process. Furthermore, the exogenous uncertainties can be estimated by the ESO, which in turn is used in the NLOEF to update the control signals. Simulation results are provided with both macroscopic MATLAB and microscopic PARAMICS platforms to show that the proposed ADRC method is capable to reject different types of exogenous disturbances.

Key words: active disturbance rejection control; freeway traffic density control; ramp metering; performance analysis

1 Introduction

Freeway traffic control is an important area in the field of traffic engineering and intelligent transportation systems. The most common causes of freeway congestion include traffic demand being greater than capacity, as well as traffic accidents, road works, weather, etc[1]. For better utilization of freeway capacity, ramp metering[2–6] is a common strategy. The purpose of ramp metering is to regulate the amount of traffic entering a given freeway at its entry ramps to maximize throughput by maintaining a desired (or optimal) occupancy on the downstream mainline freeway. Ramp metering is implemented by means of traffic lights in practice, which is used to meter the number of entering vehicles. Various schemes can be applied to the freeway ramp metering, such as the demand capacity (DC) strategy [7], the occupancy (OCC) strategy[7], ALNEA[8–10], neural network control[4], fuzzy control[11], iterative learning control [1,12], and so on.

Based on the results of several field implementations in European countries[10], ALINEA ramp-metering control strategy, proposed by Papageorgiou[8–9] in 1990s, has been shown to be a remarkably simple, highly efficient and eas-

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ily implemented ramp metering application. ALINEA is a typical I – type feedback regulator based on mainstream measurements of occupancy downstream of the ramp without including any modeling information of the plant. As a special type of PID approach, the success of ALINEA is able to overcome disturbances in most applications. However, PID is a typical passive disturbance rejection strategy. Only when the exogenous disturbances act on the control plant and cause output errors, can the controller be driven to reject these disturbances passively[13].

Active disturbance rejection control (ADRC), proposed by Han[14–15], extracts the disturbance information from the system I/O data and then uses such information to modify the control signal to reject the disturbances before they influence the control plant. As an improved nonlinear PID approach, ADRC offers a new and inherently robust controller building block that requires little information of the plant and now has been successfully applied to solve various types of control problems across many engineering disciplines, such as motion control[16–17], chemical process control[18], micro-electro-mechanical systems (MEMS) control[19], etc. It shows great potential in performance improvements, energy savings, less wear and tear, and so on.

This paper develops a new freeway traffic density ADRC approach via local ramp metering to overcome the system uncertainties and exogenous disturbances, which consists of an extended state observer (ESO), a tracking differentiator (TD) and a nonlinear output error feedback control law. Compared with the well known ALINEA[8–10], the distinct features of the proposed freeway traffic density ADRC lie in: a) It can achieve a more smooth tracking performance by arranging a transition process with a tracking differentiator; b) It is able to estimate and compensate the exogenous disturbance actively with the designed ESO; c) It is more robust to the uncertainties with a nonlinear feedback law and can use the estimation of disturbance to update the control signals. This work also extends the applications of ADRC approach[16–19] firstly to the freeway traffic system, which is a distributed parameter system. The disturbance rejection ability of the proposed approach is explored thoroughly in the simulation study on both macroscopic MATLAB and microscopic PARAMICS platforms.

The rest of this paper is organized as follows. Section 2 formulates the problem and introduces a discretized macroscopic traffic model. The new freeway traffic density ADRC approach is developed in Section 3. An illustrative example is provided with the macroscopic traffic simulator in Section 4. Further, the performance evaluation of the proposed approach is provided with the PARAMICS microscopic simulator in Section 5. Finally, Section 6 concludes this paper.

2 Problem pormulation

2.1 Macroscopic traffic model

The freeway system considered in this paper is described by a highly nonlinear dynamical traffic model developed by Lighthill and Whitham[20] and Payne[21], which is based on the analogy between traffic flow and fluid flow. Several modified versions of this macroscopic traffic model have been proposed[22–24], tested via real traffic data, and widely used in simulation and control. The spatially discretized traffic flow model[22] for a single freeway with one on-ramp and one off-ramp on each section is shown in Fig.1 below the equations (1)–(4):

$$\rho_i(k+1) = \rho_i(k) + \frac{h}{L_i}[q_{i-1}(k) - q_i(k) + r_i(k) - s_i(k)], \tag{1}$$

$$q_i(k) = \rho_i(k)v_i(k), \tag{2}$$

$$v_i(k+1) = v_i(k) + \frac{h}{\tau}[V(\rho_i(k)) - v_i(k)] + \frac{h}{L_i}v_i(k)[v_{i-1}(k) - v_i(k)] - \frac{\nu h}{\tau L_i}\frac{[\rho_{i+1}(k) - \rho_i(k)]}{[\rho_i(k) + \kappa]}, \tag{3}$$

$$V(\rho_i(k)) = v_{\text{free}}(1 - [\frac{\rho_i(k)}{\rho_{\text{jam}}}]^l)^m, \tag{4}$$

where h is the sample time interval; $k \in \{0, 1, \cdots\}$ is the kth time interval; $i \in \{1, \cdots, N\}$ is the ith section of a freeway; N is the total section number.

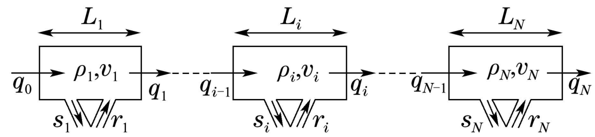

Fig. 1 Sections on a freeway with on/off ramp

Model parameter variables are listed as belows:

$\rho_i(k)$: density in section *i* at time *kh* (veh/lane/km);

$v_i(k)$: space mean speed in section *i* at time *kh* (km/h);

$q_i(k)$: traffic flow leaving section *i* and entering section *i*+1 at time *kh* (veh/h);

$r_i(k)$: on-ramp traffic volume for section *i* at time *kh* (veh/h);

$s_i(k)$: off-ramp traffic volume for section *i* at time *kh* (veh/h), which is regarded as an unknown disturbance;

L_i: length of freeway in section *i* (km);

V_{free} and ρ_{jam} are the free speed and the maximum possible density per lane, respectively.

τ, κ, l, m are constant parameters which reflect particular characteristics of a given traffic system and depend on the freeway geometry, vehicle characteristics, drivers' behaviors, etc.

Equation (1) is the well-known conservation equation, (2) is the flow equation, (3) is the empirical dynamic speed equation, and (4) represents the density-dependent equilibrium speed.

2.2 Boundary

Assume that the traffic flow rate entering section 1 during the time period kh and $(k+1)h$ is $q_0(k)$ and the mean speed of the traffic entering section 1 is equal to the mean speed of section 1, i. e. , $v_0(k) = v_1(k)$. We also assume that the mean speed and traffic density of the traffic exiting section N are equal to those of section $N-1$, i. e.

$$v_N(k) = v_{N-1}(k),\ \rho_N(k) = \rho_{N-1}(k).$$

Boundary conditions can be summarized as follows

$$\rho_0(k) = \frac{q_0(k)}{v_1(k)}, \tag{5}$$

$$v_0(k) = v_1(k), \tag{6}$$

$$\rho_N(k) = \rho_{N-1}(k), \tag{7}$$

$$v_N(k) = v_{N-1}(k),\ \forall k. \tag{8}$$

2.3 Control objective

The control objective is to determine an appropriate on-ramp traffic flow $r_i(k)$ for the i-th on-ramp locally driving the traffic density $\rho_i(k)$ of section i to track the desired traffic density $\rho_{i,d}(k)$ of section i, i.e., the tracking error $e_i(k) = \rho_{i,d}(k) - \rho_i(k)$ converges to zero asymptotically as k approaches to infinity.

3 Freeway traffic density ADRC design

The macroscopic traffic flow model described by equations (1) and (2) can be rewritten in the following form

$$\begin{aligned}\rho_i(k+1) = {} & \rho_i(k) + \frac{h}{L_i}[v_{i-1}(k)\rho_{i-1}(k) - \\ & v_i(k)\rho_i(k) + r_i(k) - s_i(k)] = \\ & a_i(k)\rho_i(k) + b_i(k)\rho_{i-1}(k) + \\ & c_i(k)r_i(k) - c_i(k)s_i(k),\end{aligned} \tag{9}$$

with

$$a_i(k) = 1 - \frac{h}{L_i}v_i(k),\ b_i(k) = \frac{h}{L_i}v_{i-1}(k),\ c_i(k) = \frac{h}{L_i}.$$

For the simplicity of formulation, the section index i is omitted in the following equations.

Remark 1 The traffic flow density is used as the control objective in place of traffic occupancy, because density is the variable closest to occupancy that may be directly provided by the macroscopic model in the simulation[9–10].

The freeway traffic density ADRC approach is designed with three parts: i) tracking differentiator (TD); ii) extended state observer (ESO); and iii) feedback control law.

i) Tracking differentiator (TD).

According to the mathematical formulation of freeway traffic system (9), a one-order nonlinear tracking differentiator is designed to arrange the transition process for expected density. The discrete algorithm of TD is given as follows

$$\hat{\rho}(k+1) = \hat{\rho}(k) + hR_1\mathrm{fal}(\hat{\rho}(k) - \rho_{\mathrm{d}}(k), \gamma, h_0), \tag{10}$$

where $\rho_{\mathrm{d}}(k)$ is the desired traffic flow density value; $\hat{\rho}(k)$ is the tracking signal of $\rho_{\mathrm{d}}(k)$, R_1, γ, h_0, are three control parameters used to tune the transition process; h is the sampling time step; and fal is defined by

$$\mathrm{fal}(e, a, \delta) = \begin{cases} |e|^a \mathrm{sgn}\, e, & |e| > \delta, \\ \dfrac{e}{\delta^{1-a}}, & |e| \leqslant \delta. \end{cases} \tag{11}$$

ii) Extended state observer (ESO).

The one-order ESO is designed as follows:

$$\begin{aligned} z_1(k+1) = {} & z_1(k) + h(z_2(k) - \\ & \beta_1\mathrm{fal}(e_1(k), a_1, \delta_1) + b_0 r(k)), \end{aligned} \tag{12}$$

$$z_2(k+1) = z_2(k) - h\beta_2\mathrm{fal}(e_1(k), a_2, \delta_2), \tag{13}$$

where $e_1(k) = z_1(k) - \hat{\rho}(k)$ is the tracking signal of the traffic density $\rho(k)$; $z_2(k)$ is the observed value of $a_i(k)\rho_i(k) + b_i(k)\rho_{i-1}(k) - c_i(k)s_i(k)$, which is regarded as the nonlinear uncertainty of the freeway traffic system; b_0 is a proper parameter; β_1 and β_2 are gains of output error; $\mathrm{fal}(e, a, \delta)$ is the best function defined in (11); δ is a filtering factor to ESO; a is a nonlinear factor; h is the sampling-time step.

iii) Nonlinear output error feedback control law (NLOEF).

According to the errors between TD output and ESO output, an output error feedback control law is designed as follows:

$$r_0(k) = \beta_1\mathrm{fal}(e_1(k), a_1, \delta_1), \tag{14}$$

$$r(k) = r_0(k) - \frac{z_2(k)}{b_0}. \tag{15}$$

Remark 2 It should be noted that the whole ADRC strategy (10)–(15) does not have any relation with the macroscopic traffic model (1)–(4) except for the I/O data.

4 Illustrative example with macroscopic traffic simulator

The macroscopic traffic flow model[22–24] performs at large regional levels and considers simple networks with major roads and aggregated flows of vehicles. It has been tested via real traffic data and widely used in simulation and control. Consider a long segment of freeway that is subdivided into 12 sections. The length of each section is $0.5\,\mathrm{km}$. The initial traffic volume entering section 1 is 1400 vehicles per hour. The desired density is

$$\rho_{\mathrm{d}} = 30\,\mathrm{veh/km}$$

per lane. The initial density and mean speed of each section are selected as:

$$\rho_i(0) = 30\,\mathrm{veh/lane/km},\ v_i(0) = 50\,\mathrm{km/h},$$

and the parameters used in this model are given as:

$$\begin{aligned} & v_{\mathrm{free}} = 80\,\mathrm{km/h},\ \rho_{\mathrm{jam}} = 80\,\mathrm{veh/lane/km}, \\ & l = 1.8,\ m = 1.7,\ \kappa = 13\,\mathrm{veh/km},\ \tau = 0.01\,\mathrm{h}, \\ & h = 0.00417\,\mathrm{h},\ \gamma = 35\mathrm{km}^2/\mathrm{h},\ \alpha = 0.95, \\ & q_0(k) = 1500\,\mathrm{veh/h},\ r_i(0) = 0\,\mathrm{veh/h}. \end{aligned}$$

There are one on-ramp located in Section 7 with known traffic demand and two off-ramps located in Section 5 and Section 9 with unknown exiting traffic flow, respectively. They were chosen to simulate a traffic scenario during rush hour. The unknown existing flows actually are chosen to mimic the exogenous disturbances to Section 7.

Note that the queuing demands actually impose certain constraints on the control inputs of ramp metering, i.e., the on-ramp volumes cannot exceed the current demands plus the existing waiting queues at on-ramps at the time k; thus

$$r_i(k) \leqslant \eta_i(k) + \frac{l_i(k)}{h},\ i \in I_{\mathrm{ON}}, \tag{16}$$

where $l_i(k)$ denotes the length (in vehicles) of a possibly existing waiting queue at time instant k at ith on-ramp;

$\eta_i(k)$ is the traffic demand flow at time instant k at ith on-ramp (veh/h), and $I_{\mathrm{ON}} = 7$ for the simulation of this paper, denotes the set of indexes of the sections where an on-ramp exists. On the other hand, the waiting queue is the accumulation of the difference between the demand and actual on-ramp, i.e.,

$$l_i(k+1) = l_i(k) + h[\eta_i(k) - r_i(k)],\ i \in I_{\mathrm{ON}}. \quad (17)$$

To show the robustness of the proposed freeway traffic density ADRC approach comprehensively, three kinds of exogenous disturbances are exposed on the freeway traffic system in the simulation. For the detail, the off-ramp traffic flow out of Section 5 is set as $400\,\mathrm{veh/h}$ (the original is $0\,\mathrm{veh/h}$) after the 250th sampling time instant to simulate the exogenous disturbance from upstream section; the off-ramp traffic volume out of Section 9 is $400\,\mathrm{veh/h}$ (the original is $0\,\mathrm{veh/h}$) after the 350th sampling time instant to simulate the exogenous disturbance from downstream section; and the initial traffic flow entering Section 1 is changed to $1800\,\mathrm{veh/h}$ from the original $1400\,\mathrm{veh/h}$ after the 250th sampling time instant. The parameters of the proposed ADRC approach are set as:

$$\hat{\rho}(0) = 22.5,\ z_1(0) = 22.5,\ z_2(0) = 0$$

for the initial values;

$$R_1 = 250,\ \gamma = 0.5,\ h_0 = 15$$

for the TD parameters;

$$h = 0.00417,\ \beta_1 = 120,\ a_1 = 0.5,\ \delta_1 = 1,$$
$$b_0 = 1.5,\ \beta_2 = 6000,\ a_2 = 0.25,\ \delta_2 = 1$$

for the ESO parameters. The simulation result is shown as the red solid line in Fig. 2. Apparently, the proposed freeway traffic density ADRC approach is well in rejecting the large fluctuation with little overshoot and smooth tracking.

For the purpose of comparison, the following standard ALINEA approach is also applied in the simulation,

$$r(k) = r(k-1) + K_r[\rho_{\mathrm{d}} - \rho(k)],$$

where $K_r = 20$ is the feedback gain of ALINEA. The simulation result is shown as the blue dotted line in Fig. 2.

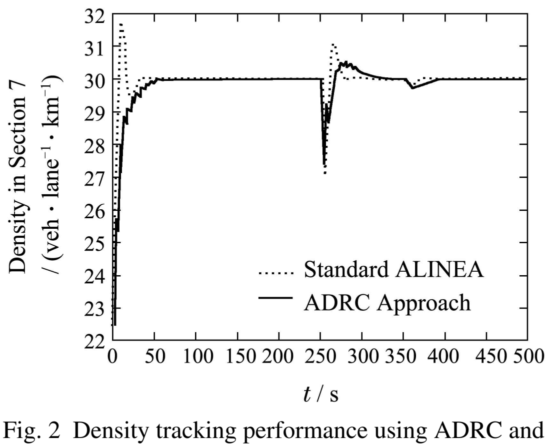

Fig. 2 Density tracking performance using ADRC and ALINEA respectively

Compared with standard ALINEA, a distinct feature of the proposed ADRC approach is that a transition process is arranged to avoid system overshoot and achieve a smooth tracking property, which is expected in practical applications.

5 Performance assessment with PARAMICS microscopic simulator

The macroscopic freeway model used in Section 4 is especially useful for theoretical analysis purposes, but the lack of detail modeling of individual vehicles and behavior of drivers makes it insufficient for the effectiveness assessment of a freeway controller[1, 11]. The parameters $(\tau, \kappa, l, m, V_{\mathrm{free}}, \rho_{\mathrm{jam}})$ which are critical for model accuracy need to be calibrated before application to a specific freeway link.

Instead, PARAMICS microscopic simulator takes into account the behavior of every vehicle several times a second and is forced to work within the constraint of the physical world and the impacts of the road geometries as well as physical size of vehicles, which have significant impacts that macroscopic or any deterministic simulators cannot achieve. Hence, it is particularly suitable for evaluation of the applicability and effectiveness of freeway control strategies. So in this section the powerful microscopic traffic simulation platform, PARAMICS, is used for evaluating the effectiveness of the proposed ADRC approach from a more practical viewpoint further.

A) PARAMICS platform and microscopic freeway model.

1) PARAMICS freeway network: A 3-lane freeway link with 14 mainline sections, 1 on-ramp and 1 off-ramp is considered. The on-ramp used to implement metering or flow control, is connected to section 3 at the beginning and the off-ramp is connected to section 8 at the end. As shown in Fig. 3, vehicles enter into the network from two defined zones, Zone 1 and Zone 2 at the beginning of the freeway mainline and on-ramp section respectively, and will have their destinations to be either Zone 3 or Zone 4, defined at the end of off-ramp and the mainline.

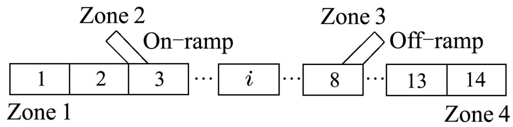

Fig. 3 Freeway simulation model

In the O–D table below (Table 1), Zone 1 and Zone 2 are used for origins to release vehicles into the network, and meanwhile Zone 3 and Zone 4 are used as destination for these vehicles. In the table, the number specified are the total number of vehicles expected to make a trip starting from the zone corresponding to the row to the zone corresponding to the column. The release rate in PARAMICS of traffic flow is specified in profile files. The duration time is divided uniformly into time intervals and a specified percentage of vehicles from the total demand are expected to be released from at each origin zone during each time interval, additionally the release probability is subject to random process. In this paper the time interval length is set to be 3 minutes which divides the simulation duration of 1 hour into 20 intervals.

Table 1 PARAMICS O-D table

	Zone 1	Zone 2	Zone 3	Zone 4	Total
Zone 1	0	0	600	3600	4200
Zone 2	0	0	150	750	900
Zone 3	0	0	0	0	0
Zone 4	0	0	0	0	0
Total	0	0	750	4350	5100

2) PARAMICS network configuration: The key parameters for traffic model are provided in Table 2. And the controller parameters of ADRC are the same at that in Section 4.

Table 2 Parameters of traffic model

PARAMICS	Duration (HH: MM: SS)	1:00:00
	Time step / s	2
	Control time step / s	30
	Demand factor / %	100
	Section length / m	500
	Orientation	Left hand Drive
	Units	Metric Units

B) Simulation and results.

By the PARAMICS microscopic simulator, the control performance of the proposed traffic density ADRC approach is assessed from a practical application viewpoint with consideration of different types of disturbances. For clarity, three different disturbances – from the upstream section, downstream section and upstream initial traffic flow respectively, are considered in three scenarios, respectively. Scenario I: The off-ramp traffic flow out of Section 5 is set as 300 veh after half an hour; Scenario II: The off-ramp traffic volume out of Section 9 is 300 veh after half an hour; and Scenario III: The initial traffic flow entering Section 1 is changed to 1100 veh from the original 1400 veh after half an hour. The PARAMICS simulation results are shown in Figs. 4–6, respectively.

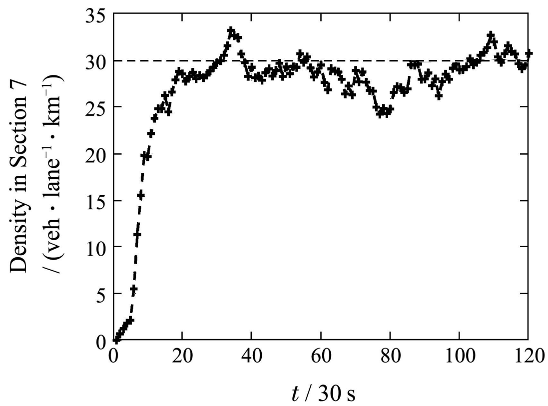

Fig. 4 ADRC performance evaluation with PARAMICS simulator in Scenario I

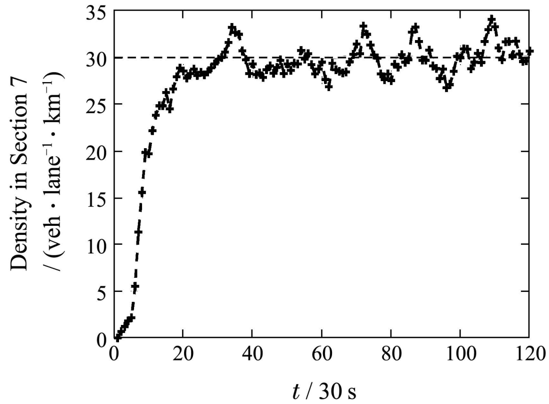

Fig. 5 ADRC performance evaluation with PARAMICS simulator in Scenario II

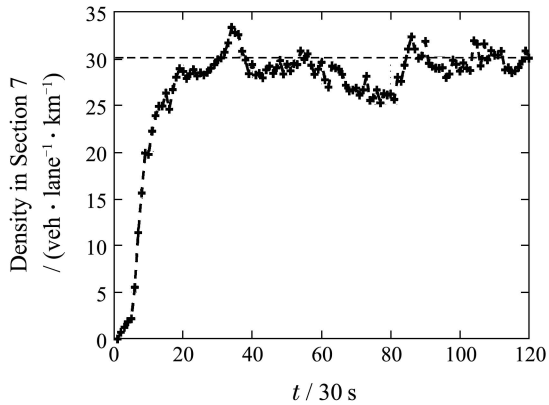

Fig. 6 ADRC performance evaluation with PARAMICS simulator in Scenario III

It is clear that: a) the proposed freeway traffic density ADRC approach is very effective in reducing the fluctuations and overshoots in the mainline flow for different types of exogenous disturbances; b) the disturbances from upstream off-ramps and the initial traffic flow entering the first section expose a major affection on the freeway mainline traffic density, while the disturbances of downstream off-ramps only make a trivial action on the traffic density. The PARAMICS performance evaluating results further confirm the efficiency and applicability of the proposed ADRC approach for different types of disturbances from a more realistic viewpoint.

6 Conclusion

In this paper, a freeway traffic density ADRC approach is developed to solve the on-ramp control problem. The proposed scheme is able to estimate and compensate various kinds of disturbances of the freeway traffic system actively using the I/O data, and the estimate disturbance is used in turn in the feedback law to eliminate the influences on the control plant. The transition process is arranged to avoid the system overshoot. The applicability and efficiency of the proposed approach are validated with both macroscopic and microscopic level freeway traffic simulators.

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