Closed-Loop Flow Regulation with Balanced Routing

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***Abstract*— A new rerouting approach for vehicular transit is introduced. The approach is illustrated with a real world scenario and evaluated through a hardware-in-the-loop simulation platform.**

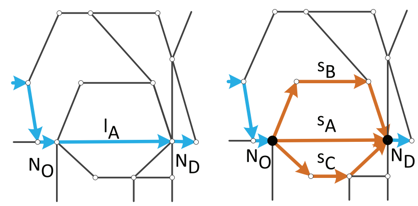
I. Introduction

There are many ways to influence congestion or pollution in urban areas. We concentrate on routing and feedback regulation as an instrument, which is, to the best of our knowledge, a completely new approach for traffic control. Feedback control is used in [1] to avoid congestion using speed limits and access ramp metering. In [2], a system-optimal routing engine was introduced, which has very different features compared to the individual shortest path calculations. For instance, it is required that the routing engine is once fed with information regarding all relevant vehicles, including information about their origins and destinations. Complementary to that, we target a situation where an unexpected change in the network conditions occurs and an ad-hoc adaptation of routing is needed. We use routing with vehicular flow control to provide a fair quality of experience for drivers, while at the same time regulating vehicular flow around a critical infrastructure. In the following, we show that a stochastic feedback loop inspired by [3] implements a simple and effective method to address both aspects.

II. Description of the Rerouting System

For this paper, we take a simplified view of the routing problem. Instead of considering a large geographic area, we consider the problem of routing vehicles around an obstruction (e.g. accident or police checkpoint) which affects the (normally) planned route. Assuming such an ad-hoc road capacity decrease, we wish to instantly start to reroute affected vehicles, while at the same time regulate the reduced vehicular flow around the obstruction. This should be done in a way that avoids all vehicles choosing the same (new) route. Relevant origin and destination information refers to the fact that all vehicles share parts of their route. Fig. 1 shows the basic idea.

Today, it is often the case that vehicles are rerouted because of traffic jams on highways. A common shortest path algorithm would identify one optimal route (here, either s_A, s_B or s_C; see Fig. 1.b) for all vehicles. Unfortunately, this kind of approach often causes congestion on the alternative path and flapping effects [4]. We wish to solve this problem using a stochastic approach which leads to heterogeneous routes for vehicles. We suggest alternative routes to drivers in a manner that balances any kind of feature (e.g. pollution or congestion) along these multiple routes; here, s_A, s_B or s_C. As we target routing for a locally limited area, communication and transport delays are not an issue, and the issue of fairness does not arise.



a) b)

Fig. 1. In a), a planned route is highlighted. We assume that all vehicles wish to travel via the nodes N_O and N_D. At some point in time, an obstruction occurs on link l_A, which connects N_O with N_D. In b), two extra routes are found, which connect N_O with N_D. The algorithm controls the load on route s_A and balances it on the alternative routes s_B and s_C.

In order to illustrate the above, we propose the following scenario, which we used for simulation and on-street experiments. At the beginning of travel, there is no obstruction and vehicles go freely from the start node to the end node according to some route planning algorithm (like shortest path). In our case, this route is the inner lap going via the link with the traffic alert (see Fig. 2), which occurs 120 time steps after the start. At time step 120, we emulate a partial obstruction, which causes a decrease in the link capacity on that path (the red link). In consequence, we wish that not all upcoming vehicles stick to this initial route choice (through the obstruction s_1) but choose from one of the two other possible routes s_2 and s_3, with probabilities p_1, p_2 and p_3 according to a feedback control loop for the vehicular flow F_1 on s_1 (Fig. 3) and a balancing algorithm for vehicular flows F_2 and F_3 on s_2 and s_3, respectively.

For the particular example shown in Fig. 2 and Fig. 3, we have (the controller)

$$p_1(k) = \begin{cases} 0, & \text{if } e(k) < 0, \\ 0.5, & \text{otherwise.} \end{cases}$$

and

$$p_{23}(k) = p_2(k) + p_3(k) = 1 - p_1(k),$$

where our objective is to control the flow of vehicles on route

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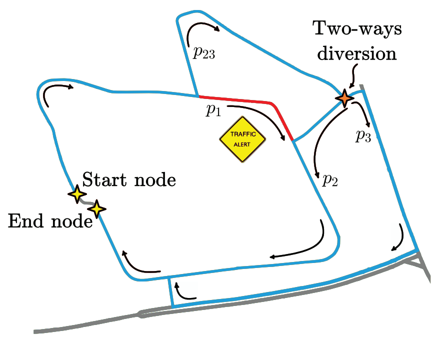

Fig. 2. Setup for simulation and on-street experiments.

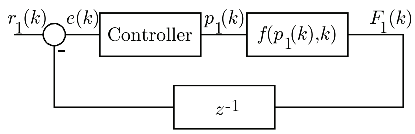

Fig. 3. Feedback control for vehicular flow $F_1(k)$ through the partially obstructed section, where $r_1(k)$ is the set point, $e(k)$ is the difference between the set point and measured traffic flow, and p_1 is the probability to take such a section, which leads to the vehicular flow F_1 on that route.

s_1, and where $p_{23} = p_2 + p_3$ is such that $\{p_2, p_3\}$ guarantee that F_2 and F_3 are balanced. This balancing is done by letting vehicles, which have not chosen s_1, choose between the route alternatives s_2 and s_3 stochastically. The probabilities may be related to the current conditions, e.g. noise emissions on that particular route. For the sake of simplicity, we want the flow of vehicles F_i for $i \in 2, 3$ on both routes balanced, i.e. the probability p_i to choose route s_i with $i \in 2, 3$ is calculated according to

$$p_i = \alpha\left(1 - \frac{F_i}{F_2 + F_3}\right), \quad \alpha = \begin{cases} 1, & \text{if } p_1 = 0, \\ 0.5, & \text{otherwise.} \end{cases} \quad (1)$$

III. Preliminary Results

The evaluation of the rerouting system is performed with the simulation platform described in [5]. For the experimental test, we drove the target car through the NUIM's North Campus and ran the SUMO simulation for 278 seconds (time steps) with an initial vehicular flow of 30 cars per minute released at the start node. The results from the test with the aforementioned scenario are shown in Fig. 4.

The results show that the general idea and control approach defined in (1) performs well. Seventy-four time steps after the beginning of the simulation, the first vehicles reach the beginning of s_1. They go freely through s_1 until time step 120, when the obstruction occurs. From time step 121 on, the control approach starts. Note that vehicles are associated with s_1 while they pass the obstructed section (coloured red in Fig. 2) and that they are associated with s_2 after having passed this section. That is the reason for having vehicles associated with s_2 before time step 120 (and the initial imbalance of F_2 and F_3). In the upper part of Fig. 4, it can be seen that F_1 (or even better $\bar{F}_1$, which is the average of F_1 with a moving window of the last 50 time steps) is properly controlled and converges to the set value r_1. In the lower part of Fig. 4, we illustrate the results of the balancing approach. The initial

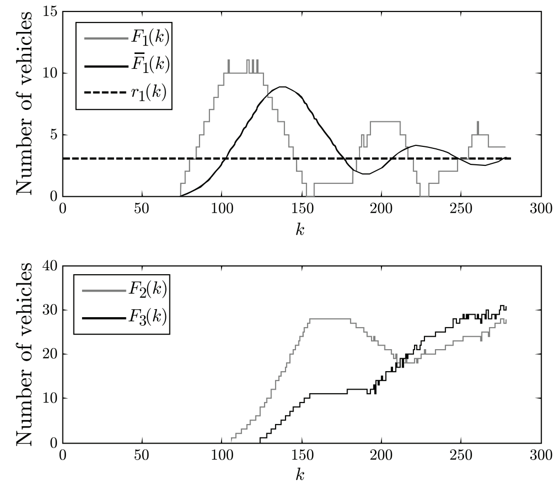

Fig. 4. Evolution of the vehicular traffic, where $F_i(k)$ is the vehicular flow through route s_i at instant k, $\bar{F}_1(k)$ is the average of $F_1(k)$ with a moving window of the last 50 time steps, and $r_1(k)$ is the set point for $F_1(k)$.

imbalance (see above) of F_2 and F_3 is equalised over time. F_2 and F_3 are well-balanced roughly from time step 220.

The advantage of testing the rerouting system with the platform described in [5] is that it allows real drivers to gain a feel of the technology being tested. The target vehicle was equipped with a smartphone that displayed the reroute, dealt to the target vehicle, to the driver. The driver was able to follow the reroute successfully.

IV. Conclusions and Future Work

In this paper, we introduced the general idea of a stochastic routing algorithm, combined with feedback control, and showed by simulation including on-street experiments that it helps to control and balance traffic in a locally limited area. Regarding the next step, the valid size of the area should be discussed. Furthermore, we assumed that vehicles would choose one of n possible routes randomly to get from a common origin to a common destination. We did neither discuss the generation of the set of possible routes nor an advanced or constrained selection per vehicle. Both aspects should be further analysed as they are critical for user acceptance.

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