A HIERARCHICAL-DECENTRALIZED TRAFFIC LIGHT CONTROL SYSTEM. THE FIRST REALIZATION: "PROGETTO TORINO"

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Abstract. A modern approach to the design of traffic light control is prerequisite for solving some major problems of urban transport systems.
The foundations of a hierarchical-decentralized traffic light control are presented and the first application of these concepts - the Progetto Torino - is described. Significant results from simulations are given, for comparison with actual data which will be available by mid 1984.

INTRODUCTION

The latest years have seen an increasing awareness of the need for a more realistic and also more scientific approach - than the one of the early seventies - to the problem of urban transportation.
A deeper understanding of the limitations of the so called "innovative systems" (or new modes) - also based on experimental results - has shown that one should not rely on them for getting rid of congestion and pollution in urban areas and for offering on a wide basis better transport service to the users.
On the other hand it became increasingly clear that "conventional" modes - underground and surface rails, buses etc. - still offer a large potential for improvements and innovations [1].
Unimodal surface sybsystems (the rail system, the bus system, etc.) as well as the multimodal coordinated transport system - f.i. for a metropolitan area - need, for being exploited in an optimal way, a composite operation control, which is practically split into "central monitoring and surveillance" and "traffic light control".
This paper is concerned only with the latter. Fairly comprehensive reviews of theory and state of the art have been published recently [2] [3]: so far a truly traffic - actuated control of urban intersections using the opportunities offered by today's engineering developments has never been put in regular operation in an urban area. The "Progetto Torino" should fill this gap.
The design concepts presented in this paper are applied in defining and building what can be called a hierarchical decentralized traffic light control system. First, the objectives and basic specifications of the system are summarized. Then model and control concepts developed in order to meet the previous requirements are briefly described. Finally an outline of the "Progetto Torino" is given.

OBJECTIVES AND BASIC SPECIFICATIONS

The objectives which required a hierarchical decentralized traffic light control system to be worked out are the following:

a - absolute priority to selected public transport lines at every intersection, except when conflicts or interference among these vehicles could occur.
b - significant improvement of private vehicles mobility.
c - continuous control of public vehicles in operation.
d - information - through suitable displays - to users waiting at the stations, about the arrival of the next coming public vehicle.
e - high reliability of the whole system, including self-diagnosis, and automatic information to the central control room about failures at any point

of the traffic light network under control.
(Objective b) is an almost normal feature of experimented and operating traffic light control systems, objective a) has never been reached).
With reference to this set of objectives the basic design and operation specifications are:
- exploitation of the advantages offered by traffic lights co-ordination,
- attention payd to slow phenomena of the private traffic (use is made of their propagation in space),
- priority to selected public transport lines on reserved lanes, through point-wise forecasting the motion of every vehicle,
- freedom to the traffic light control at every intersection, through local closed-loop operation. (That means a possibility of even strong deviation from a reference timing plan).

It is apparent that these guidelines contain substantial innovations with respect to the conventional concepts of traffic light control. In fact their implementation leads to a hierarchical-distributed system which, in the specific case of the "Progetto Torino", has been set up with a two level structure. Correspondingly the tasks are subdivided into central (at the higher level: area) and into local ones (at the lower level: zone).

THE DYNAMIC TRAFFIC MODEL

The urban traffic is described by three dynamic models:
- the macroscopic model of private traffic, representing the behavior of traffic streams over the whole controlled area,
- the microscopic model of private traffic, giving a detailed representation of the private traffic at each intersection,
- the public traffic model which describes in detail the behavior of every vehicle of the lines with priority.

The macroscopic model of private traffic

Description

The major directions of traffic are here represented as interconnected "storage units" of vehicles (Fig. 1). Actually several intersections with traffic lights correspond to each storage.
The model, in discrete-time, is composed of two parts:

a - The vehicle law of motion.

Assumption is made that for each storage the relationship be known between number of vehicles present during the i-th time interval and number of vehicles, which during the same time interval can move to the successive storage. Two parameters are in evidence: the first (α^k in what follows) is, roughly speaking, related to the average overall travel speed on the route (link) considered; the second (β^k) is related to the saturation flow.
Calling x_i^k the number of vehicles over link k during the i-th interval, and O_i^k the number of vehicles which can leave the same link, then:

$$O_i^k = f^k(x_i^k,\ \alpha_i^k,\ \beta_i^k).$$

b - The vehicle propagation law.

It is assumed that the private traffic be made up of:
- the traffic "origin-destination", described by its major components, for every one of which the sequence of network crossings is known.
  We assume that for each major component the rate of change of traffic at the origin be known or detectable in real time;
- the "distributed" traffic, grouping all traffic components which can not be modelled according to the previous description. The only hypothesis made is that its dynamics be slow enough.

Use of the model

The macroscopic model is used for:
- recognition of traffic perturbations at their origin, which must be performed in real time, through data from detectors;
- continuous identification of parameters characterizing the traffic, which is also performed starting from detector data. However the results of identification algorithms are updated daily.

Finally this model is used for the area control algorithms.

The microscopic model of private traffic

Description

The microscopic model describes every intersection with traffic lights, as discrete dynamic system. An intersection is regarded as a set of links (network elements connecting adjacent intersections).
The "state" of the intersection is given by the vector of the arrivals at the intersection itself of the vehicles already on the link:

$$y_i^k = \eta_i^{k,1},\ \eta_{i+1}^{k,1},\ \ldots\ldots\ldots\ \eta_{i+L}^{k,j},\ldots\ldots\ldots$$

where: $\eta_{i+L}^{k,j}$ represents the number of vehicles already on link j of intersection k and at a distance from the intersection equal to L time intervals.

The propagation law is deterministic and known as function of the traffic lights state at the intersection

$$y^k_{i+1} = f(y^k_i,\ c^k_i,\ y^m_i,\ c^m_i,\ y^n_i\ ....)$$

where: c^k_i is a suitable vector representing the state of the traffic lights at the intersection; y^m_i, c^m_i, y^n_i etc. refer to intersections m, n etc. adjacent to intersection k.

This model depends upon some parameters (typically: "percentage of turns", "average overall travel speed", "saturation flow").

Use of the model

The model now described is used for:

- local control
- continuous identification of the above mentioned parameters
- diagnosis of anomalous traffic or plant conditions.

The public traffic model

The public traffic model is deterministic as regards the vehicle generation (the departure time table of each vehicle is assumed to be known and enforced) and the routes of each trip. It is stochastic instead as to travel times.

Hypothesis is made that the travel time of a vehicle for each section can be subdivided into three components:

- free travel time
- waiting time at stop or station
- lost time at intersection with traffic lights.

The third component is subject to the system control whereas it is assumed that the first two (and in particular the second one) can be described by a stochastic process - non stationary in the expected value - whose expected value has a slow variation with respect both to the absolute time (time-of-day) as well as to the trip.

This model is used on-line:

- to forecast - through bidimensional linear filtering - the individual time components of each section,
- to diagnose automatically the disturbances.

THE CONTROL

Generalities

The control philosophy, strictly connected with the models previously described, aims at minimizing the total time lost be private vehicles during their trips, subject to the constraint that public vehicles of lines with priority shall not be stopped at intersections with traffic lights. That must occur also in compliance with the safety constraints on sequence as well as on minimum and maximum length of traffic light phases.

Since the phenomenon is under the influence of strong perturbations both local and global and the major constraint is based, as we saw, on stochastic variables, a closed-loop control is required. Furthermore, because of the problem size, suitable decomposition methods must be applied.

Hence the control system follows the general scheme already described with two hierarchical levels:

- at the higher level the area control: based upon information which can be obtained from the area model, it transmits, to the lower level, control rules such to optimize the overall performance,
- at the lower level: every one of the many local controllers acts on its own local model, using at its best the information coming from the higher level.

The area control

The goal of the area control is

$$\min_{\alpha^k_i,\ \beta^k_i,} \sum_i \sum_k p^k(x^k_i,\ \alpha^k_i,\ \beta^k_i)$$

where x^k_i are interrelated as previously described in the area model and realizability constraints exist on variables α^k, β^k.

The cost associated with each storage unit is usually linear. However in some cases it might be useful for the calculations to insert quadratic terms in $p(\cdot)$. The sum with respect to time (i) is extended over an interval for which comparatively sure information can be obtained (from half an hour to one hour).

The optimization algorithm must give results continuously: therefore it is implemented through a feasible method, in which partial results are usable in any case. Besides, when traffic conditions change, iterations are not ended, but it is simply modified the propagation model and the previous results are used as starting data.

Finally the area control transforms the results α^k (which-recall-correspond to the average travel speeds) and β^k(which correspond to flows to be assigned to the routes) in suitable reference rules for the local controllers (roughly speaking into a "reference plan" and into weights to be assigned to the individual components of local cost functionals).

The local control

The local control is implemented through an open-loop feedback strategy.

In fact the constraint "priority to some public vehicles" sets the strict requirement to control in closed loop the traffic lights regulators, but the safety constraints on sequence as well as on minimum and maximum phase lenghts require to evaluate the consequence of each choice over a long enough time.

At every decision instant, the local controller k sets the goal

$$\min_{c_i^k} \sum_i l^k (y_i^k, c_i^k)$$

where the sum is extended over an interval of the order of few minutes (typically 2 or 3 minutes). In the functional l^k are taken into account (with weights dynamically assigned by the area controller):

- the time lost by the vehicles at intersection k,
- the number of vehicle stops at intersection k,
- the maximum queues at intersection k,
- the same parameters, but seen at the adjacent intersections as caused by the propagation after intersection k (this term is inserted to guarantee the strong interaction between local controllers)
- the correspondence of decisions on state c^k with decisions given as reference by the area controller (in order to be able to change dynamically the interaction level from above).

The public vehicles with priority are seen as constraints for the optimization problem.

The decision instants are spaced in time few seconds (typically 5-6 seconds) from each other, to react promptly to fast perturbations on public vehicles. Clearly in order to make the control reaily operating in closed loop, the local controllers must act on the basis of "observed" and not simply forecast state vectors y^k. With each controller, a state observer is associated, that on the basis of measurements from local detectors as well as of information on the policies of the controller itself (c^k) and of the adjacent controllers constructs dynamically an estimate of the state vectors (y^k).

The structure of the control system

According to the previous description the most suitable structure of the control system is the following:

- a network of local controllers, mutually connected in such a way as to reproduce the topology of connections between intersections (Fig. 2);
- a dense network of public and private traffic detectors placed in such a way as to give the state estimation (Fig. 3);
- an area controller connected with the network of local controllers (Fig. 2).

THE "PROGETTO TORINO"

General structure

The basic tasks of the major system elements are briefly described with reference to Fig. 4.

The "private vehicle detectors" detect every single vehicle moving on the streets, sensing across all lanes. The data are first checked and processed at local (zone) level, then sent to the central (area) control.

The "public vehicle detectors" are installed for sensing and identifying the public vehicles of the priority lines. The significant time instants to be determined for each of those vehicles are:

- the entering time into a link,
- the arrival time at a station (stop),
- the departure time from a station (stop).

The "actuators of traffic lights" are very simple devices. They do not take any decision and, as a rule, they are triggered by the controllers. Only in case no triggering comes, the actuator operates automatically following a predetermined sequence of phases.

The "local (zone) controller" is a microcomputer, with modular structure, able to collect data from detectors, to process them, to exchange information with other local controllers and with the central (area) controller.

It is equipped with interfaces to: light actuators, detectors (of private and public vehicles) and data transmission lines.

The "central (area) controller" is a minicomputer with high processing capacity. Because of its tasks, it must have a very fast floating point arithmetic unit, a large core memory, a fast access mass memory, two interactive terminals (one with line printer and the other one with video display).

Like the local controllers, it is equipped with interfaces to data transmission lines. Reliability reasons recommend a multiprocessor structure.

Numerical data about the first realization

For the experimental realization completed by end 1983 it has been chosen an area of Torino (predominantly industrial town with a population of about 1.1 millions) close to the center (Fig. 5), at both sides of a 6 km long section of the street-car line N. 10 (in both directions). This area has been subdivided into 33 zones including 43 intersections with traffic lights and 15 km of road network. Two other street-car lines (N. 1 and N. 12) share partly the same track with N. 10 in this area.

For identification and location of public vehicles, 150 street-cars are being equipped with transmitters, and 110 detectors have been installed fixed to ground.

Other 414 detectors fixed to ground will sense the private vehicles.

Finally 25 stations along the line section considered are provided with information displays for waiting passengers.

Reliability aspects

Considerable research effort aimed at obtaining a reliable design. The distributed structure allows to include conveniently in the system some features which favour and increase realiability, like:

- efficient diagnostics of the traffic and of the system itself,
- high redundancy in the realization of the essential tasks,
- high structural modularity,
- possibility of degraded operation in case of some failures.

Furthermore, suitable testing procedures were worked out (type tests, acceptance tests, field tests) and imposed on the system components after adapting the requirements on their MTBF (mean time between failures) values.

The whole system performance has been evaluated in terms of two "unavailability figures", one for each system's objective i.e. for private as well as for public traffic.

That was necessary because the system presents intermediate degraded behaviors between 0 and 1 which are originated by different causes for private or for public traffic.

From the simulation carried out, the results expressed in hours per year of "system unavailability" are 25 for public and 20 for private traffic.

Expected benefits

The cost-benefit analysis of the "Progetto Torino" as a whole can not be extrapolated and generalized since many financial aspects are peculiar to this specific case. There are however two points of interest and significance also for other applications of the design concepts which have been presented.

First, for checking the algorithms and control strategies it has been used a traffic microsimulation model developed by the Istituto Elettrotecnico Nazionale "G. Ferraris", Torino as part of a C.N.R. Special Project on Energy Research. It was possible to compare during 30 minutes real-time three different situations referred to the area of the Progetto Torino:

A - the original existing situation i.e. a control system without co-ordination of traffic lights.

B - a control system according to a pre-timed fixed plan (applying the well known "Transyt" model).

C - the hierarchical distributed control system developed as "Progetto Torino".

The results obtained for the average speed on the network were:

	Private transport	Public transport (street-car line with priority)
A)	27.7 km/h	19.5 km/h
B)	31.6 km/h (+ 14%)	19.7 km/h (+ 1%)
C)	31.9 km/h (+ 15%)	24.9 km/h (+28%)

A benefit for both types of transport has therefore to be ecpected.

A second remark concerns the energy consumption of private vehicles. The results of an extensive experimental program carried out in Torino confirm the validity of a simple mathematical model based on a linear relationship between distance covered, time spent and fuel consumed. Distances covered and corresponding times have been derived through the microsimulation model mentioned before.

The average composition of the car fleet in Torino has been estimated and finally the energy savings which should be obtained through the "Progetto Torino" with regard to the present situation came out of the order of 6%.

CONCLUSIONS

The design concepts outlined in this paper will be checked in field through the "Progetto Torino". Its installation has been completed by end 1983 according to plans. The calibration procedures were then immediately started, with the control working in open loop in order to check the observer. The first results are good: regular operation should start by mid 1984.

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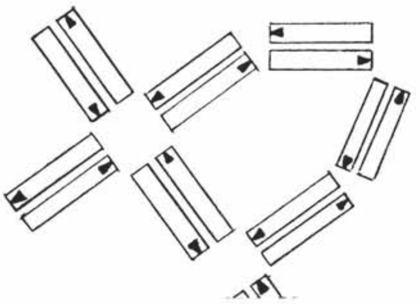

Figure 1. Storage units of vehicles.

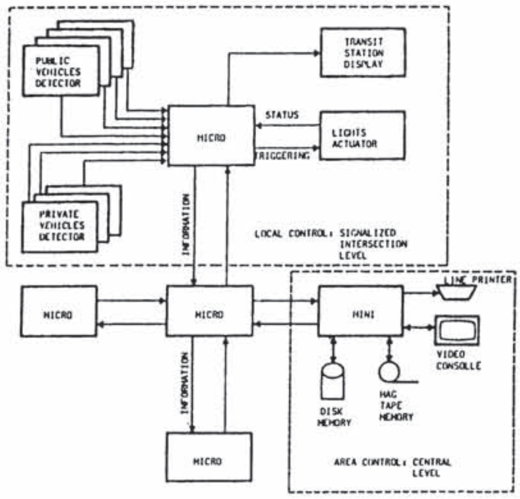

Figure 4. The "Progetto Torino" control system.

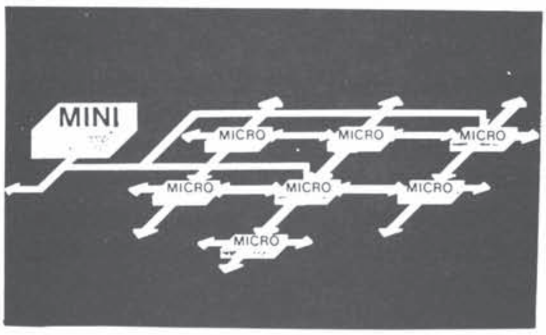

Figure 2. Area controller (Mini) and network of local controllers (Micros).

Figure 5. Area of the first realization of the "Progetto Torino".

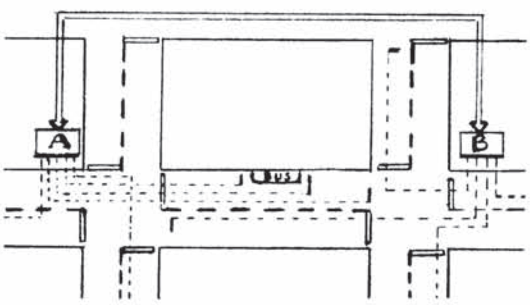

Figure 3. Location of public and private traffic detectors.