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# TRANSPORTATION, AUTOMATION AND THE QUALITY OF URBAN LIVING

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## 1. Motivation

In the past, new technologies such as the wheel, the sail, the steam engine, the electric motor, the internal combustion engine, the jet engine and others (cf. Figure 1) have created breakthroughs to entirely new modes of transportation, resulting in well-known changes in the structure of cities and the quality of urban living. Where formerly cities grew up along waterways, railroads and streetcar lines, they now grow up along highways or around airports [3].

It seems reasonable to ask whether the fundamental new technology of our age -- modern automation and computer technology -- could contribute to a new breakthrough in urban transportation (cf. Figure 1).

This question is the subject of the present paper. Special attention is paid to the new possibilities provided by quite recently developed LSI (large scale integrated) electronic systems for control, computation and communication, especially by so-called mini-computers and microprocessors. These are characterized by high computation speed and capacity, small dimensions, great reliability, the capability of being operated in a rough environment, and low and ever decreasing costs (cf. [10, 13, 41] and Figure 1).

There obviously exists a strong motivation to consider carefully all possibilities for fundamental changes in the present urban transportation systems, since increasing misuse of a special transportation technology, that of automobiles and highway systems, has already caused tremendous difficulties in several countries [2, 5, 8, 11, 15,

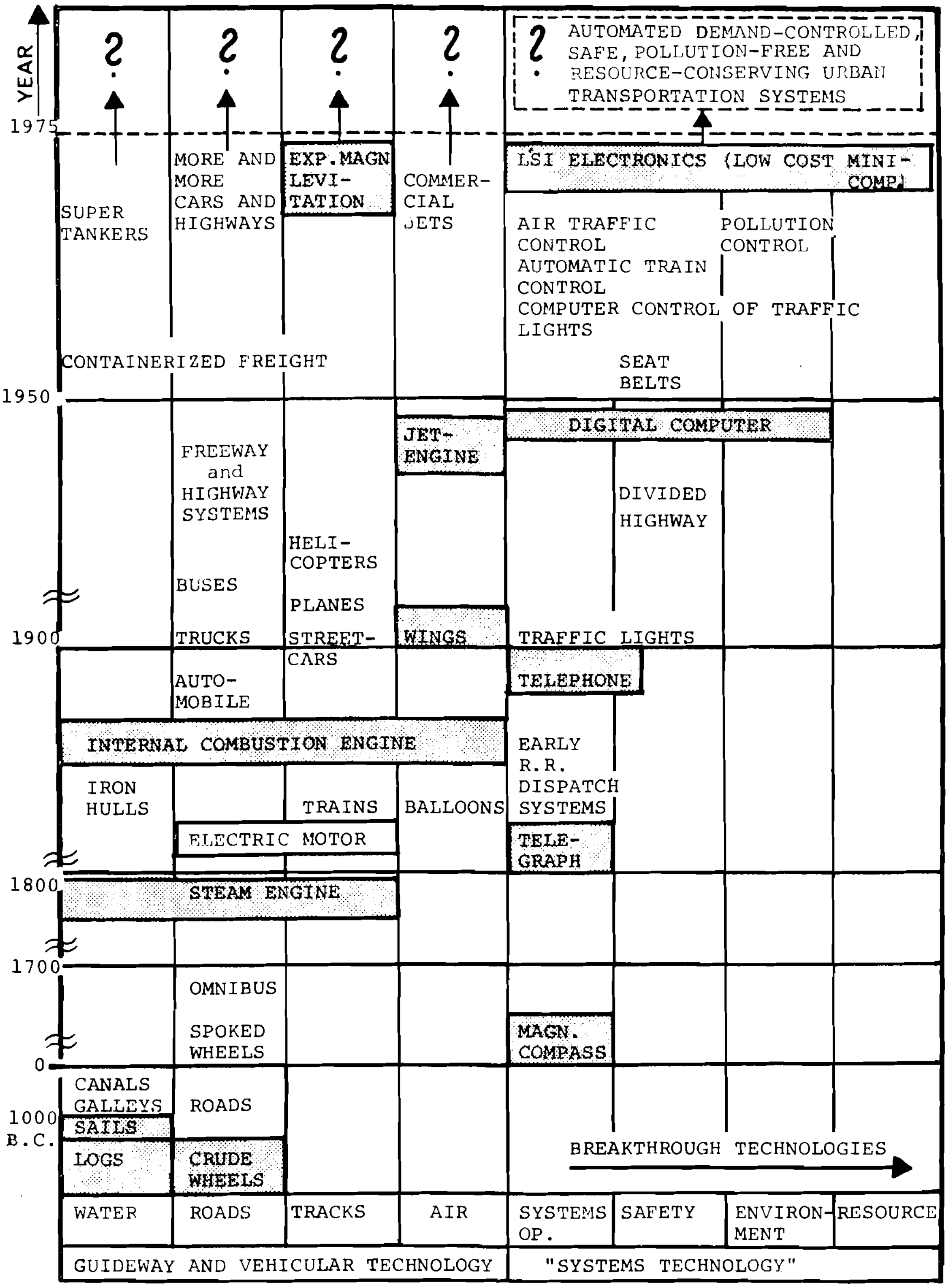



FIG. 1: New technologies that have or probably will create breakthroughs to new modes of transportation resulting in essential changes in urban structure and the quality of urban living (cf. [3]).

17, 18, 20, 29, 46, 113] and will cause similar ones in other industrialized countries in the near future [6].

Compared with railroads or streetcar lines, the highway seemed to provide the essential advantage that it can go anywhere if the city wants it. For several decades it was believed -- especially in the U.S.A. -- that the more highways one builds, the better life would be [3]. During the last few years the truth began to dawn, that such random growth can lead to undesirable results of various kinds; bad urban form getting worse rapidly; congestion, accidents and fatalities; air and noise pollution; ineffective use of limited resources in terms of energy and land. This has already led in some places to a real degradation in the quality of urban living, which can be traced directly to a misuse of technology, the highway transportation system [3].

But what could be the role of automation in this scenario? This new technology offers the first possibility to change from an extensive development of transportation systems to an intensive one. What does that mean? Any past development of transportation systems has been achieved by brute force -- more and bigger traffic areas using more concrete, stronger engines, more and more vehicles -- at higher cost. Obviously it is in principle impossible to continue in this manner in more and more cities. The digital computer and the related automation technology provide a promising alternative. The extensive use of automation in urban transportation systems can lead to an entirely new level of transportation service, an increase in capacity and a decrease in operating costs (including a decreased impact on energy reserves and environment), as well as to new standards for safety.

It is reasonable to assume that this new systems technology could give an impulse to better urban transportation similar to that given by the magnetic compass to the extension of the sea transport from the local to the global arena, or by the telegraph and telephone to the development of nationwide railway dispatching systems (cf. Figure 1). This assumption will be considered in more detail in the following. A brief summary of the fundamental concepts proposed for the solution of urban traffic problems is presented first.

## 2. Concepts for the Reduction of Urban Traffic Problems

### 2.1 The Problems

The social, economic and other effects of urban traffic that are particularly important to cities of IIASA's NMO countries may be divided into those influencing safety, mobility, resources and environment (cf. Figure 2 and [2, 5, 6, 11, 17, 18, 20, 46]).

(i) Traffic safety (accidents and fatalities): Figure 3 illustrates that there exists a correlation between the number of human beings killed in accidents and the number of private cars. In 1970, about 56,000 fatalities occurred in the U.S.A. and 19,000 in the Federal Republic of Germany (FRG) [8, 18, 19]. The economic losses caused by street accidents in the FRG have been estimated to be about $1 billion per annum. In other countries, especially in the Eastern European ones including the Soviet Union, such a serious situation is at present non-existent. However, as one can see from the curve in Figure 3 for Berlin, the number of motor cars in cities is rapidly increasing also in these countries, and -- with a certain delay -- similar difficulties can be expected if future development is not analyzed and controlled carefully. Joint activities concerning the increase of traffic safety have therefore been started recently [6].

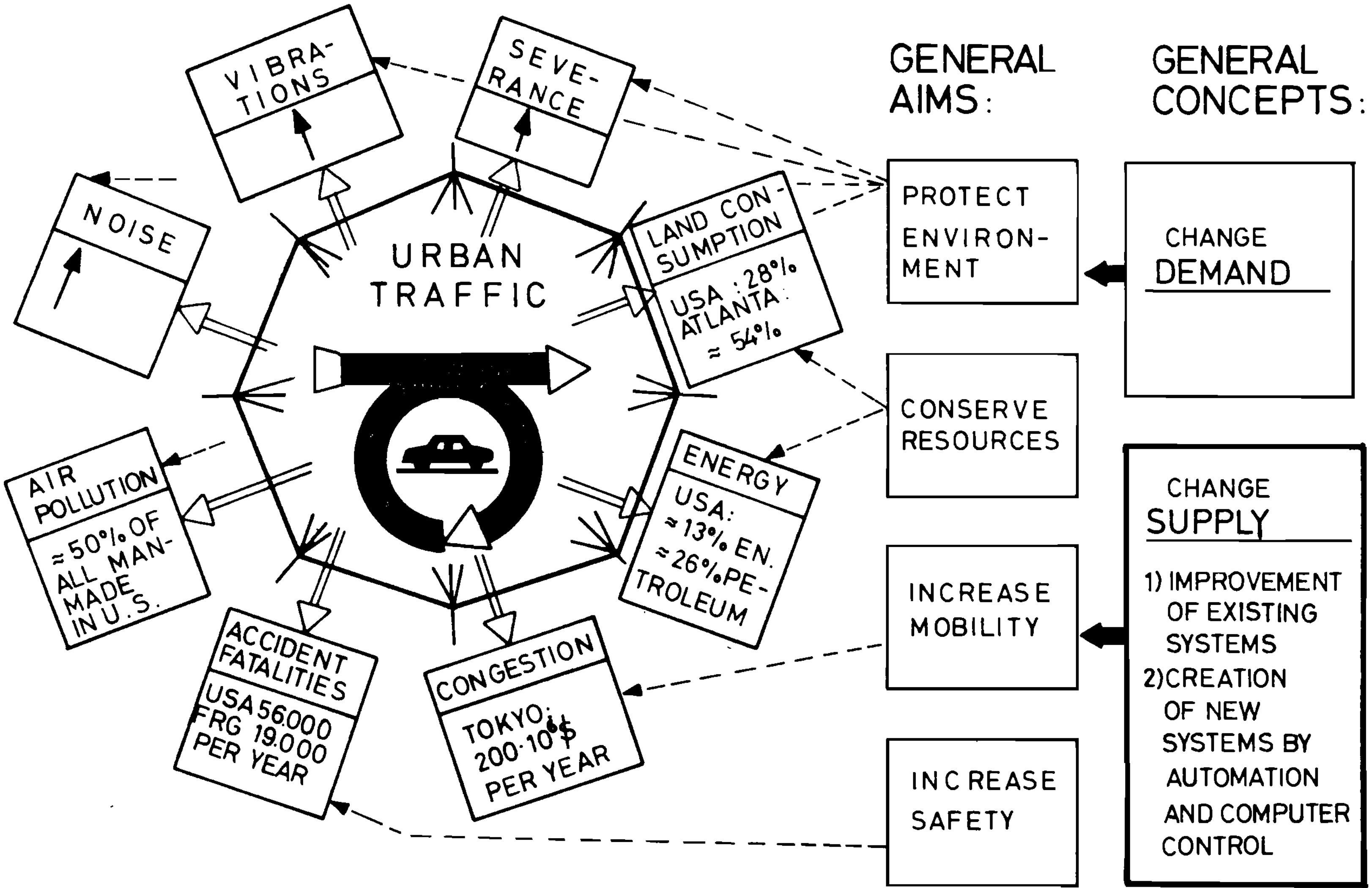



FIG. 2: URBAN TRAFFIC PROBLEMS AND PROPOSALS FOR THEIR SOLUTION.

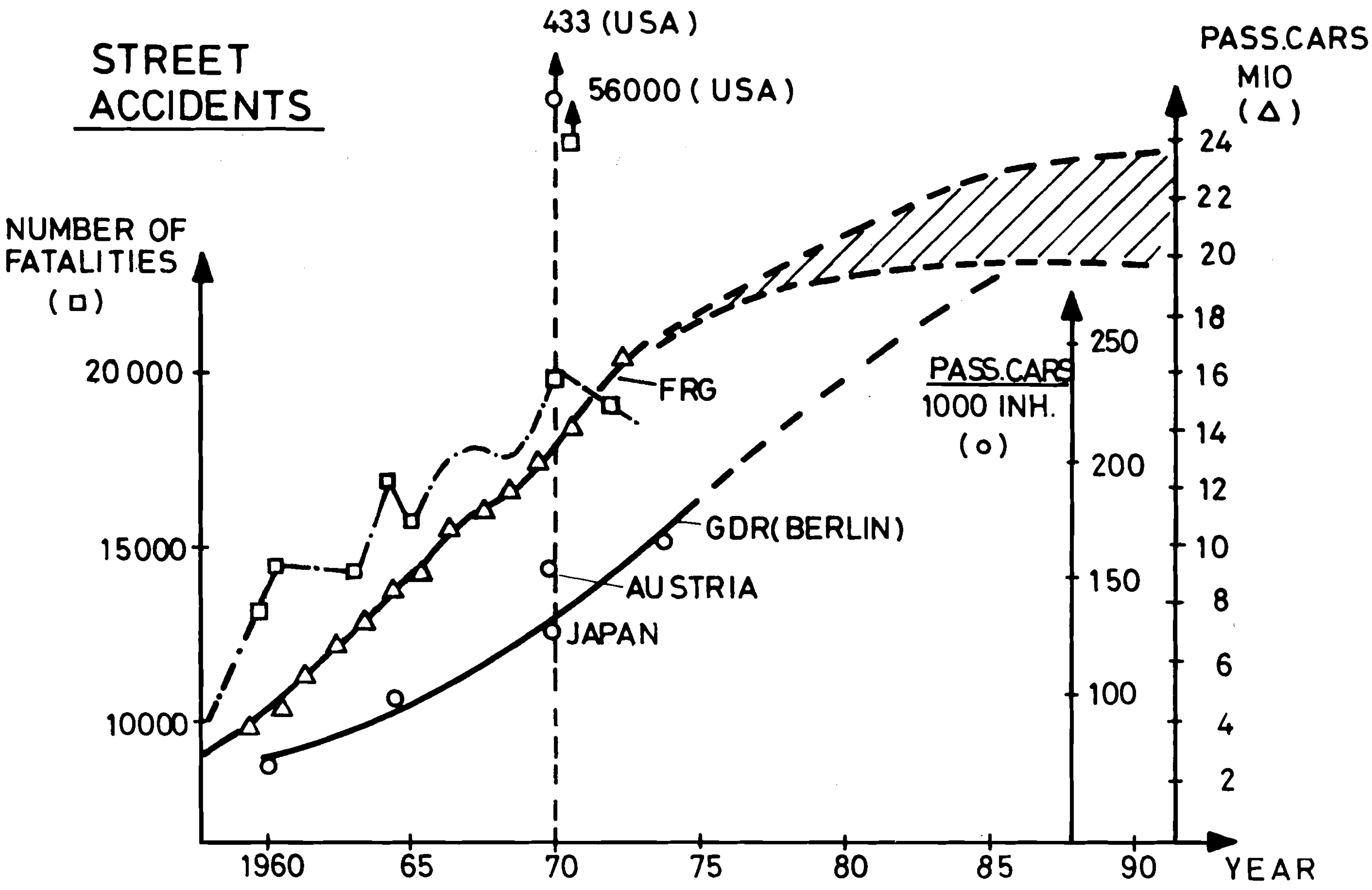



FIG. 3 : DEVELOPMENT OF NUMBER OF CARS AND FATALITIES. (cf.[8,18,19])

(ii) Mobility: Traffic congestion is another serious problem caused by increasing use of motor cars in cities. It has been estimated that the time losses caused by congestion in Paris are approximately equal to the daily working time of a city with 100,000 inhabitants. The Road Research Laboratory [48] has found that in Britain the loss to the community from delays in a city with about 100 intersections is in the order of £4 million per year. This value does not take into account the fact that traffic congestion also results in a remarkable increase in air pollution and noise levels. For Tokyo it has been estimated that the overall losses caused by inefficient traffic flows through the main 268 intersections amount to 57 billion yen, i.e. about $200 million, annually [58].

(iii) Endangering of the urban environment: Increasing levels of air pollution, noise and vibration of buildings, as well as the severance of the urban area by more and bigger freeways and arterial streets, is the third negative factor in the increased use of the automobile [8, 20]. Approximately 50% of all manmade air pollution in U.S. cities is produced by motor cars. These environmental problems motivate the migration of people from cities to suburban areas, thus creating more traffic.

(iv) Resources: The fourth main problem concerns ineffective consumption of resources, i.e. energy and land [8, 20]. Of all energy consumed in the U.S.A., about 13% is used for motor cars, i.e. approximately 26% of all petroleum. Twenty-eight percent of the areas in the U.S. cities is devoted to vehicles. In Atlanta, 54% of the downtown area is reserved for parking and driving, which is still insufficient.

## 2.2 The Concepts

Now let us turn to the question: What solutions can be offered for these problems which vastly influence the quality of urban living? The general aim must be to reorganize existing traffic systems and to design new ones in such a way that (cf. Figure 2):

- the urban environment is protected;
- the resources, in terms of energy and land, are conserved as much as possible;
- the safety is increased;
- the mobility is increased.

The gap between automobile transportation demand and supply can be reduced only by means of a complex policy to control (cf. Figure 4 and [58]):

- the transportation demand changing in time and space;
- the transportation supply characterized by the capacity of roads, parking lots, and other transport facilities.

In developing such control policies the time span between their formulation and the realization benefits from them must be considered carefully; that is, a distinction between short-term and long-term policies is necessary.

### 2.2.1 Control of Demand (cf. Figure 4)

(i) Long-term strategies: Automobile transportation demands arise and are concentrated as a result of the configuration of urban land use and activities. The first level of policy to control demand, therefore, is to implement controls on the *spatial distribution* of origin-destination demands generated in the city. These would include measures such as urban redevelopment, new town construction, factory and market relocation and reorganization of other urban facilities. These measures are long-range and require sustained expenditures over long spans of time to implement.

(ii) Medium-term strategies: The second level of policy to control demand is to implement controls on demand *volumes* which, given the existing configuration of urban land use and activities, aim to reduce use and ownership of

| | CONTROL OF SUPPLY | CONTROL OF DEMAND |
|---|---|---|
| LONG TERM | CHANGING THE STRUCTURE OF THE TRANSPORTATION SYSTEM (e.g. creation of new systems) | CHANGING THE SPATIAL DISTRIBUTION OF DEMAND |
| TIME SPAN (to accomplish results) | CHANGING THE PHYSICAL CAPACITY OF THE TRANSPORTATION SYSTEM (e.g. enlargement of traffic areas) | CHANGING DEMAND VOLUMES (by controlling automobile use and ownership) |
| SHORT TERM | CHANGING (IMPROVING) THE OPERATION OF EXISTING TRANSPORTATION SYSTEMS | CHANGING THE TIME DISTRIBUTION OF DEMAND |

FIG. 4: LONG AND SHORT TERM TRANSPORTATION SUPPLY AND DEMAND POLICIES (cf. [58]).

the automobile. Such controls could take the form of increased automobile taxes, stricter requirements for automobile ownership, curbs on driving into the central business district, increased gasoline taxes, etc. In addition to these steps to discourage driving, measures could be taken to encourage people to use the telephone instead of travelling and to use public transportation. Unfortunately existing public transportation systems cannot, in many cases, provide an acceptable alternative to private cars. This is due to their lower attractivity and the fact that busses and streetcars often operate in the same traffic areas as the private cars, so that their travelling speeds decrease as do those of private cars.

A sociological study carried out by INFAS (cf. Figure 5 and [134]) illustrated that the following three criteria are the most significant in the choice of transportation mode:

(1) travel time,

(2) convenience,

(3) independence with respect to departure time and destination.

Most drivers prefer using a private car, even though it is more expensive and less safe than public transportation (cf. Figure 5).

(iii) Short-term strategies: The third level of policy to control demand is to institute measures aimed at controlling the *time distribution* of transport demands in the city -- for example, those generated by commuting to work and school. In general, traffic congestion is caused merely by excessive concentration of demand. By controlling the time distribution of demand, therefore, a better balance between supply and demand can be achieved. Included in this catagory are measures such as staggering work and school hours.

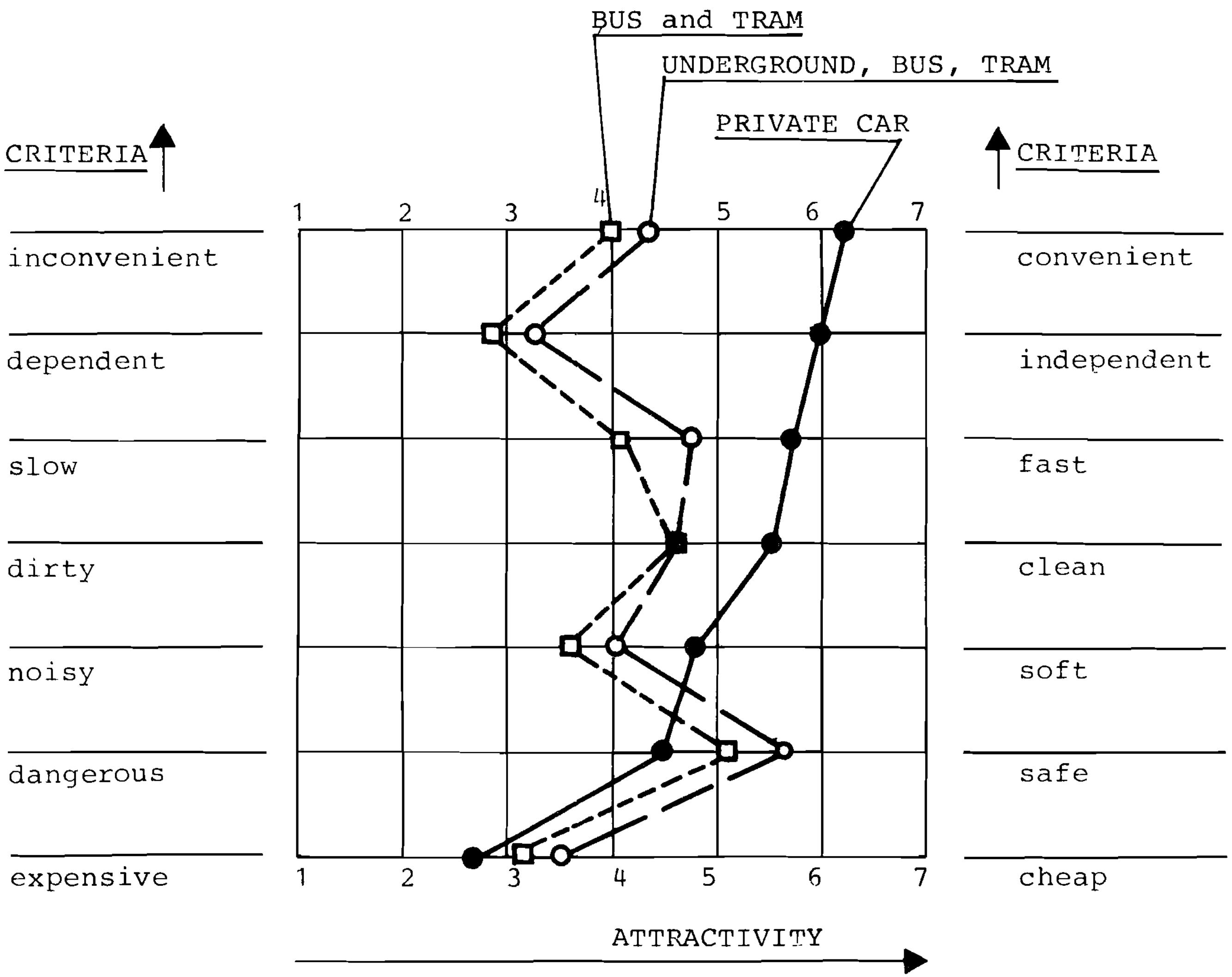



FIG. 5: RESULTS OF AN INQUIRY CONCERNING THE ATTRACTIVITY OF PRIVATE CAR AND PUBLIC TRANSPORTATION USE CARRIED OUT BY 'INFAS' IN HAMBURG, BREMEN, DORTMUND IN 1968 (248 DRIVERS) (cf. [134]).

### 2.2.2 Control of Supply (cf. Figure 4)

(i) Long-term strategies: The first and most basic level of policy to control the supply of transportation concerns the *structure* of the system, e.g. road networks, subway lines, etc. By constructing new roads, bypasses, overpasses and parking lots and by abolishing old roads, it is possible, for example, to change the overall structure of the road network and thereby the flow of traffic over it. On the other hand the increased construction of more and bigger highways alone will not present an acceptable solution: more highways produce additional traffic, land consumption and endangering of the urban environment will continue, and in principle it will be impossible to build traffic areas sufficient by large for the increasing number of cars in cities. This is especially true for most of the European cities which have grown up historically. Moreover, as mentioned under 2.2.1 (cf. Figure 5), changing the structure of existing modes of public transportation will probably not lead to reduced automobile traffic demand. Therefore one basic long-term policy consists in the development of entirely new (automated, demand-oriented) public transportation systems (cf. Section 5).

(ii) Medium-term strategies: The second level of policy to control the supply of automobile transportation concerns the physical *capacity* of the system to link origin and destination points. Included in this category are measures which alter the capacity of the road network, such as widening roads and enlarging parking facilities.

(iii) Short-term strategies: The third level of policy to control supply concerns the *operation* of the different parts of the transportation system as well as of the whole system. Included in this category are measures which restrict or limit the use of a link or its connection with other links, e.g. establishing one-way roads, speed limits, etc. Moreover, the optimization of system operation by automation and computer control belongs to this level. Policies of this kind focus on short time units of weeks, months or even a few years.

## 2.3 Towards Computerized Traffic Control

It is quite obvious that the feasibility of the supply and demand control policies summarized here depends on conditions differing from country to country. For example, measures of the first (long-term) levels mentioned above aim at fundamentally restructuring transportation supply and demand by changing the configuration of urban land use and activities, and thus will require many years to formulate, implement and realize. It is equally difficult to restructure transportation demand, since demand is closely related to the pattern of land use, the location of urban functions, and social customs and practices. While working toward long-term policies, therefore, it is important to implement measures which will help to close the gap between supply and demand by short-term strategies, i.e. improving operation of existing systems and changing the time distribution of demand. One promising measure consists in changing operation of the urban highway system in such a manner that the capacity of the road network as far as possible is automatically adapted to the automobile transportation demand changing in time and space.

A possibility for dynamically changing the capacity of road network has now been created by traffic-responsive computer control of the traffic flow. This application area of modern automation and computer technology, which is fast developing, is the subject of Section 3. The possibilities for improving existing public transportation by automation and computer control are considered in Section 4. In those sections we try to find answers to the question: What benefits can a city expect concerning the improvement of existing transportation systems by the implementation of computerized traffic control systems? Finally, Section 5 examines the role modern automation technology will play in the creation of new modes of transportation characterized by high adaptability of their supply to changing demand. Here the following question is of primary interest (cf. Figure 1): Will it be technologically possible to create during the next ten years or so entirely new highly automated urban transportation systems characterized by demand-oriented, safe, pollution-free and resource-conserving operation?

It is obvious that this paper cannot go in depth into all details of these topics. Its aim is rather to identify promising areas of future research work by presenting a survey of the following:

- the *concepts* developed for automation and computer control of urban transportation systems;
- the *methods* used, proposed or needed for implementation and optimal operation of these systems;
- the *results* obtained in real applications or expected from simulation studies, theoretical investigations, etc.

## 3. Computer Control of Urban Street and Freeway Traffic

In large urban areas one must distinguish the following control problems:

- surveillance and control of traffic on freeways, main roads, tunnels, etc. (freeway and road traffic control, cf. [21-37]);
- surveillance and control of vehicular traffic in urban street networks (area traffic control, cf. [38-76]);
- integration of freeway and area control systems into a traffic corridor control system [29, 46, 57, 58].

### 3.1 Freeway and Road Traffic Control

If the traffic variables volume, density, and mean speed exceed certain critical values, then the danger of congestion and accidents increases rapidly, and implementation of an automated surveillance and control system for the freeway becomes necessary. These critical values are given by the following relations [29]:

| | | |
|---|---|---|
| Volume | $\geq$ | 3,000 vehicles per hour per two lanes |
| Density | $\geq$ | 50 vehicles per km per two lanes |
| Speed | $\leq$ | 60 km/hour. |

It is interesting to note that existing control concepts can be regarded as levels of an integrated hierarchically structured control systems (cf. Figure 6). These levels are:

(1) optimal guidance of main traffic streams through a network of freeways and surface streets [21, 23, 24, 27, 29, 33, 35];

(2) optimal control of traffic flow on freeways and at access points [24, 25, 26, 27, 28, 28a, 29, 30, 32, 33, 34, 37];

(3) optimal control of movement of individual vehicles.

### 3.1.1 Optimal Guidance of Vehicular Traffic Streams (cf. Figure 6, Level 1)

(i) The concept: The computing system will assist the driver in finding the (in some sense) best route leading from a certain origin {O} to a desired destination {D}, taking account of changing traffic conditions in different parts of the network caused e.g. by accidents, weather, maintenance operations (cf. Figure 6, Level 1). The computer is provided with information by traffic detectors, evaluates the traffic situation by certain estimation techniques, and determines the optimal routes in real time operation. These routes are shown to the drivers by changeable computer-controlled road signs located at freeway off-ramps and essential intersections of the arterial street network [21, 24, 27, 33, 35]. Several concepts propose the additional use of displays within the cars, so that drivers need not pay too much attention to the road

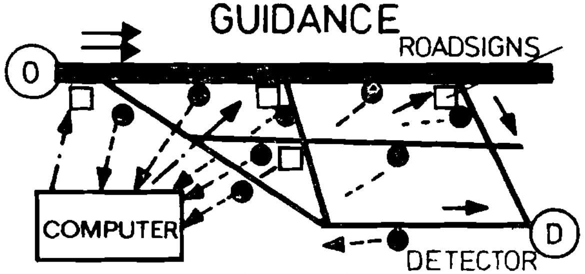
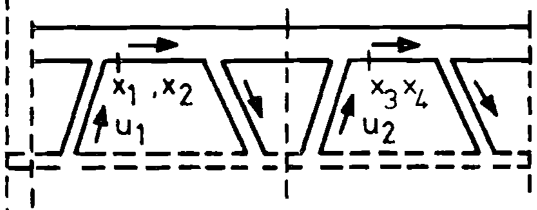
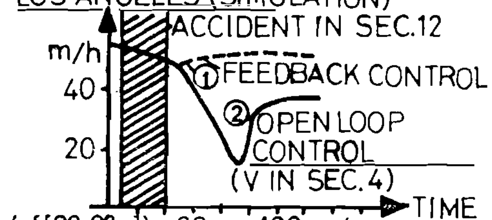
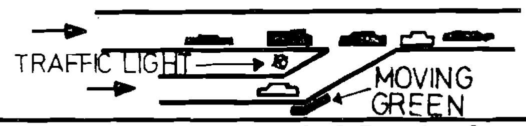
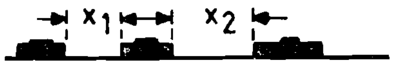
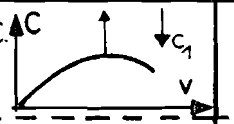
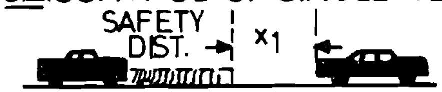
| CONCEPTS | METHODS | RESULTS |
|---|---|---|
| <u>LEVEL 1</u>: OPTIMAL TRAFFIC GUIDANCE   | IN USE: HEURISTIC METHODS<br>• <u>CRITERIA</u>: EQUAL TRAVELLING TIMES FOR DIFFERENT ROUTES<br>• <u>METHODS</u>: ESTIMATION OF TRAVELLING TIMES AND PREDICTION BY MACROSCOPIC SIMULATION MODEL | <u>FRANCE</u>: PROJECT "PORTE DU LANGUEDOC" (LYON-NIMES)<br>– 40% 70% DECREASE CONGESTION [kmh]<br>–50%...80% OF DRIVERS FOLLOWED THE CHANGEABLE SIGNS<br>[cf.(21)] |
| LEVEL 2 — <u>2.1</u>: RAMP METERING   | • <u>CRITERION</u>: MAX. THROUGHPUT<br>• TIME OF DAY (OPEN LOOP) CONTROL: MATHEMATICAL PROGRAMMING<br>• TRAFFIC RESPONSIVE (FEED BACK) CONTROL | <u>LOS ANGELES (SIMULATION)</u>   (cf[28 28a]) |
| <u>2.2</u>: MERGING CONTROL   | • <u>CRITERION</u>: SAFE AND UNDELAYED MERGING | <u>HOUSTON</u>: SPEED 30% ↑<br>CAPACITY 10% ↑<br>ACCIDENTS 30% ↓<br>(cf.[24]) |
| LEVEL 3 — <u>3.1</u>: REG. OF A STRING OF VEHICLE   | • <u>CRITERION</u>: MAX. CAPAC.<br>$c = \frac{V}{L + c_1 V + c_2 V^2}$   | SIMULATIONS ONLY<br>(cf.[34a, 36a]) |
| <u>3.2</u>: CONTROL OF SINGLE VEHICLE   | • <u>CRITERION</u>: INCREASING SAFETY AND CAPACITY | <u>JAPAN, USA, FRG</u>:<br>TEST VEHICLES |

FIG. 6: FREEWAY AND ROAD TRAFFIC CONTROL (cf.[21-37])

signs (cf. Section 3.3 and [24, 25a, 34b, 57, 58, 75]).

(ii) Results: Some systems using changeable road signs have been implemented with extraordinary success, in France during the last five years [21, 27]. Comparative before-and-after studies, carried out for the project "Ponte du Languedoc" in the area of Lyon and Nimes during the summer of 1970 and 1971 respectively, resulted in the following conclusions:

(1) traffic congestion expressed by queue length (in km) multiplied by waiting time (in hours) could be reduced by 40-70%;

(2) before starting the first experiment, it was assumed that 30% of the drivers would follow the changeable road signs; in actuality, 50 to 80% accepted the advice given to them.

This experience suggests that a sophisticated and successfully implemented route guidance system could result:

- in a remarkable reduction of travelling times;
- in the avoidance or at least reduction of traffic congestion and a decrease in the number of accidents by more equable utilization of the available traffic areas, and in an enlargement of network capacity;
- as a consequence, in a decrease in the level of noise and air pollution.

(iii) Methodology: The methodology used in the French system is relatively simple. As a control criterion, the requirement for nearly equal travelling times through different alternative routes is considered useful. The control algorithm contains two essential parts:

(1) estimation of travelling times in different links of the network using detector data;

(2) prediction of traffic conditions during the next time interval, i.e. traffic forecasting for a time period of about 5 to 10 minutes. This has been done by a macroscopic traffic flow simulation model [21].

It seems that these problems are a fruitful field for the application of modern methods of parameter and state estimation, e.g. of Kalman filters [31, 36].

### 3.1.2 Freeway Traffic Flow Control

#### 3.1.2.1 Ramp metering (cf. Figure 6 - Level 2.1)

(i) The concept: The aim of this control system consists in maintaining traffic demand along all parts of the freeway below the critical level by restricting freeway access using signal lights at the entrance ramps or the neighboring surface streets. Most successfully implemented systems use a bang-bang control policy, i.e. the ramp is closed if there is congestion in the flow direction [24, 26, 30]. A control system which continually changes the inflow rates depending on traffic flow by changing the green times of the traffic light at the on-ramps is being developed.

(ii) Methodology: The number of cars $u_1$, $u_2$, $u_3$ entering ramps 1, 2, 3... of the freeway per time interval may be introduced as control variables (cf. Figure 6). The state of the freeway is characterized by mean speeds $x_1$, $x_3$... of the traffic flow in these sections and the corresponding traffic densities, $x_2$, $x_4$..., i.e. the number of cars in them (cf. Figure 6, Level 2.1).

Two different control problems can be distinguished:

- *time of day (open loop) control*, in which signal time plans are computed for the traffic lights at entrance ramps using given traffic demand patterns obtained from historical data. One obtains nominal values of the control variables $u_i$ and the state variables $x_i$, speed and density, which will ensure a maximum of traffic throughput. This is, of course, no longer true if disturbances, e.g. an accident occur. For this situation, it has been proposed to use
- *a feedback control system* which minimizes deviations between the nominal and actual values; i.e. these deviations are now considered as control and state variables and described by $u_i$ and $x_i$ respectively in Figure 6, Level 2.1.

This has the advantage that a linear state equation

$$\dot{\underline{x}} = (A)\ \underline{x} + (B)\ \underline{u} \tag{1}$$

can be used. Here $\underline{x}$ represents the state vector

$$\underline{x}^T = (x_1,\ldots,x_n) \tag{2}$$

which describes the deviations of the nominal values of the mean traffic speeds and densities in the freeway sections $i = 1(1)n/2$, and $\underline{u}$ characterizes the control vector

$$\underline{u}^T = (u_1,\ldots,u_{n/2}) \tag{3}$$

which describes the deviations of the nominal traffic volumes entering the freeway via the entrance ramps $k = 1(1)n/2$. The matrices (A) $(n \times n)$ and (B) $(n \times \frac{n}{2})$ are constant if one assumes stationary conditions (cf. [28, 28a] for more details). If one accepts, as an optimality criterion, the minimization of the quadratic cost functional

$$I(\underline{u}) = \int_0^\infty \left\{\underline{x}^T(t)\ (Q)\ \underline{x}(t) + \underline{u}^T(t)\ (R)\ \underline{u}(t)\right\} dt \quad , \tag{4}$$

i.e. the minimization of the integral over the deviations from the nominal values weighted by the positive, definite and semi-definite cost matrices (R) and (Q) respectively, then the optimal control vector $\underline{u}^*(t)$ can be obtained in feedback form by

$$\underline{u}^*(t) = -(R)^{-1}\ (B)^T\ (P)\ \underline{x}(t) = (K)\ \underline{x}(t) \quad , \tag{5}$$

where (P) is the unique symmetric positive-definite solution of the matrix Riccati equation

$$(P)\ (A) + (A)^T\ (P) - (P)(B)(R)^{-1}\ (B)^T\ (P) + (Q) = 0\ . \tag{6}$$

The regulator matrix

$$(K) = -(R)^{-1}\ (B)^T\ (P) \tag{7}$$

permits determination of the control variables $u_i$ by means of the state variables $x_i$ (cf. equation (5)). Unfortunately, it is not possible to take measurements for the state variables, namely for:

- the density deviations (in vehicles per mile) and
- the mean speed deviations (in miles per hour per length of the freeway section) directly.

By means of traffic detectors, one can measure only at single points, i.e. at the beginning and the end of a freeway section (cf. Figure 6, Level 2.1):

- the traffic volume (in vehicles per hour)
- the mean speeds (in miles per hour).

Therefore, one has to deal with a state estimation problem, i.e. applying a suitable estimation procedure to determine the state variables with sufficient accuracy using stochastically disturbed measurements of the volumes and speeds. Only a few authors have tried to apply modern estimation techniques such as the extended Kalman filter to this problem (cf. Nahi [31], and Szeto and Gazis [36]).

(iii) Results: There are several systems in operation which use fixed time metering or even bang-bang control, where the entrance ramp is closed for a certain period of time [24, 26, 30]. Specially designed road signs suggest that drivers use another entrance ramp [24]. The development of feedback control systems is still a subject of fundamental research. Results obtained in simulation studies carried out by Isaksen and Payne [28a] suggest that such a system can lead to remarkable results in avoiding congestion caused by certain incidents, e.g. an accident. For example, in a study for the Los Angeles Freeway they assumed that a stalled vehicle was blocking one lane in section 12 for about 30 minutes (cf. Figure 6, Level 2.1), causing congestion in the previous (upstream) sections after a certain delay. Now it is interesting to note that in Section 4, for example, *for* the fixed time control system, the speed decreased to about 5 mph in 50 minutes after the incident happened, and after 60 minutes remained for some time at 20 mph below the initial speed (compare curve 2 in Figure 6). On the other hand, the feedback control system can obviously avoid such serious disturbance by optimal limiting of upstream freeway access to the point where the incident has happened (compare curve 1 in Figure 6).

There is an unusual phenomenon of freeway ramp control that is not widely understood. Ramp control improves the traffic flow not only on the freeway itself, but also on the adjacent surface streets. At first glance, this seems impossible, since reducing input rates at freeway ramps must divert some vehicles from the freeway, which one would assume could only produce congestion on the surface streets. However, as can be shown, ramp control improves the efficiency of the freeway itself, actually enabling it to carry more vehicles and resulting in a net benefit to the whole freeway corridor (cf. Ross [67a]).

#### 3.1.2.2 Freeway traffic flow control by speed limitations and other measures

Other possibilities of controlling traffic flow on a freeway consist in using changeable remote-control road signs

- to limit the speed of traffic flow if large traffic volumes exceed certain values or if weather conditions are bad,

- to forbid takeover maneuvers,
- to inform drivers about emergency situations, e.g. accidents in the flow direction.

Several systems of that kind have been successfully implemented [24, 26, 29, 30, 32, 33, 37].

3.1.3 Merging Control (cf. Figure 6, Level 2.2)

The aim of this control system is to assist drivers to merge with a high-density traffic stream and thus to increase the ramp capacity and traffic safety. The following concept is applied. If a driver enters a freeway, he must stop his car at the red traffic light at the entrance ramp until acceptable gap values and the gap speed in the traffic stream are identified by the control computer. The computer is provided with information by gap detectors. If the traffic light changes to green than the driver accelerates and meets the traffic stream at the predicted gap, assuming he uses an average value for the acceleration of his car. To reduce the difficulties which could be caused by wrong acceleration values, several systems use a band of green lamps moving with the required speed. If the driver keeps the position of his car within the limits given by the green band, he will reach the predicted gap in the traffic stream safely [24, 29].

Experimental installations have already demonstrated that the system helps reduce congestion and increases capacity. By a system of that kind, which was operating on Gulf Freeway in Houston, the number of accidents dropped by 30%, freeway speeds rose by 30%, and capacity improved by 10% [24].

3.1.4 Optimal Control of the Movement of Individual Vehicles (cf. Figure 6, Level 3)

The problems of Level 3 of the control hierarchy concern:

- distance regulation in a string of moving vehicles (cf. Figure 6, Level 3.1),

- speed and acceleration control of individual vehicles, including collision prevention systems using radar distance measuring devices inside the car (cf. Figure 6, Level 3.2).

The main aim in developing these systems is to increase traffic safety (collision prevention) and enlarge freeway capacity. The capacity C of a freeway, in vehicles per hour, depends, according to the well-known formula

$$C = \frac{V}{L + c_1 v + c_2 v^2} , \qquad (8)$$

on speed v, average car length L, and the two parameters $c_1$ and $c_2$. Here $c_2$ is inverse proportional to the maximum rate r of deceleration and $c_1$ is equal to perception plus reaction time of the driver, which can be assumed to be about 1 second. The maximum of the capacity curve (cf. Figure 6, Level 3.1) depends on $c_1$ and $c_2$. If it were possible to reduce parameter $c_1$ from 1.0 to 0.1 seconds, street capacity could be increased by 150% or more in certain speed interval; i.e. 50% more motor cars could drive on the street at the same speed. The question is how to reduce parameter $c_1$. This can be done by automatic control of the distances between individual cars. Such a system is generally considered a first step in an automated highway system which we must consider as a total-systems innovation (cf. Section 5). At present research is underway to investigate the feasibility of a semi-automatic control system in which the driver is an active systems element; the aim of the system is to assist the driver in finding an optimal (in some sense) way of smooth and safe driving in a string of vehicles.

Such a system needs a sophisticated electronic system on board for automatic distance measurement by radar, automatic computation of an optimal driving regime, and control of driver displays. The progress made in the development of LSI electronic circuits during the past few years will probably allow construction of an electronic device that is sufficiently small, reliable and cheap [10, 25a]. A more serious problem is the development of control algorithms ensuring stable and safe traffic flow of the whole vehicle string [36a] and the optimal design of the man-machine (driver-car-environment) system, especially of the driver displays [34a]. These problems are still open for fundamental research work [10, 34a, 36a].

### 3.2 Traffic Control in Urban Street Networks

The concepts proposed for computer control of vehicular traffic in an urban street network may be considered -- as in Section 3.1 of this paper -- at different levels of a hierarchically structured control system (cf. Figure 7):

(i) optimal traffic guidance,

(ii) optimal coordination of traffic lights:

- (ii.1) area traffic control,
- (ii.2) traffic control in arterial streets,
- (ii.3) traffic control at single intersections.

#### 3.2.1 Optimal Guidance of the Main Traffic Streams Through an Urban Street Network (cf. Figure 7, Level 1)

(i) The concept: This problem is obviously quite similar to that already discussed for freeway traffic control (cf. Figure 6, Level 1); that is, the computing system has to identify the (in some sense) optimal route between certain origin and destination points (e.g. between A and B in Figure 7), taking into account the real traffic situation in different parts of the network. On the other hand, it is much more complicated because of the more complex network structure and origin-destination relations.

(ii) Methodology: The methodology in use is concerned with the so-called *static assignment problem* widely used for planning purposes [61]. These methods can obviously be used

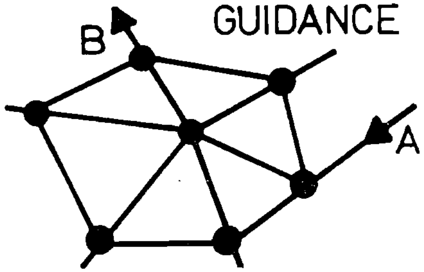
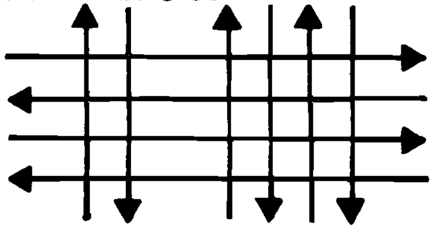
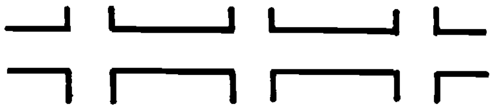
| CONCEPTS | METHODS | RESULTS |
|---|---|---|
| LEVEL 1: OPTIMAL TRAFFIC GUIDANCE<br><br> | CRITERIA: ↓ TRAVELLING TIME<br>↓ AIR POLLUTION<br>METHODS IN USE: STATIC – TRAFFIC ASSIGNMENT BY MATH. PROGRAM<br>METHODS PROPOSED: TIME OF DAY (OPEN LOOP) CONTROL<br>TRAFFIC RESPONSIVE (FEEDBACK) CONTROL | EXPECTED RESULTS:<br>• ENSURE EQUILIBRIUM (STABILITY) OF NETWORK TRAFFIC<br>• MORE EQUABLE USE OF LIMITED AREAS<br>(cf. [39, 42, 57, 58, 59, 69, 71, 75]) |
| LEVEL 2: TRAFFIC LIGHT COORDINATION<br>2.1: AREA TRAFFIC CONTROL<br><br>2.2: ARTERIAL STREET CONTROL<br><br>2.3: SINGLE INTERSECTION CONTROL<br> | CRITERIA:<br>• STOPPAGE MODE FOR LIGHT TRAFFIC<br>• DELAY — " — MEDIUM — " —<br>• CAPACITY — " — SATURATED — " —<br>• QUEUE — " — VERY DENSE TRAFFIC<br>• JAM MODE FOR CONGESTIONS<br>METHODS:<br>• TIME OF DAY (OPEN LOOP) CONTROL: MATHEMATICAL PROGRAMMING<br>• TRAFFIC RESPONSIVE SIGNAL PROGRAM SELECTION (ADAPTIVE OPEN LOOP CONTROL)<br>• TRAFFIC RESPONSIVE SIGNAL PROGRAM GENERATION OR MODIFICATION (FEEDBACK CONTROL) | TOKYO:<br>• 13% ..... 31% DECREASE OF DELAY IN SPITE OF 15% INCREASE OF VOLUME<br>• 30% DECREASE OF ACCIDENTS<br>• RUSH HOUR SPEED INCREASED FROM 8mph to 16mph<br>• 24% ----- 45% DECREASE STOPS<br>(cf. [51, 46]) |

FIG. 7: TRAFFIC CONTROL IN URBAN STREET NETWORKS

for a time-of-day open-loop control system, i.e. for precomputation of optimal routes and changing road signs in dependence on time. Little work has been done so far for developing traffic-responsive feedback control systems permitting adaptive routing in the arterial network of a large city [39].

(iii) Expected results: So far a route guidance system for a complex urban street network has not been implemented. But during the last few years there has been growing interest in such systems [42, 57, 58, 71, 75], from which the following results are expected:

- keeping the traffic in a certain equilibrium state even in the case of incidents, such as accidents, maintenance operations, stalled vehicles, etc., in certain parts of the network;
- more equitable utilization of the available traffic areas;
- decreasing levels of air pollution in endangered areas. (Work on this topic is under way in Japan as part of the general "Environmental Pollution Control Project" [11, 50, 54, 62, 68]).

Route guidance represents one of the main routes toward the integration of freeway and urban street network controls into a comprehensive automobile control system (cf. Section 3.3, and [57, 58, 75]).

3.2.2 Coordination of Traffic Lights (cf. Figure 7, Level 2)

The largest number of traffic computers are in operation for problems of traffic light coordination, i.e. for area traffic control, traffic light coordination in an arterial street, and traffic light control at single (complex) intersections (cf. [38, 40-49, 51-53, 55, 56, 60, 63-67, 69-73]).

(i) The concept: Traffic control deals with the coordination of traffic lights in a street network using a control computer or system of computers. Traffic detectors installed in the roadbed or at the roadside provide information on the real traffic situation, i.e. traffic volume, speed, etc. By means of a stored control strategy, the computer selects or generates optimal signal light programs for the traffic lights -- the length of the red-yellow-green cycles, the proportion of red to green and the offset between the beginning of the green lights at neighboring intersections.

The first control system of this kind was sucessfully implemented in Toronto in the early sixties; and by now a large number of cities all over the world have computerized traffic control systems [38, 45, 46, 47, 49, 51, 69, 72, 73]. The most advanced area traffic control system has been installed in the Tokyo metropolitan area [51]. A hierarchically structured computing system has been coupled with several thousand signalized intersections (8,000 in the final stage).

(ii) <u>Methodology</u>: The traffic control methods in use in different countries can be classified under the following headings:

- precomputation of optimal signal programs for time-of-day open-loop control using heuristic methods or methods of mathematical programming, e.g. dynamic programming;
- traffic-responsive signal program selection, i.e. adaptive open-loop control;
- traffic-responsive signal program modification and generation, i.e. feedback control

(cf. [46, 48, 64, 67, 69, 70] and Figure 7, Level 2).

For adaptive open-loop control the signal programs are stored in the computer as fixed-time programs, from which, on the basis of traffic detector information, a program is selected which corresponds to the existing traffic situation. The number of fixed-time programs stored depends on the expected number of traffic-flow fluctuations in the course of the day; the usual number lies between 10 and 20. The signal programs change at certain intervals which depend on the extent and frequency of the traffic-flow fluctuations. However, in order to avoid frequent switching over of programs, i.e. instability of the system, the measuring values have to be smoothed.

Another control system promising the greatest adaptability for changing traffic situations is signal program generation or modification, i.e. feedback control. Here only the given restrictions are stored in the computer while the actual signal programs are continuously calculated on the basis of detector information. This feedback control concept is used only in advanced systems [43, 44, 51, 52, 60, 67].

Traffic conditions change in time and space in an unpredictable manner; in complicated situations, one must thus handle the traffic control problem by a multicriterion approach. This has been done for the Tokyo system, which uses a multicriterion control strategy with feedback features. One optimal control criterion is first selected from a number of criteria, and then the system is optimized. The following criteria are used [51, 52, 60] (cf. Figure 7):

- stoppage mode for light traffic,
- delay mode for medium traffic,
- capacity mode for saturated intersections,
- queue mode for very dense traffic,
- jam mode for congested conditions.

In most existing area traffic control systems one of the first three criteria is used together with adaptive open-loop control, i.e. signal program selection. On the other hand, a feedback control structure will always be necessary for heavy traffic conditions, e.g. for the jam or queue mode criteria. This is the point at which methods of modern control theory become useful and necessary, as illustrated in Appendix A by an example for the so-called jam-mode criterion (control of a congested or oversaturated network; cf. [74, 63]). It may be said that, although a number of traffic control computers have been successfully installed, the potential advantages of their programmable flexibility remain largely unexplored by most of the traffic engineers.

(iii) Results: We will now consider what results can be obtained with systems already in operation. For the Tokyo system, a comparison of the operational experiences with the old (non-computerized) system (1969) and the new computerized one (1970) revealed that, despite a 15% increase in traffic volume during one year, delays decreased by 13 to 31% and traffic accidents by 30% [51]. The travelling speed during rush hours increased 8 mph to 16 mph.

The installation of traffic signal control systems is easier and involves less investment than any alternative measures such as, for example, building new roads or completely replanning the city center. Cost/benefit analysis performed in various cities that have installed area traffic control systems (Glasgow, West London, Madrid, Turin) indicates that the actual cost of initial installation is balanced by the benefits accumulated in the first six months of operation [46]. This result does not take into account the decrease in the number of accidents. Such a favorable ratio exceeds the most optimistic expectation of any cost/benefit analysis in public works or business enterprises by at least one order of magnitude. From the methodological point of view it is important to emphasize that the cost/benefit relation is highly dependent on the efficiency of the methodology used, i.e. the control strategy.

In spite of these successes, several problems remain unsolved and new problems are still occurring -- problems concerning risk evaluation (in the case of destroying a control center coupled with thousands of intersections) [51], reliability and centralization or decentralization of computing power, e.g. using mini-computers or even micro-processes [41, 44].

### 3.3 Integrated Urban Automobile Traffic Control Systems

One can observe a recent trend to integrate area traffic and freeway traffic control systems into a comprehensive urban automobile traffic control and information system [57, 58, 75, 76].

(i) The concept: One main concern of such a system is to handle the whole urban automobile traffic in a coordinated manner. An essential feature is the improvement of communication links between the drivers and the control center. The following are basic functions of control and information systems [58].

- *Route guidance:* the most important task is to integrate the freeway and urban street network guidance systems described in Sections 3.1.1 and 3.2.1 respectively, by means of a comprehensive information exchange between the control center and the individual automobiles. The following concept has been proposed [58] (cf. Figure 9):

  At the start of a trip, the driver puts the code number of his destination picked from a map into a keyboard mounted in the vehicle. This number is transmitted by a vehicle antenna and an inductive loop embedded into the street surface to a roadside unit, probably a micro-processor, which is connected with the central computation system. The micro-processor is informed by the central system about the optimal route and transmits that route, via the loop antenna, to the vehicle where it is shown on a driver display. The driver thus receives the instructions to turn right, turn left or proceed straight (cf. Figure 9). By reacting appropriately, he avoids areas of traffic congestion and reaches his desired destination by a (in a certain sense) optimum route (cf. also Sections 3.1.1 and 3.2.1).

- *Driving information:* advance information on speed limits, stop signs, and other road regulations is transmitted from the roadside units and visually displayed to drivers. Moreover, the system monitors individual vehicles and issues a warning to the driver if a breach of driving regulations occurs. In this way the system helps to prevent accidents due to driver carelessness.

- *Public-service vehicle priority:* traffic signals at major intersections are controlled such as to give police cars, ambulances, busses and other public-service vehicles priority to pass through the intersection. One essential feature is therefore coordination with public transportation systems (cf. Section 4).

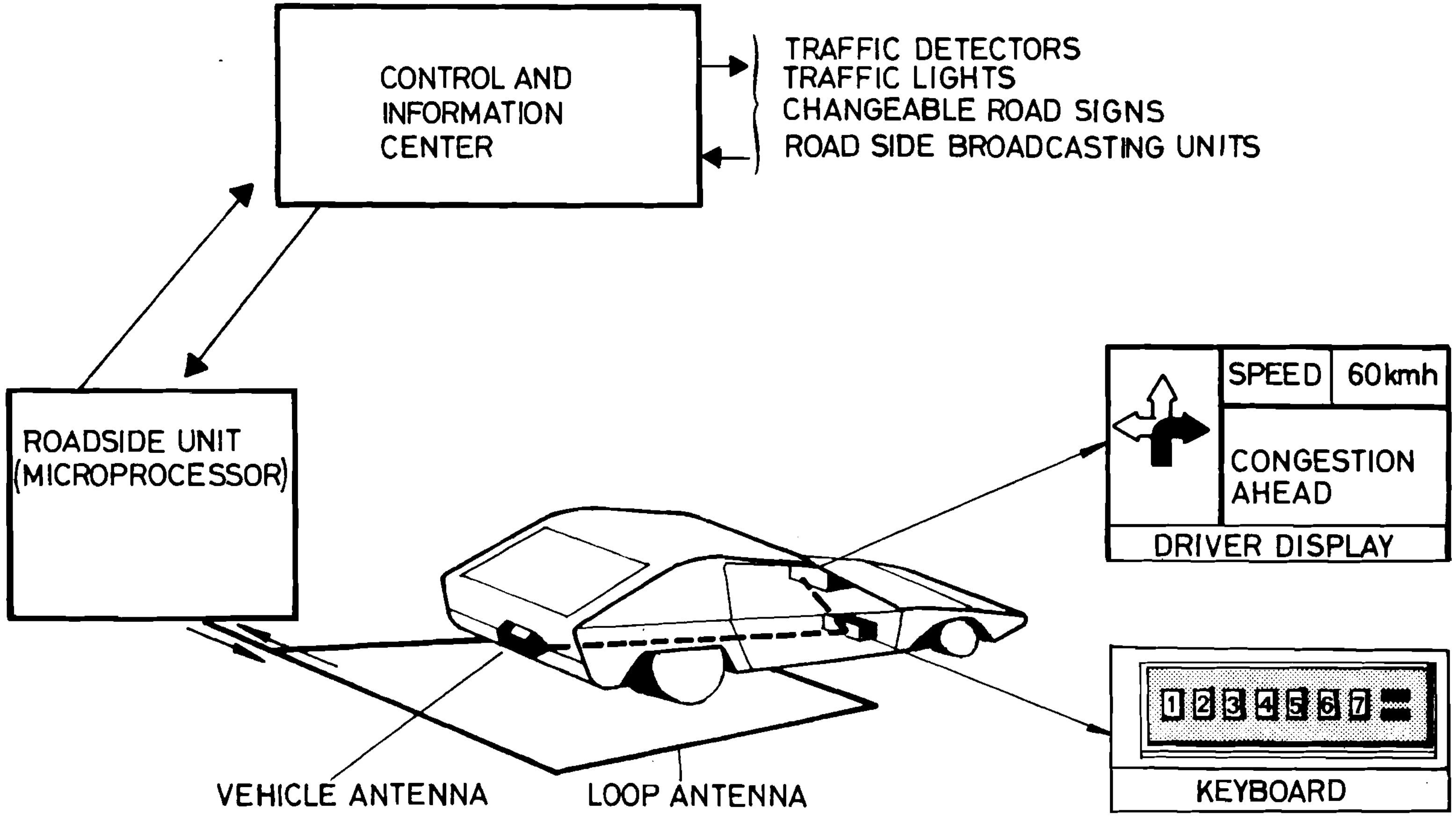



FIG.9: INTEGRATION OF VEHICLES INTO THE TRAFFIC CONTROL SYSTEM

- *Emergency information:* information on fires, accidents, earthquakes and other emergency situations which affect driving safety is directly communicated by the control center to drivers. It is broadcast via roadside units and picked up immediately by the vehicle radios (automatically activated). The objective is to prevent traffic congestion in emergency situations.
- *Other features:* other possible functions are concerned with guidance of vehicles to empty parking spaces, monitoring the location and direction of moving police cars, and providing drivers with information on travel services.

The technology needed to implement such a traffic control and information system consists of the following components:

- *The control center,* containing *central processing units* for traffic data processing, route guidance, communication control, etc.; a *central display unit* which monitors and displays overall operating conditions; a *communication control unit* transmitting and receiving all data between central processing unit and roadside units; additional units for *man-machine interaction* and *traffic data processing.*
- *The roadside units* (cf. Figure 9) consisting of roadside communication and control units; roadside broadcasting units; route display boards (changeable road signs), and vehicle detectors.
- *The vehicle units* (cf. Figure 9), containing an operating keyboard; a two-way digital communication unit for receiving and transmitting data to or from roadside units; a display panel, and a device which automatically activates the car radio to receive information transmitted from roadside broadcasting units.

(ii) Expected results: Concepts for integrated traffic control systems are especially highly developed in Japan [57, 58, 75, 76]. The "comprehensive automobile control system" (CAC), for example, is one of the best supported research projects of the Japanese Ministry of International Trade and Industry [57]*. In 1977 a pilot project is to be carried out in an area of 25 $km^2$ in the southwestern section of Tokyo with about 1,330 equipped vehicles. The following benefits from CAC technology are anticipated:

---

*The description presented here is closely related to this project [57, 58].

- more efficient and rational management of automobile transport;
- improvement of the flow of automobile traffic and reduction of traffic congestion;
- reduction of automobile fuel consumption by improving traffic flow;
- reduction of local air pollution by reducing traffic congestion;
- reduction of driver tensions and burdens;
- reduction of accidents;
- improvement of the social utility of police cars, busses, ambulances and other public-service vehicles.

It seems reasonable to expect the new technology to bring an essential improvement in existing and future traffic problems. On the other hand, it should be emphasized that technologies proposed for large cities such as Tokyo cannot simply be adapted to others, for example in Europe; the concept described here must first be carefully examined for its feasibility elsewhere, given the specific problems of different countries represented in IIASA.

## 4. Automation and Computer Control in Public Transportation Systems

Current activities in the field of computer control of public transportation systems are related to the application of computers in automatic bus and train monitoring and control systems [99-205], and to automatic scheduling and control of train operation for underground or other rapid rail transit systems [77-98].

### 4.1 Urban Railway Systems Control

For urban railway systems, one can distinguish the following hierarchy of tasks [77-98]:

(i) optimal scheduling, seat reservation, etc. [79, 81, 82];

(ii) automatic fare collection and optimal real-time control of train operation [77-80, 83, 86-88, 90-93, 97, 98];

(iii) control of the movement of individual trains [79, 84, 92, 93, 95].

In level (ii), one must deal, for example, with the following problem. The computing system is coupled via line section remote control or local interlocking plants to the railway lines. Aided by a special train movement tracing program, each train on every track section is then accounted for by the computer. The actual train positions obtained are then compared with the nominal positions stored in the memory of the computer. Should the deviations exceed given limits, the computer starts an optimizing program for determining new crossings and turnout points within a preset disposition time interval so as to reduce existing delays and keep follow-up delay as small as possible. In other words, the computer has to set up an optimally modified timetable that permits reducing the existing deviations between the nominal and the actual situation, or, at the very least, keeping irrevocable delays within reasonable limits [86, 87, 91, 92, 93].

In level (iii) the following optimal control problem, among others, occurs: The trains must cover the distances between given starting-points and a fixed target point both in the running times prescribed by the schedule, and with a minimum of traction energy consumption. The task is to find a closed-loop control algorithm, i.e. a computer program for the on-board control computer, which permits calculation in real time of the optimal driving regime by the measured state variables "target distance", "running speed" and "running time still available". This problem could be solved by the application of modern optimal control theory, i.e. the maximum principle of Pontryagin [92, 93]. It can be shown that implementation of such a control system will result in an substantially improved adherence to time tables and savings in driving energy of about 15% (cf. [93]).

Systems which are making extensive and successful use of at least some of the principles described here are

- the COMTRAC (computer aided traffic control system) of the Japanese Shinkansen line [81, 82, 83, 86, 87, 88, 91, 94]; and

- the computer control system for BART (Bay Area Rapid Transit) in the San Francisco area [78], though--as is well known--this system has met difficulties in reaching sufficiently safe and reliable operation.

These and other railway systems [77-98] have demonstrated that extensive use of automation and computer control of urban railway systems will both increase their attractivity to the public (because of increased regularity, availability and quality of transportation service), and decrease personal and operating costs.

### 4.2 Bus and Tram Traffic Monitoring and Control

The increasing automobile traffic causes delays and other irregularities for public transportation systems operating in the same traffic areas as automobiles. This situation motivated the creation, during the last five years, of computer surveillance and control systems using the following two concepts:

(i) Computerized control centers have been established which permit automated identification of the bus positions, communication between drivers and dispatcher, and control of the transportation service if irregularities occur. Possible control strategies are advancing and retarding busses; use of recovery time; short turnaround times for busses; interchanging busses; and plugging a gap by injecting a bus from a reserve pool, removing a bus from a bunch going in the opposite direction on the same service, or removing a bus from another bunch in another service (cf. [99]).

The objectives of these control systems are to maintain adherence to schedule or headways between busses, to ensure that crews are relieved at scheduled times and places and can take their breaks at the correct time, and to deal with emergencies (breakdowns, traffic blocks) as they arise (cf. [99, 102, 104, 105]).

So far no essential improvement of bus service has been achieved by such systems; but several countries are continuing their activities in developing more sophisticated concepts and methods for control and communication.

(ii) A second concept of improving public transportation service by computer control consists in giving priority to busses and trains in traffic-light control systems [103]. This may be considered a first step toward integration of area traffic control and public transportation system control [64].

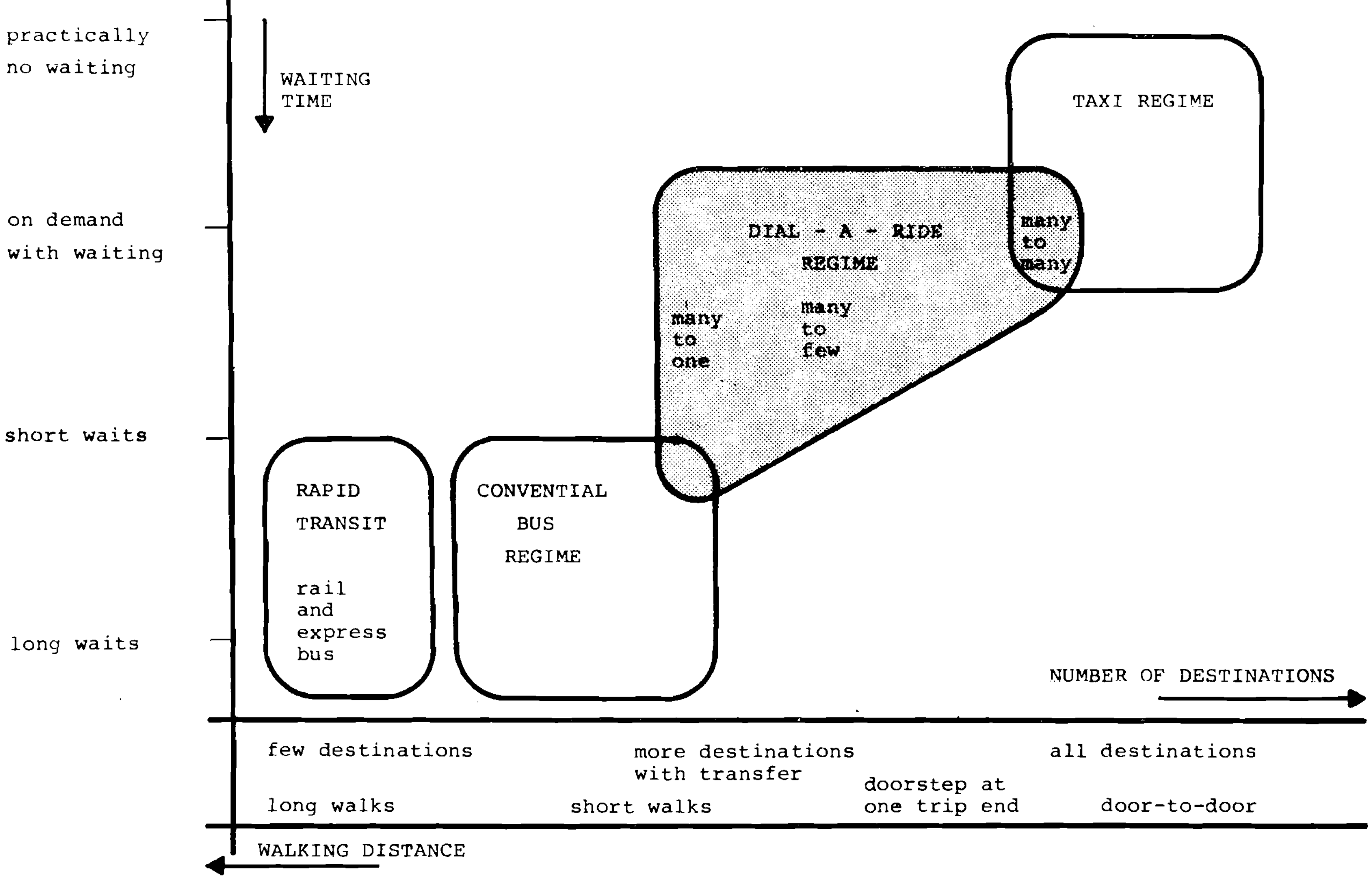
## 5. New Modes of Urban Transportation

Now let us turn to the role automation and computer control will play in the creation of new urban transportation systems. Two classes of innovations are considered: operational innovations, using existing components, and total-systems innovations.

### 5.1 Operational Innovations: DIAL-A-RIDE

The basic aim of introducing operational innovations into existing public transportation systems is to provide a possibility for adapting supply to changing traffic demand. This led to so-called Dial-a-Ride, Dial-a-Bus, Bus-Taxi or Demand-Bus systems [106-111]. The prospective passenger rings the control center either from his home telephone or by direct line free telephones at fixed stops, explaining his desired destination, the point of origin, and the number of people who want to make the journey. The dispatcher selects the appropriate bus and informs the passenger of the approximate arrival time. The request is written onto the appropriate bus tour schedule and is passed to the driver, either by hand, if the bus starts its tour from the control center office, or by two-way radio. Such a concept obviously covers a wide variety of transport needs, broadly filling the gap between the conventional scheduled and routed bus service and the taxi or private car (cf. Figure 10). It has the advantages that (1) more than

FIG. 10: DIAL-A-RIDE IN THE PUBLIC TRANSPORTATION SPECTRUM (cf. 110 )



one party may take the vehicle at any given time; (2) the routing is programmed to yield a combination of high usage and reasonable waiting and trip times; and (3) the fares are substantially below those for taxis.

The simplest version of the demand-responsive bus system is the Many-to-One concept; here one important destination, e.g. the town center, a railway station, a bus station or a suburban shopping center, has to be connected with the surrounding service area. The Many-to-Few concept describes a Dial-a-Ride service which is focussed onto a small number of major nodes extending service between them and their tributary areas. Such a Dial-a-Ride system could operate in a small town, providing trips to and from the town center, industrial districts and railway stations. Finally, the Many-to-Many concept provides transportation from any origin to any destination within a given service area (cf. Figures 10 and 11).

What role will modern computer technology play in such new systems? If only a few busses are operated in a Many-to-One system within a relatively small service area, dispatching can be done by a human controller [108]. This is obviously not possible for the other two concepts or if the number of busses is larger than about five to ten. In this case a sophisticated computing system must assist the dispatcher by real-time scheduling and routing of the trips. For this purpose a comprehensive algorithm, the Computer Aided Routing System (CARS), has been developed by MIT [107].

Several computerized Dial-a-Bus systems have been developed [109, 110], but most of them are at the stage of a demonstration project only (cf. [106-111] for more details).

## 5.2 Total-Systems Innovations: Automated Demand-Responsive Urban Transportation

The proposals for total-systems innovations can be divided into two groups. The first are proposals for automated demand-responsive guideway systems: "PRT (Personal Rapid Transit)",

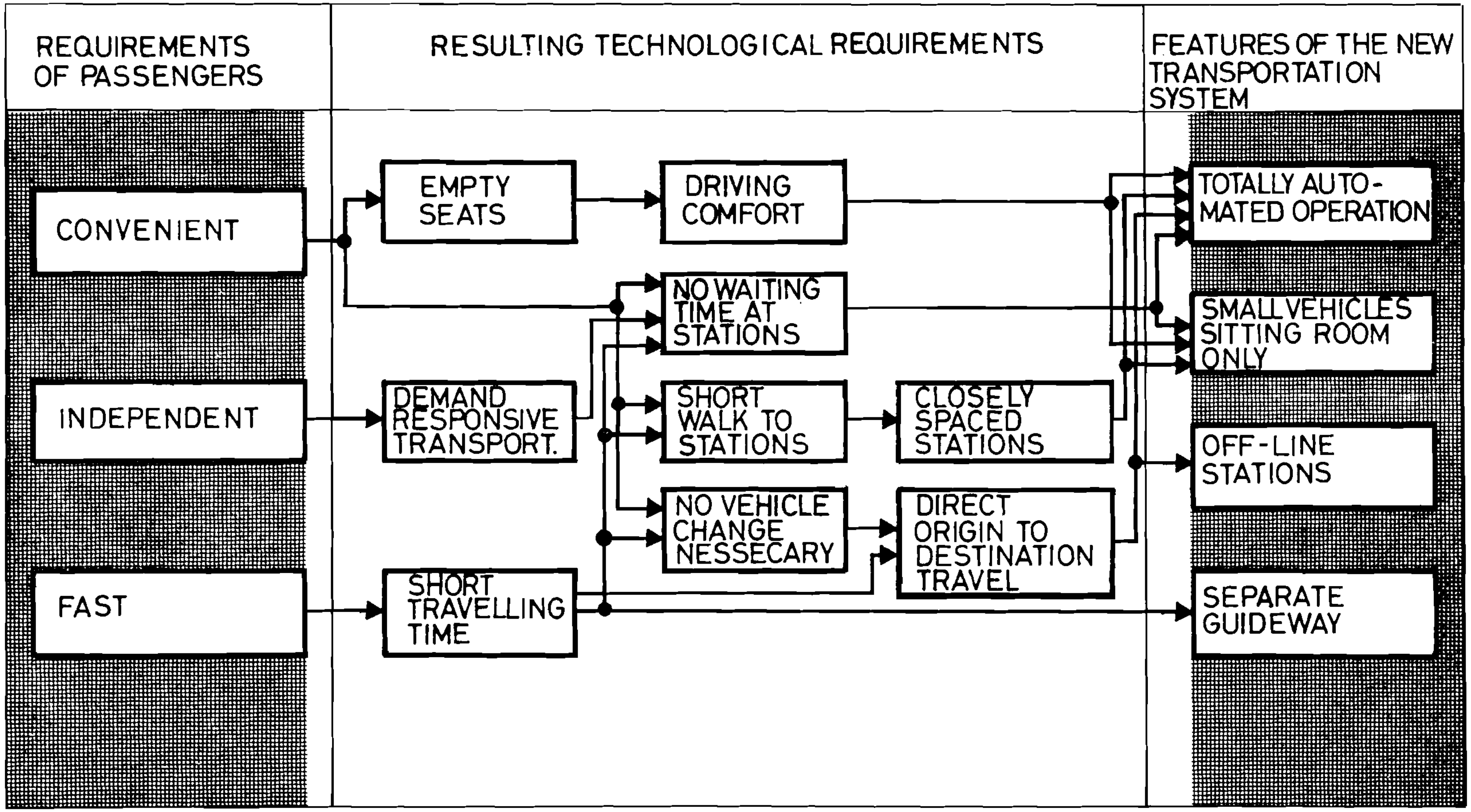



FIG. 11: PROSPECTIVE PASSENGER REQUIREMENTS AND RESULTING FEATURES OF THE NEW TRANSPORTATION SYSTEM (cf.[134])

"people-mover", "Cabinentaxi", "CVS (Computer Controlled Vehicle Systems)" [112-118, 124, 126-129, 132, 134]. The second ones are those for the dual-mode systems [119 - 122].

### 5.2.1 Automated Demand-Responsive Guideway Systems

(i) Basic concept and expected results: A solution of the problems described in Section 2 requires that the new systems fulfill as far as possible the requirements for mobility, safety, resources, and the environment.

Public acceptance of a new system requires that the system be attractive to prospective passengers: it must be convenient, independent concerning departure time and destination, and fast. Since the system would be a public one, it must be very reliable in operation and offer the possibility of integration into existing systems. From the point of view of protection of the environment and saving of resources it should be characterized by no air pollution, and low noise pollution; high capacity in small traffic areas, (low land consumption); low energy consumption; and adaptability to existing city structures.

These requirements, especially those of prospective passengers, are leading to a concept for a new system which is characterized by the following features (cf. Figures 11 and 12):

- small but comfortable vehicles, containing seats only, which are available at any station and any time with little or no waiting time; closely spaced stations providing easy walking access,
- direct origin-destination travel without the need for vehicle changing; off-line stations,
- high travelling speed (about 30 km/h),
- guideway separated from streets and highways,
- electrically driven vehicles (to reduce air and noise pollution and energy consumption),
- totally automated system operation: no drivers (which is essential for decreasing operational costs).

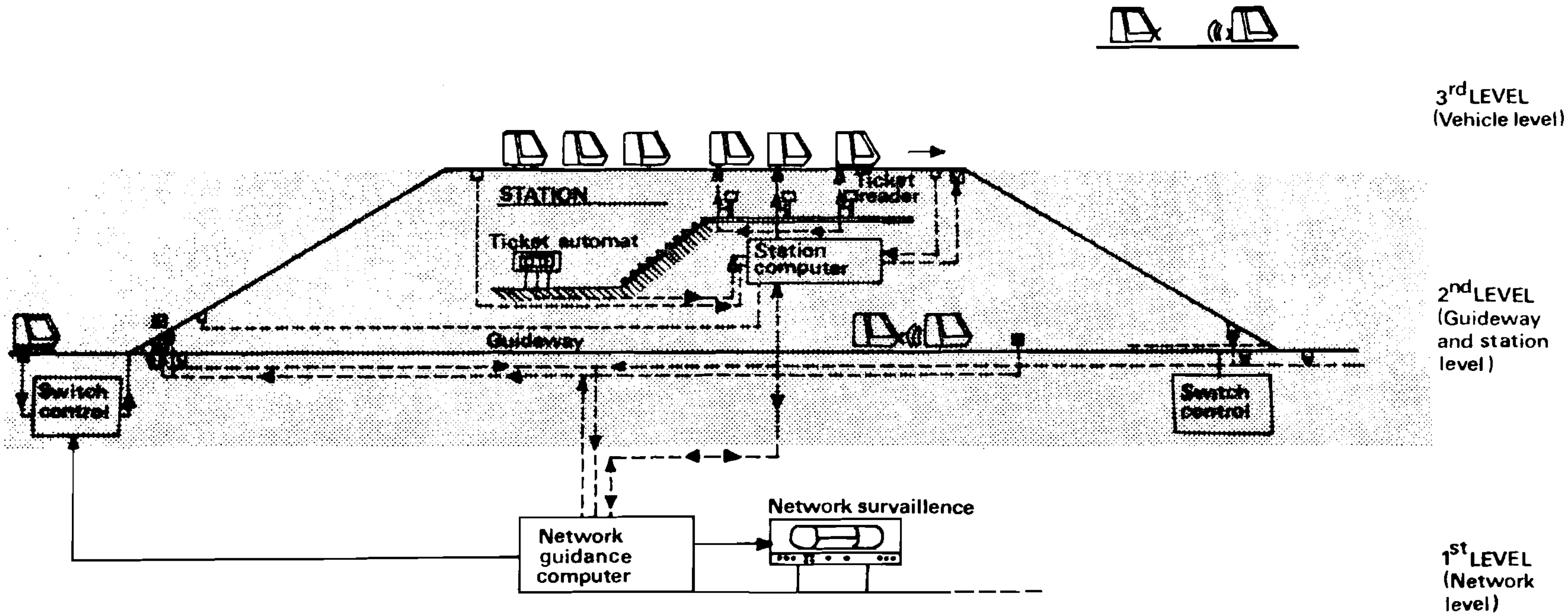



Fig 12: Hierarchical control system for guideway systems
(cf. [116–118] "Cabinentaxi")

A system of that kind could represent [112-118, 127, 128] the main public transportation system for medium-sized cities with a population of about several hundred thousand; an additional system for large cities, working in conjunction with existing rapid rail systems; the main system for new suburban areas, connecting them with railway stations; and a suitable system for area transportation service from, to, or within airports, large industrial regions, exhibition and fair areas, etc. Moreover, some systems are expected to provide not only passenger service but also the possibility of goods transportation [112, 113].

From the point of view of the traveller the system would be operated in the following way (cf. Figure 12). The passenger buys a ticket for his destination point from an automatic selling device. This ticket contains, e.g. a magnetic code which characterizes the destination point. He puts his ticket into a reading device, which transmits this information to a central control computing system, and then enters a car which was waiting for him or was sent to the station by the computer; and the car leaves electrically driven. Computer controlled, it moves through the network non-stop to its destination point. When the passenger has left it, the empty car is guided by computer to the station where cars are needed. In the cabin-taxi system [116-118, 127] the cabins will be able to operate hanging below the guideway or on top of it.

It has been proposed to design small-sized cars in such a manner that they can be operated above or along streets, above a train or underground and in the interior of a building, e.g. a department store.

(ii) Concepts and methodology for automation: The most significant feature of these new urban transportation concepts is obviously automation and computer control; without extensive use of this new technology they are not feasible. This becomes even more obvious if one considers the relation between system capacity and its attractivity to passengers

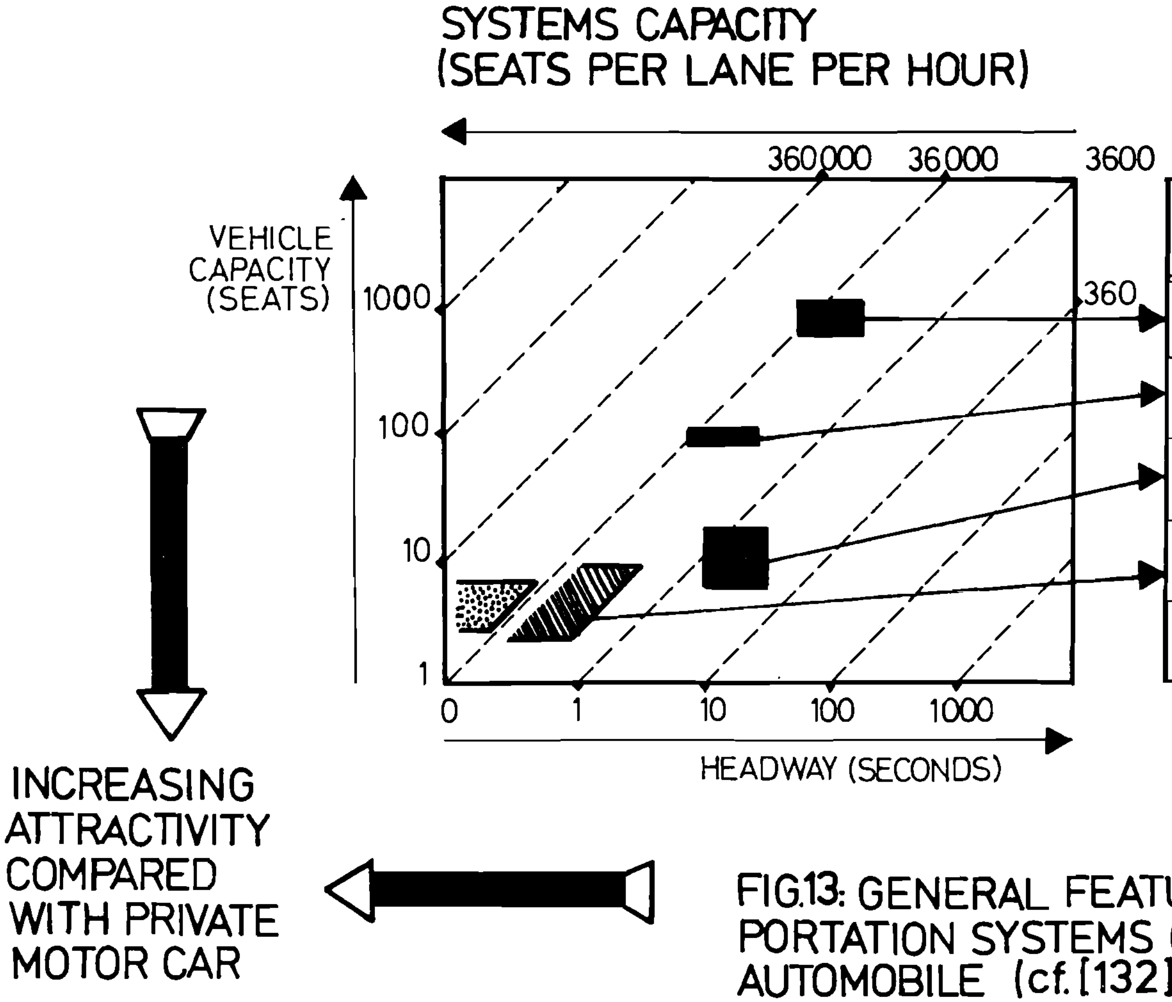
(Figure 13). The system capacity, in seats per lane per hour, should be of a similar order of magnitude as for a modern rapid rail system (for a subway, about 30,000 persons per lane per hour). To offer an attractivity comparable to that of the private automobile, the vehicles should be small (not more than four seats) and the service should be demand-oriented. The headways between vehicles must be extremely small, i.e. in the order of 0.5 to ten seconds, if the capacity of the system is to be much larger than for private automobile traffic (cf. Figure 13). Obviously, a system with such parameters can be operated only with a very complex and efficient control system; this is of vital importance and will essentially determine the efficiency and the attractivity of the whole system. On the other hand, such service properties impose very high requirements concerning the reliability and safety of the control system. Therefore one distinguishes between PRT systems of the first, second and third generation (cf. Figure 13).

A representative of the first generation is the Morgantown (West Viriginia) system [114], now at the demonstration stage. That system is supposed to operate eight-seat vehicles with 15-second headways, achieving a capacity of about 1900 seats per lane per hour (cf. Figure 13).

For the second- and third-generation (high performance and high capacity) PRT systems, five concepts have been developed:

(1) Cabtrack (UK) [128],
(2) Aerospace (USA) [128],
(3) Cabinentaxi (FRG) [116-118, 127, 134, 135],
(4) CVS (Computer Controlled Vehicle System) (Japan) [112, 113],
(5) Matra "Aramis" (France) [115].

The first two systems have been developed to the conceptual stage, with hardware developed and tested for some components. The latter three systems have gone beyond, to the prototype fabrication and test stage; Table 1 summarizes some of the parameters of these three systems.




| SYSTEM | EQUIV LANT EXPRESS-WAY LANES |
|---|---|
| RAPID RAIL (BART) | 8.9 |
| BUSWAY | 9.3 |
| PRT FIRST GENERATION | 2.8 |
| PRT 2nd and 3rd GENERATION | 8.9 |
| AUTOMOBILE | 1.0 |

FIG.13: GENERAL FEATURES OF NEW TRANS-PORTATION SYSTEMS COMPARED WITH THE AUTOMOBILE (cf. [132])

Table 1: Parameters of second and third generation PRT Systems.

| Name | Aramis | CVS | Cabinentaxi |
|---|---|---|---|
| Country | France | Japan | FRG |
| Developed by | Engins-Matra | JSPM[1)] | DEMAG + MBB[2)] |
| Test system in | Paris-Orly | Tokyo | Hagen/Westphalia |
| Vehicle capacity [seats] | 4 | 4 | 3 |
| Minimum headway [seconds] | 0.2 | 1 | 0.5-1.0 |
| Vehicle speed [km/h] | 50 | 60 | 36 |
| Maximum lane capacity [seats per hour] | ≈75,000 (with platooning) | ≈15,000 | ≈15,000 |

The demand-responsive operation of these high-capacity and high-performance PRT systems requires the implementation of an hierarchically structured multi-computer control systems. In this connection it is interesting to observe that we have a 3-level hierarchical control system:

(i) <u>Network level</u>: The first level is concerned with supervision and control of traffic in the whole network by a central computer. This problem is very similar to that already discussed for street traffic. The computer must ensure that a certain cabin is guided from its starting point to its destination with a minimum of travelling time, taking into account traffic densities in the different parts of the

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[1)] Japanese Society for the Promotion of Machine Industry, supported by the Japanese Government and the Tokyo University.

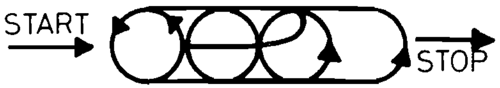
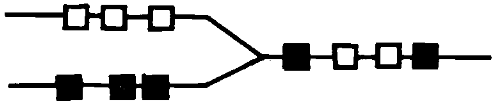
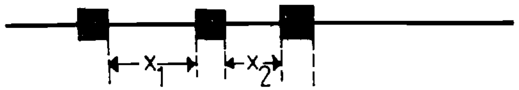
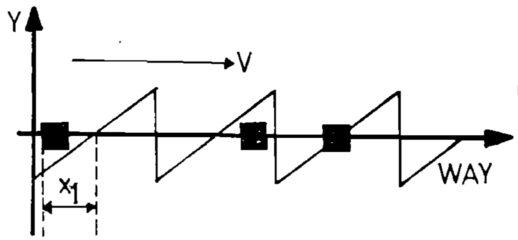
[2)] Cooperation of DEMAG Fördertechnik and Messerschmidt-Bölkow-Blohm GmbH, supported by the Ministry of Science and Technology, FRG.

network. In this connection, a new problem arises, that of optimal distribution of empty cars (cf. [15], pp. 553-564).

(ii) Station and guideway level: In the second level we have to distinguish the following problems: (1) Merging two traffic streams into one. Here some similarities to highway merging control can be observed. (2) Headway regulations for the string of moving vehicles. This is obviously a problem quite similar to that one we have already discussed for a string of ordinary cars moving on freeways and it seems that a practical solution of this problem is only possible for guideways and not for freeways.

The proposed methodology uses the linear regulator theory with quadratic cost function. However, even a small group of about ten vehicles requires tremendous numbers of feedback loops, which will result in unacceptably costly communication links between the central control computer and each individual car. On the other hand, if one considers only two vehicles and tries to control the distance between them by an uncoupled control system, then serious queue stability problems will occur if the leading car changes its speed [129]. Therefore, the so-called moving cell principle has been proposed: in a cable embedded in the guideway, an electrical signal of the form shown in Figure 14 (Level 2.2) is generated and picked up by sensors in the individual vehicles. This signal moves along the guideway at a speed prescribed by the computer. Now an on-board control system has the task of ensuring that the vehicle stays at the zero points of this curve and thus moves with the prescribed velocity [121]. This principle can be extended to the merging control problem [129].

There are further possibilities to achieve the same effect as the moving cell principle, all of them are based on the idea that each vehicle is assigned to an electronically generated point which it follows along the guideway [112, 113].

| CONCEPTS | METHODS | RESULTS |
|---|---|---|
| **1. NETWORK LEVEL**<br>SUPERVISING AND OPTIMAL CAR GUIDANCE AND EMPTY-CAR DISTRIBUTION<br> | • CRITERION: MINIMIZING TRAVELLING TIMES<br>• EQUABLE USAGE OF NETWORK CAPACITY<br>• METHOD: ADAPTIVE ROUTING | JAPAN, USA, FRG:<br>SIMULATIONS<br>(cf. [112, 113, 118, 122]<br>and [15] pp. 553–564) |
| **2.1 STATION LEVEL**<br>MERGING CONTROL<br> | • CRITERION: MAX. CAPACITY<br>• METHOD: FEEDBACK CONTROL<br>• PROBLEM: COMMUNICATION LINKS | USA, JAPAN, FRG, FRANCE:<br>TEST CENTERS [112, 118, 126] |
| **2.2 GUIDEWAY LEVEL**<br>DISTANCE CONTROL<br> | MOVING CELL PRINCIPLE:<br> | |
| **3. VEHICLE LEVEL**<br>SPEED CONTROL<br>COLLISION PREVENTION | EMERGENCY BRAKING SYSTEM | **FIG. 14: COMPUTER CONTROL OF PRT SYSTEMS** |

### 5.2.2 The Dual-Mode Concept

The second class of total-systems innovation in the dual-mode concept. Here a vehicle -- an automobile or bus -- would operate as an ordinary vehicle on city streets and then enter a station where it is switched onto a guideway and controlled in much the same way as described above. A potential economical advantage of the system is that the costly, low-density suburban collection and distribution functions could be performed by persons driving private cars or public busses to and from collection points just as they drive to and from freeways today. At the downtown end of the trip, the car would exit from the system and might then move along on the downtown streets or be dispatched automatically to some peripheral parking area. It seems that such a system could combine the advantages of a rail transit system with respect to high speed, capacity and safety, and also be pollution-free and quiet in operation with the flexibility and attractivity of the private motor car and the area transportation service of an ordinary or a demand bus (cf. [119-122]).

## 6. Conclusion

The aim of this paper was to discuss the contribution to be expected from a comprehensive application of modern automation and computer technology in the solution of the serious present and future urban traffic problems.

It has been shown that computerized urban traffic control systems already play an important role in the improvement of existing transportation systems, especially of urban railway systems and freeway and street transportation systems. Moreover, automation and computer control seem to provide the possibility of fundamental changes in existing urban transportation systems during the next ten years. This is indicated by several recently developed demonstration projects in different countries which are now used for experimental tests. Nevertheless, a number of problems and conflicting opinions (cf. e.g. [131]) still exist. Most of these problems are concerned with:

- the safety and reliability of totally automated systems,
- cost-benefit analysis,
- risk evaluation (e.g. deliberate or accidental destruction of the control center),
- public acceptance of automated modes of transportation,
- prediction of the expected effects of introducing new modes of transportation on the quality of urban living and city development in general.

At present one cannot be sure that the automated transportation modes now being developed will really bring the needed breakthough to better urban transportation. This is especially true if one considers the essential differences in the economic and social structures of different countries.

Nevertheless there is a strong motivation to proceed in the development of new automated demand-responsive urban transportation systems. Any fundamental change in transportation will need a certain period of time for experimentation: this was certainly true for highly rationalized railway systems, whose development began with the invention of the steam engine. It will doubtless be true for the development from the invention of the new "systems technology"--the large-scale integrated digital computers and the related automation techniques--to totally new urban transportation systems (cf. Figure 1). The complexity and interdisciplinarity of this subject needs international cooperation at a very early stage.

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## APPENDIX A

### Optimal Traffic Control in the Presence of Congestion

Consider an over-saturated network; that is, at one or more intersections traffic demand exceeds capacity (Figure 8a). As state variables $x_i$, define the number of cars waiting at the different intersections; and as control variables $u_i$, the length of the green times or the number of cars leaving the link during the green light. Now one can formulate the following optimal control problem. The state vector

$$\underline{x}^T(k) = (x_1(k) \ldots x_n(k)) \qquad (1)$$

of the system is to be changed from a given initial state $\underline{x}(0)$ characterizing over-saturation (congestion) to a final state $\underline{x}(N)$ corresponding to under-saturation (normal traffic conditions) in minimum time or at least with a minimum number N of green-yellow-red cycles. Now the corresponding optimal control vector can be calculated from the measured state variables $x_i(k)$ considering the constraints

$$M_i \geq u_i(k) \geq U_i \qquad (2)$$

of the control variables. The $M_i$ represents the minimal and the $U_i$ the maximal length of green times that are acceptable from a psychological point of view. If one assumes that the travelling time between two intersections is small compared to the waiting time, then it is possible to set up a system of state equations of the form

$$\underline{x}(k + 1) = \underline{x}(k) + (B)\ \underline{u}(k) + q(k) \quad , \qquad (3)$$

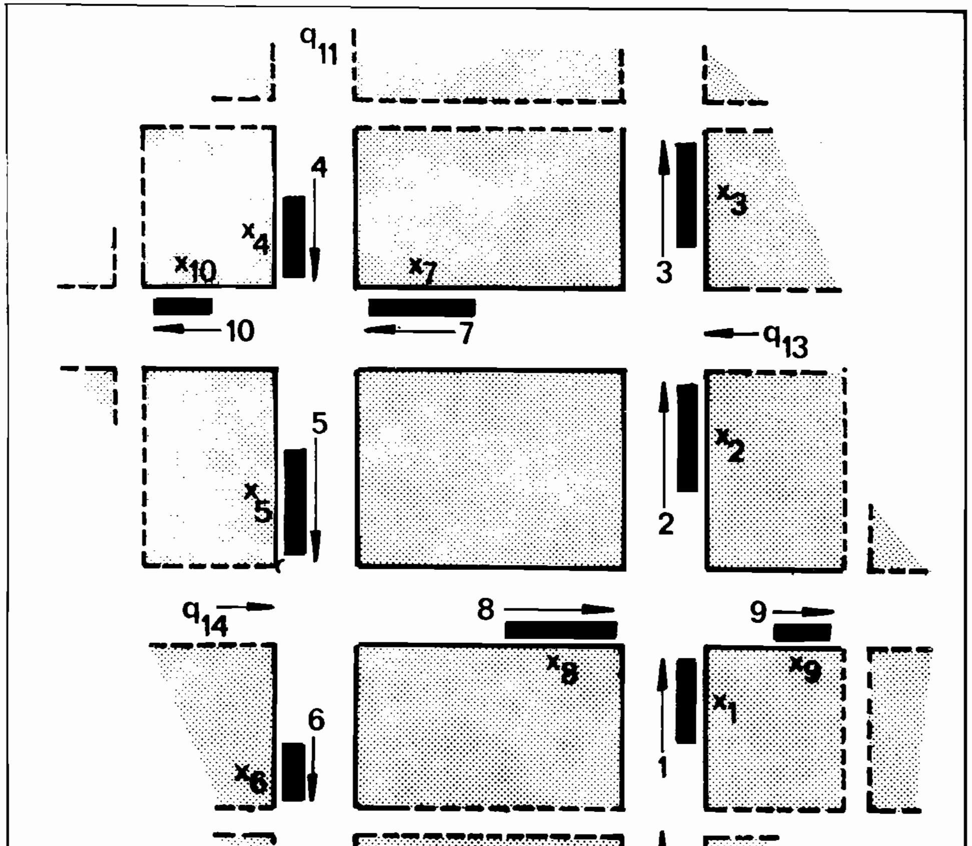


FIG. 8a

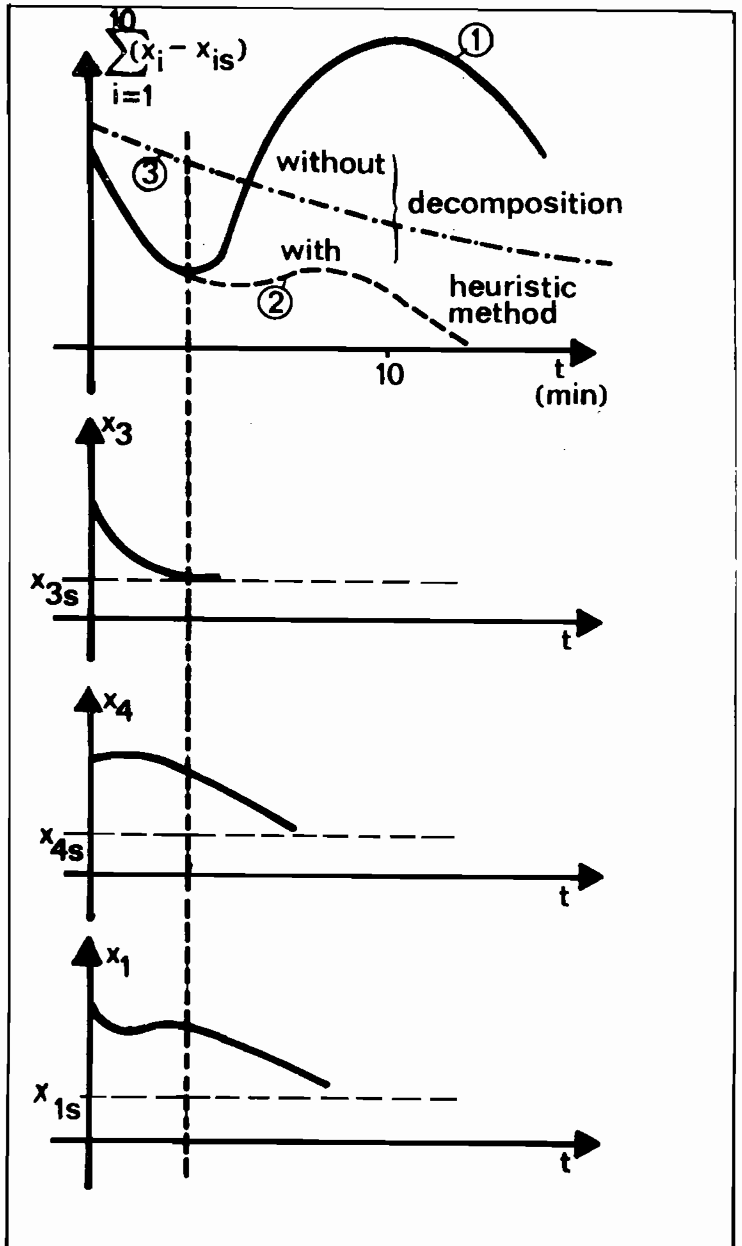


FIG. 8b

FIG. 8: EXAMPLE OF JAM-MODE CRITERION CONTROL OF A CONGESTED NETWORK

8a: NETWORK STUDIED

8b: RESULTS OBTAINED

describing the relation between the number of waiting cars at the end of time intervals k + 1 and k, the control variables $u_i(k)$ and the number of cars $q_{ij}(k)$ arriving at the controlled area during time interval k. For the example shown in Figure 8a, the matrix (B) is of the form

$$(B) = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ s_1 & -1 & 0 & 0 & 0 & 0 & 0 & r_8 & 0 & 0 \\ 0 & s_2 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & s_4 & -1 & 0 & r_7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & s_5 & -1 & 0 & 0 & 0 & 0 \\ 0 & r_2 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & r_5 & 0 & 0 & -1 & 0 & 0 \\ r_1 & 0 & 0 & 0 & 0 & 0 & 0 & s_8 & -1 & 0 \\ 0 & 0 & 0 & r_4 & 0 & 0 & s_7 & 0 & 0 & -1 \end{bmatrix} \qquad (4)$$

Elements $r_i$ and $s_i$ describe the percentage of cars turning right or left $\{r_i\}$ and going straight ahead $\{s_i\}$. According to Pontryagin's maximum principle, the optimal control strategy $\underline{u}^*(k)$ is that which maximizes the Hamiltonian

$$H(\underline{u},\underline{p}) = \sum_{i=0}^{n} p_i x_i(k+1) \quad . \qquad (5)$$

As shown in [74], one can in this way develop the following relations for the optimal control variables characterizing a bang-bang control system:

$$u_3^*(k) = \max(\min(U_3, x_3), M_3)$$

$$u_2^*(k) = \max(\min(\min(U_2, x_2) \quad , \quad \left|\frac{u_3^* - r_{13}q_{13}}{s_2}\right|), M_2)$$

$$u_6^*(k) = \max(\min(U_6, x_6), M_6)$$

$$u_5^*(k) = \max(\min(\min(U_5, x_5) \quad , \quad \left|\frac{u_6^* - r_{14}q_{14}}{s_5}\right|), M_5)$$

$$u_9^*(k) = \max(\min(U_9, x_9), M_9) \tag{6}$$

$$u_{10}^*(k) = \max(\min(U_{10}, x_{10}), M_{10})$$

$$u_1^*(k) = \max(\min(\min(U_1, x_1) \quad , \quad \left|\frac{s_8u_2^* - r_8u_9^*}{s_1 + s_8 - 1}\right|), M_1)$$

$$u_8^*(k) = \max(\min(\min(U_8, x_8) \quad , \quad \left|\frac{s_1u_9^* - r_1u_2^*}{s_1 + s_8 - 1}\right|), M_8)$$

$$u_4^*(k) = \max(\min(\min(U_4, x_4) \quad , \quad \left|\frac{s_7u_5^* - r_7u_{10}^*}{s_4 + s_7 - 1}\right|), M_4)$$

$$u_7^*(k) = \max(\min(\min(U_7, x_7) \quad , \quad \left|\frac{s_4u_{10}^* - r_4u_5^*}{s_4 + s_7 - 1}\right|), M_7) \quad .$$

A small example demonstrates the efficiency of the method: We assume an initial state which is characterized by the vector $\underline{x}^T(0) = (35, 25, 30, 25, 30, 40, 30, 30, 30)$, i.e. 25-40 cars are waiting at the different intersections. Let the number of cars arriving per time interval at the controlled district be constant. Let parameters $r_i$ and $s_i$, i.e. the percentage of cars going straight ahead and turning right or left, respectively, also be constant.

Using the control strategy obtained in (6), one gets curve 1 in Figure 8b for the sum

$$Q = \sum_{i=1}^{n} \Delta x_i = \sum_{i=1}^{n} (x_i - x_{is}) \tag{7}$$

of the differences $x_i - x_{is}$ between the numbers of waiting cars $x_i$ and their nominal numbers $x_{is}$ characterizing under-saturation which shall be reached by the control strategy in a minimum of time.

We observe a decrease of Q according to equation (7) and then an unexpected maximum (cf. Figure 8b, curve 1). This is caused by the fact that the desired state of under-saturation is not reached at all intersections at the same moment of time (cf. Figure 8b, diagrams for $x_3$, $x_4$ and $x_1$ for $t = t_1$). Therefore, a certain kind of dynamic decomposition is used; i.e. if an intersection has reached the state of under-saturation it is excluded from the network and controlled according to another criterion. Curve 2 illustrates the success of this technique. Curve 3 represents a result one can obtain by a certain rule-of-thumb strategy often recommended by traffic engineers. The advantages of the optimal strategy are obvious.

So far it has not been possible to apply a strategy of the type described. This field is thus still open for fundamental research work (for more details, cf. [74, 74a]).

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