# Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

## Malfunction Management Activity Area Report for AHS Health Management

U.S. Department of Transportation
**Federal Highway Administration**

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# FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is amulti-year,multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

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# NOTICE

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# 1. Executive Summary

In contrast to most automobiles, commercial vehicles are bought and operated to earn a profit. Desirability and feasibility of an MIS for commercial and transit vehicles depends on the readiness of the commercial truck operators to pay for MIS investments. The final MIS concepts as well as the steps to get to there have to be designed with this in mind.

Commercial vehicles are already today operated in platoons. Up to three unmanned trailers are towed by a tractor for long-distance freight transport. Costly transfer of the cargo to distribution trucks for final delivery is normally necessary. A logical AHS-like concept would be to equip the trailers with an own drivetrain and to couple them electronically to the leading vehicle - hereby forming truck convoys.

In order to provide maximum use of truck convoys from the beginning, the system should be usable on any highway without extra infrastructure and keep the driver as a backup and supervisor. Truck convoys that are driven by a driver are feasible in mixed traffic situations and can be driven on normal non-instrumented lanes.

To start with, two vehicles can be electronically coupled. The leading vehicle will be steered by the driver, followed by the second, unmanned one. Personnel costs for long-distance driving will be reduced. The two vehicle system can be extended to allow an arbitrary number of vehicles to be coupled together. As soon as the number of convoyable vehicles extends a certain percentage, special AHS-lanes will be assigned to them or built for them around congested regions. Operators of equipped cargo vehicles will get an extra benefit due to small and predictable travel times.

Combining trucks in convoys frees up space for passenger cars. Moreover those combined truck convoys drive at longer distances that make it more likely that the space between them is actually used. This shows that even from automating truck traffic, cars will have substantial benefits on manual lanes.

Stable longitudinal control of a truck platoon driving with very short distances will be one of the most challenging problems for commercial MIS. The long lagtime in the drivetrain due to diesel engines, the relatively small engine power per mass and the large variation of possible loads represent a special challenge for the control of trucks as opposed to passenger cars.

Experience with previous realizations of laterally guided systems shows that reliable operation can be achieved.

## 1.1. Prior Research and Key findings

### 1.1.1. Introduction Strategies for Commercial AHS

Databases containing German freight distribution data have been extensively analyzed to assess the potential for combining trucks in convoys. A significant percentage of traffic is generated from carriers sending more than one truck between the same cities within a short period of time. These all are prime candidates for MIS introduction. Combinable volumes are greater for typical shipment places like port-cities.
Several factors influence the feasibility of bundling. The technology to realize the bundling need only be standardized within one carrier but would certainly be less expensive if it were standardized and used between potentially competing companies.

Sufficient travel distance between origins and destinations and available similar travel plans for two or more trucks are necessary. Additional manpower at the destination site can reduce the benefit especially for longer truck convoys.

### 1.1.2. Simulation of mixedAHS and non-AHS Traffic

Extensive studies have been conducted simulating mixed traffic consisting of truck platoons and manually driven passenger cars. Depending on the truck to car ratio and the length of convoys, significant increase in throughput and/or decrease in travel time were found.

### 1.1.3. Communication and Control Concepts for Commercial AHS

Truck Platoons with sophisticated control and communication structures have been realized in simulation. Two-vehicle platoons have been studied in reality.

Under normal driving conditions, longitudinal and lateral control can be independently designed. However in emergency situations, like sharp braking in a curve, lateral and longitudinal movements are coupled and must be regarded together.

Lateral control can be realized with known approaches and linear models. Good control quality can be achieved with a variety of controllers.

Longitudinal control however deals with strong nonlinearities in the drive train and with large variations of the parameters. Specific difficulties with respect to longitudinal control of trucks have been identified. These are caused by drivetrain properties, mass of the vehicle, engine power and braking capabilities.

Most of these difficulties have been overcome. The longitudinal control of a truck following a leading truck with a headway ofl0m has been demonstrated in practice. This headway is precisely maintained even if the leading truck brakes and accelerates. Extremely heavy braking of the leading vehicle absorbs about 3.5 m of this distance.

A 2.45 GHz link between the convoy vehicles was used and has proven to be a safe and economical communication means. Communication of speed and acceleration of the leading vehicle enhances stability and comfort of the convoy.

A standard video camera has been used successfully as a sensor for both following standard road markings as well as for precise distance measurements to the preceding vehicle (maximum distance error at 10m about ~ 1 cm).

Lateral vehicle guidance along pavement markings using these video sensors has successfully been adapted to heavy trucks. A test truck is able to drive at a speed up to 90 km/h with a lateral deviation of less than 10cm.

O-Bahn is a transportation system consisting of busses that can be steered by the driver but also guided like trams. A bus is driven manually in suburbs and will enter a special roadway in the city center changing to an automatic guided mode. Thus the width of a special bus lane or tunnel is kept to a minimum. The report describes the components of the system and the operational data and experiences with the system, covering also the acceptance of the system by customers and practical experience in every days operation.

## 1.2. Recommended Further Investigations

Data on freight movements are highly competition sensitive and difficult to get. Current experience is based on available German data but the developed methodology will be applied to U.S. freight data as soon as available.

Lane change and following behavior on U.S. freeways is significantly different from driving behavior on German two-lane freeways. The developed simulation model for studying the effect of truck convoying in mixed traffic should be modified accordingly.

Longitudinal control of trucks is much less developed than their lateral control. Further research is needed to control the drivetrain and the braking properties of trucks. Different brake systems simultaneously in use in today's commercial vehicles like engine brakes, retarders and pneumatic brakes and the additional degree of freedom of articulated trucks need special attention. Compatibility between brake Systems of tractors and trailers, often belonging to different freight companies, impose an additional challenge.

## 2. Commercial Vehicle and Transit AHS Analysis (Activity Area F)

### 2.1. introduction Strategies for Commercial AHS

### 2.1.1. Elements of AHS Operation

#### 2.1.1.1. Infrastructure

Different networks may be the base of MIS

- public networks

reserved/opened networks or lanes . closed networks

combined networks

Public networks display greater length and have narrower mesh size than all the other networks. Yet AHS-trucks have to be compatible with needs of all other vehicles and design elements of these networks (e.g. axle weight, curvature, etc.):

In order to meet special needs of MIS operation, dedicated networks or lanes have to be reserved for it. This can be achieved either temporarily (e.g. during night times) or unlimited in time.

Closed networks allow more liberal design of the MIS-system (e.g. driverless operation, higher operating speed, higher axle weight), which means infrastructure can be designed more adequately (e.g. control and safety devices).

While MIS-operation temporary closed networks may be interpreted as closed networks, because no other use of the network is allowed during dedicated MIS-operation.

In combined networks, advantages of closed networks can be utilized for MIS-operation. Entries and exits are in boundary positions to public networks.

#### 2.1.1.2. Vehicle Operation

Three different kinds of operation may be distinguished with respect to MIS vehicles:

single operated MIS-trucks

. dynamic platooning (improvised)

platooning in terminals or at transition points (planned))

Operations with automatic and driverless vehicles is a fascinating idea of tomorrow's freight transport. This idea may be completed by the possibility of putting automatically operated vehicles together to platoons on the way (improvised dynamic platooning).

Planned platooning and separation of platoons in terminals or transition points of combined networks are predestined for operation with one driver in the leading truck.

The critical conditions for MIS comprise the legislative presupposition for admission of MIS Systems, MIS operations, and clarification of liability and assurance issues.

When forming platoons, an engagement between the partners of a platoon arises. The contract has to take into account, that the expenditure for the operation of the leading vehicle, especially with driver, is higher than with the following vehicles. Advantages and disadvantages of the partners must be compensated for monetarily by contract

The safety requirements are to be developed for different MIS concepts dependent on those elements described in chapters 2.1.1.1. and 2.1.1.2. and their combinations.

### 2.1.2. Sketches of AHSOrganization

#### 2.1.2.1. Single Operated Commercial AHS-Vehicles in Public Networks

At first, the efficiency of MIS systems will not be as great as to allow driverless operation on public networks. MIS vehicles must be tolerant to errors as well as to be able to handle conflicts under traffic conditions like specially trained drivers do. As long as a driver has to be on board, there is only little economic benefit of commercial MIS, because the driver must be paid during his presence.

Additionally, the interfaces of the vehicle-to-vehicle communication within the range of AHS-operation should to be standardized stringently and the liability must be determined by law.

#### 2.1.2.2. DynamicPlatooning in Public Road Networks

Dynamic platooning, e.g. improvised platooning during operation postulates freely operated commercial MIS as described in chapter 2.1.2.1. That means there is only little economic benefit because the drivers remain on board and need to be paid.

Any time, when platooning takes place contracts must be concluded by the partners of the platoon via standardized vehicle-to-vehicle communicationThe contracts comprise liability and recompense between leading vehicle and the other platoon members.

In addition, future platoon lengths longer than today's vehicle lengths as well as liability issues must be regulated by law.

#### 2.1.2.3. Planned Platooning in Terminals

The commercial MIS vehicles are combined into planned platoons at defined points of composing and decomposing by their operators.

The engagement of the platooning partners, e.g. operators of commercial MIS is possible over a long term. The vehicle-to-vehicle-communication interfaces are only necessary for a dedicated MIS truck pool. There is no need for general vehicle-to-vehicle-communication.

In closed network operations, driverless MIS-trucks or MIS-platoons are also possible. These networks could be time-dedicated highways, e.g. a night-time operated networks.

### 2.1.3. AHS-Potentials

#### 2.1.3.1. Efficiency of Truck Platoons

The voluntary introduction of commercial MIS only depends on economic efficiency. To date it is only possible to drive without driver or only one driver in the leading vehicle if that way of operation lowers or eliminates personnel costs. If the devices for platooning (communication, control are independent of the platoon length, operators will want to platoon as many trucks as possible (fig. 1).

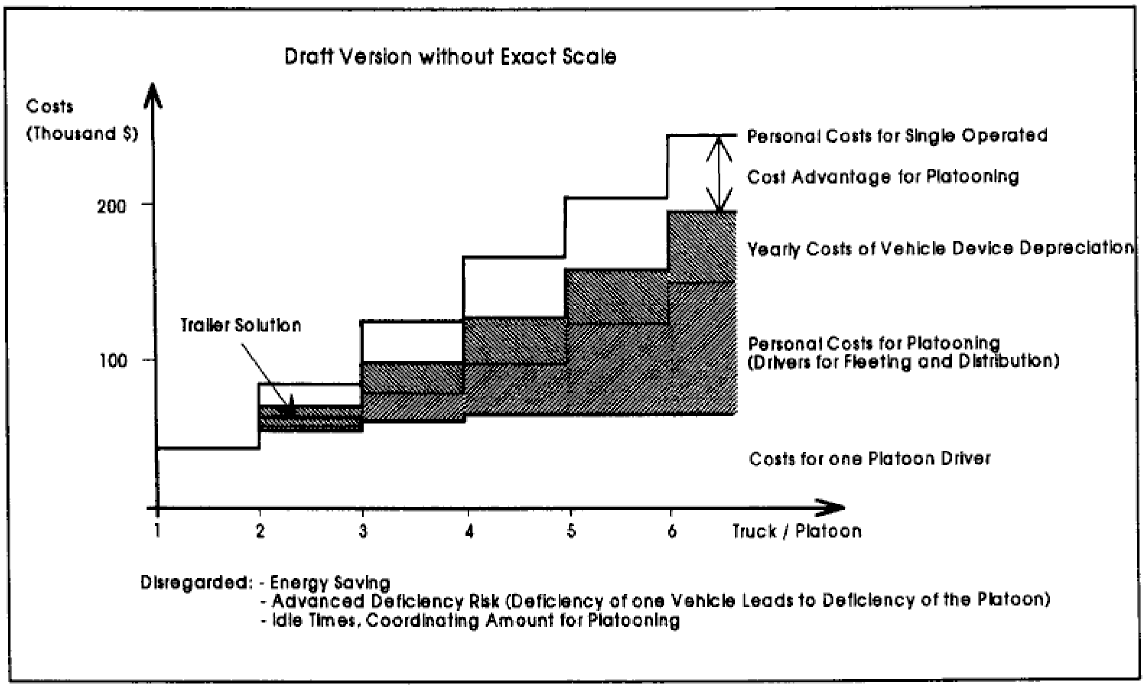



Figure 1. Comparison of truck costs and truck platoon costs

Platooning of truck-couples may not always lead to cost-efficiency. Examples are:

1. The most cost-efficient solution is the so called trailer solution because of a simple dedicated vehicle equipment. But in that case there is no possibility to exchange leading and following vehicle. That means a high coordination effort for an all time operation of truck-couples is necessary.

2. The personnel costs are higher if there is a need for higher qualified drivers of leading vehicles. Higher personnel costs may also result from legal safety derivatives (e.g. second driver in lead vehicle).

3. Personnel costs are also generated by composing and decomposing truck platoons and feeder services at points of origin and destination.

#### 2.1.3.2. Estimation of AHS potential

Based on the facts of chapters 2.1.2.3. and 2.1.3.1. and the assumption of freight terminals in agglomeration areas the potential for MIS-platoons of at least two trucks can be estimated.

Figure 2 shows the domestic long-haul freight demand of 1986 in Germany between 329 transportation cells.

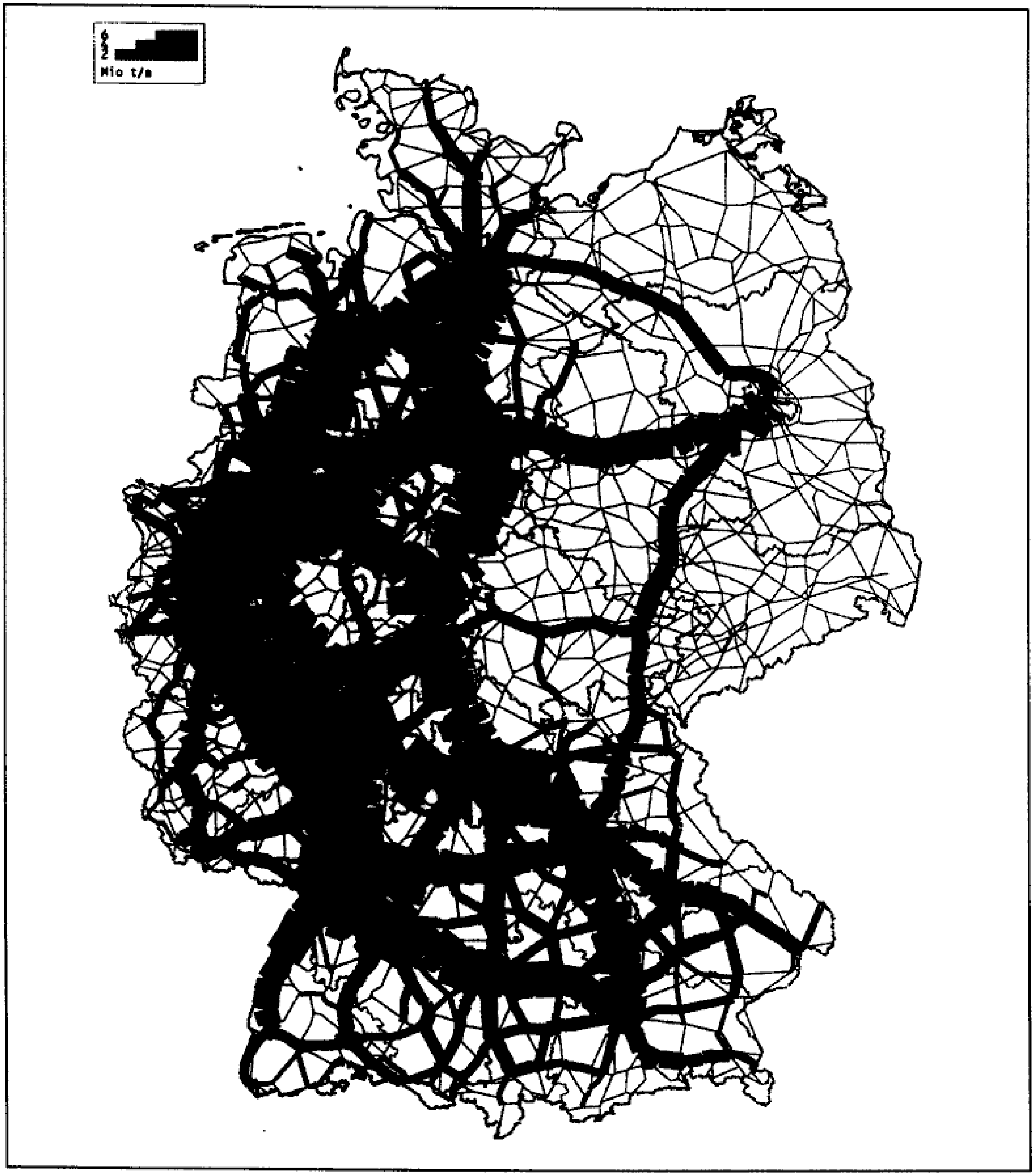



Figure 2. Long-haul freight transport in Germany 1986

By an evaluation function (fig. 3) long-haul transportation of distances with no more than 100 km are eliminated. The potential for platooning increases from about 10% to 100% for distances between 100 and 400 km, respectively and remains 100% for longer distances.

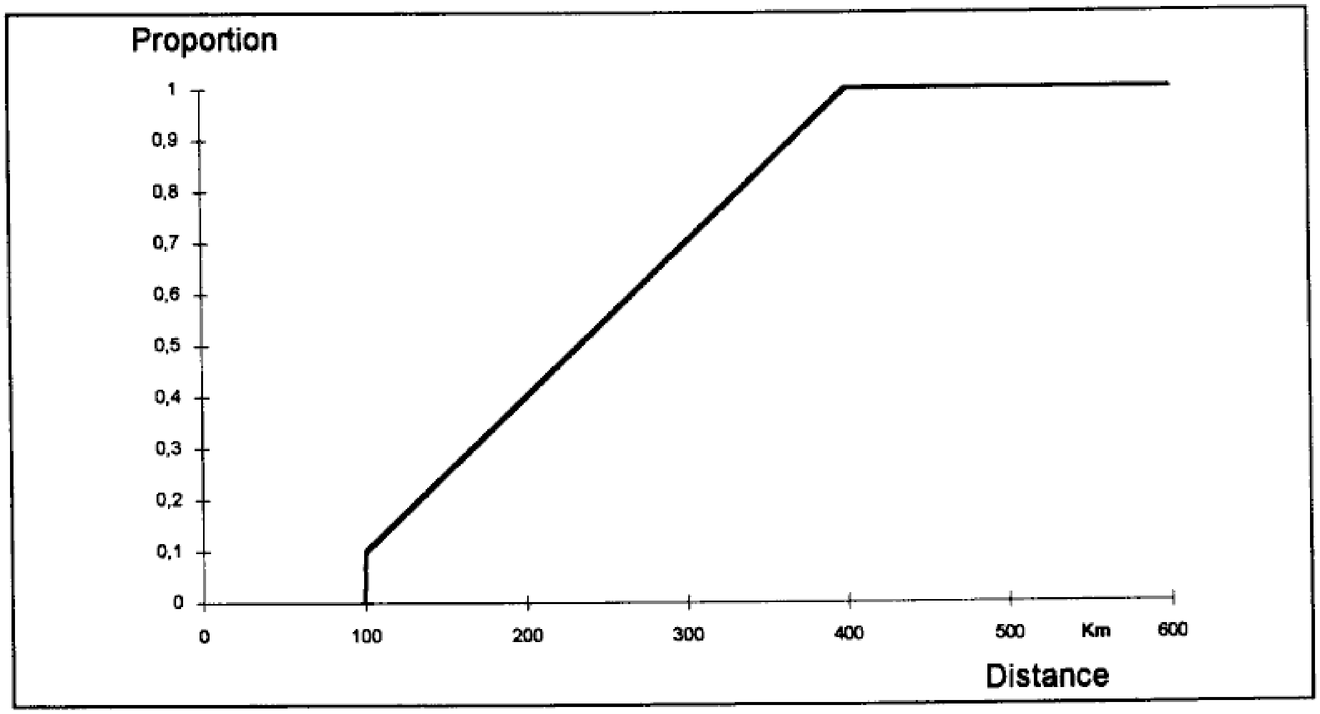



Figure 3. Valuation filter

Figure 4 shows the resulting potential for Germany.

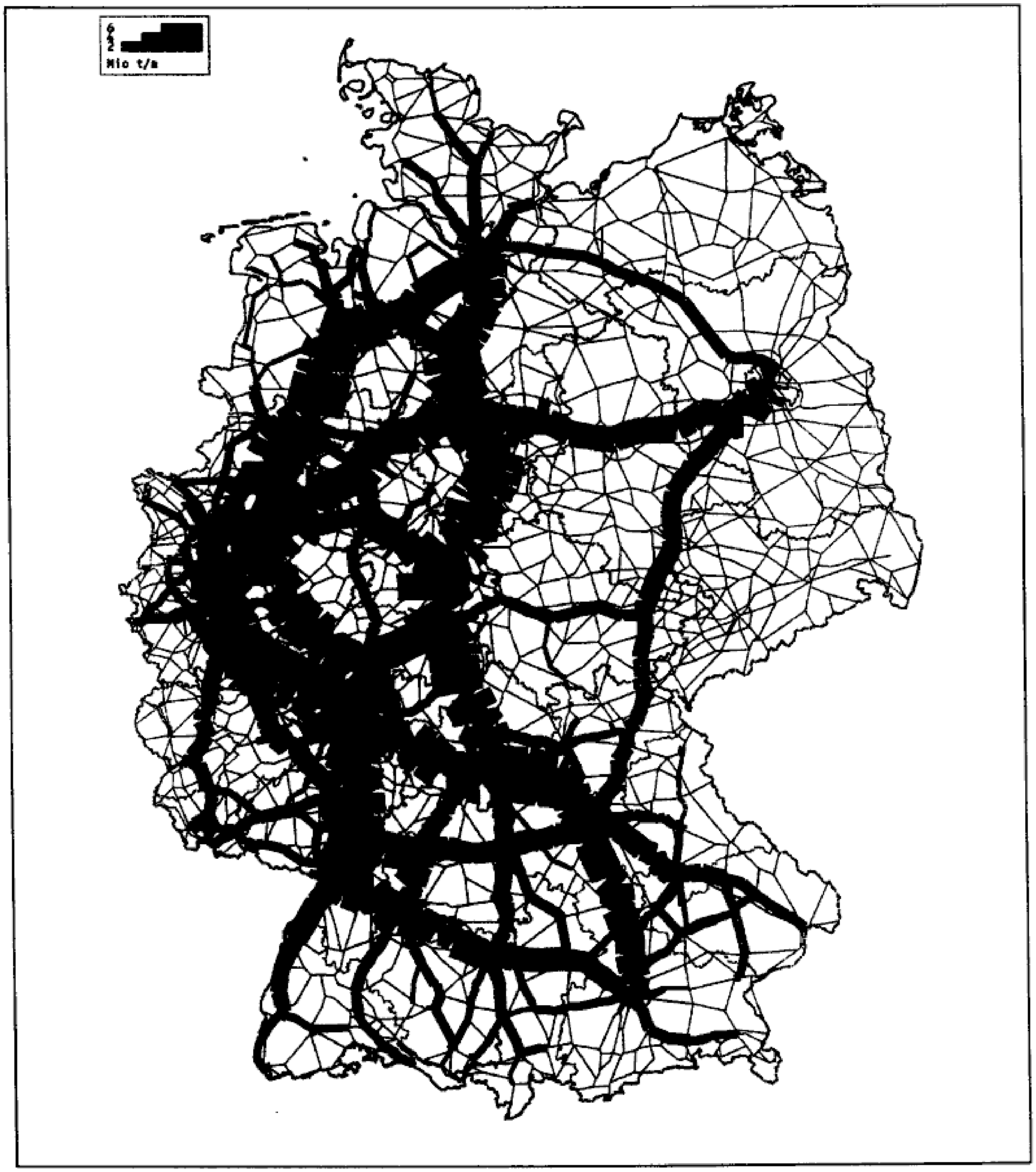



Figure 4 Long-haul freight transport in Germany 1986
Capable of bundling

In a second step the daily potential of two-truck-platoons is estimated, which corresponds to an annual freight demand of more than 6000 t in dedicated relations (fig. 5).

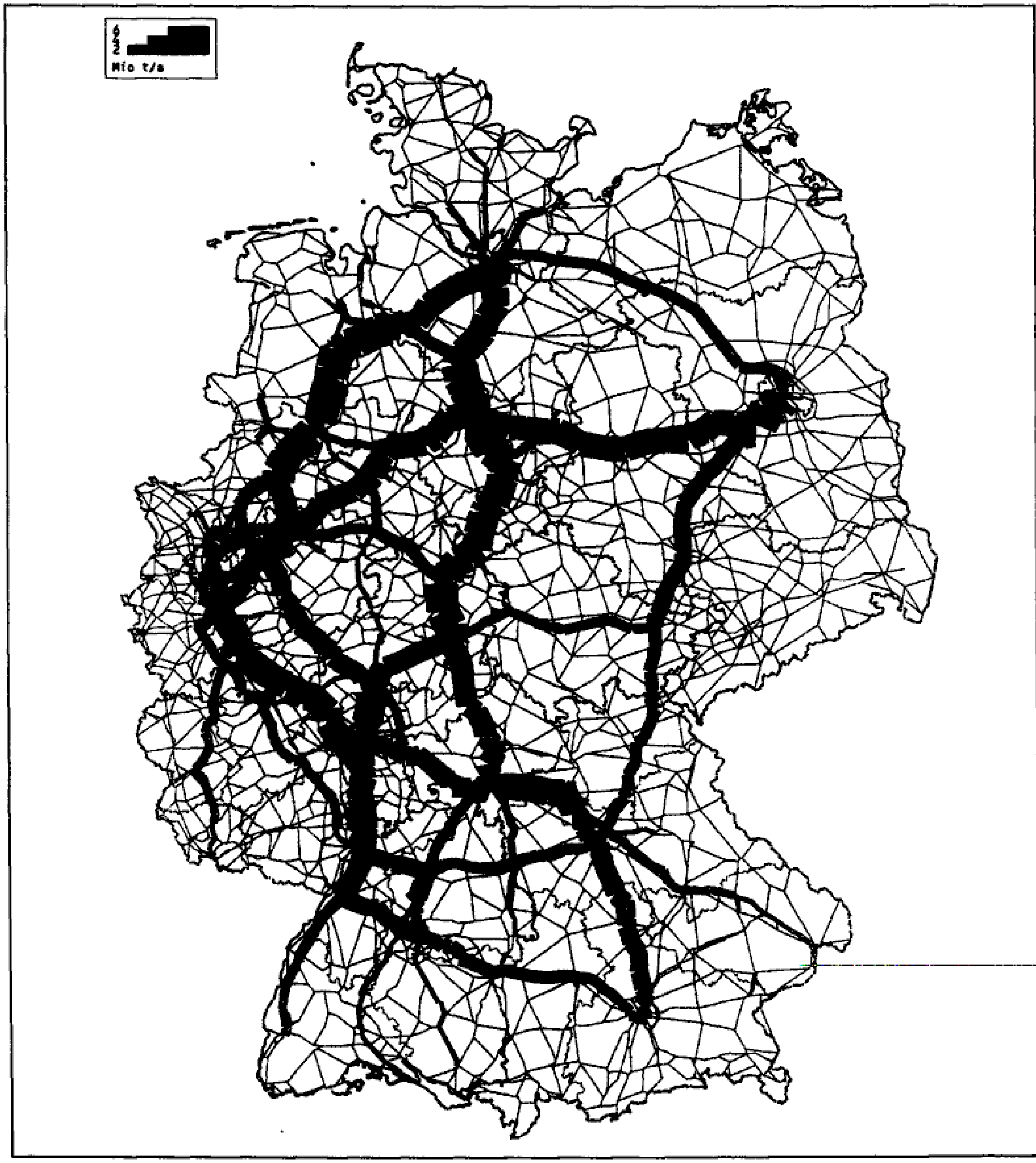



Figure 5. Long-haul freight transport in Germany 1986
Capable of daily bundling

As an example for such a district with high freight demand, Hamburg is shown with its domestic transportation relations (fig. 6). Filtering of freight demand by the procedure outlined before, leads to the annual (fig. 7) and daily potential (fig. 8).

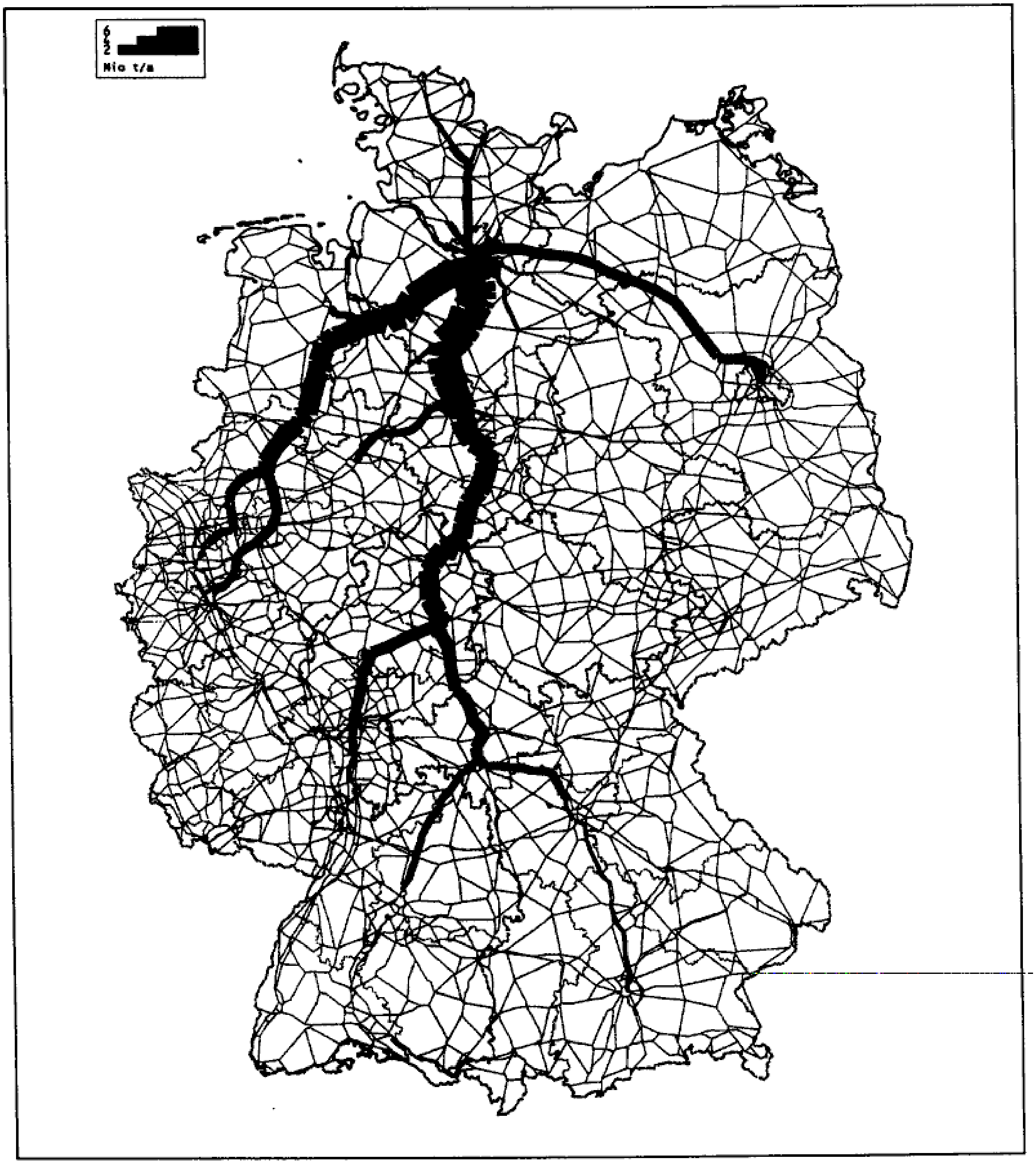



Figure 6. Long-distance freight transport to and from Hamburg 1986

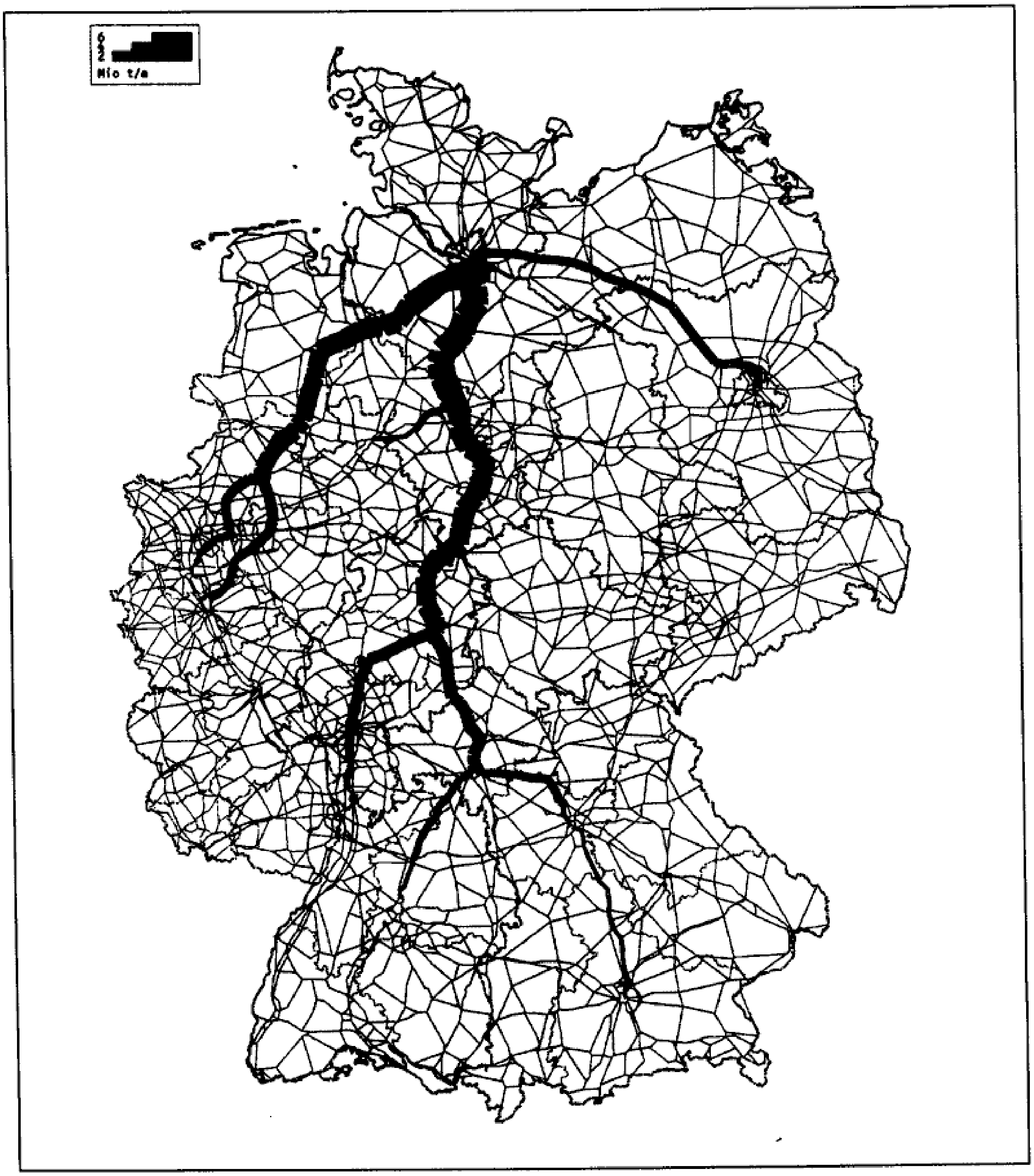



Figure 7. Long-distance freight transport to and from Hamburg 1986
Capable of bundling

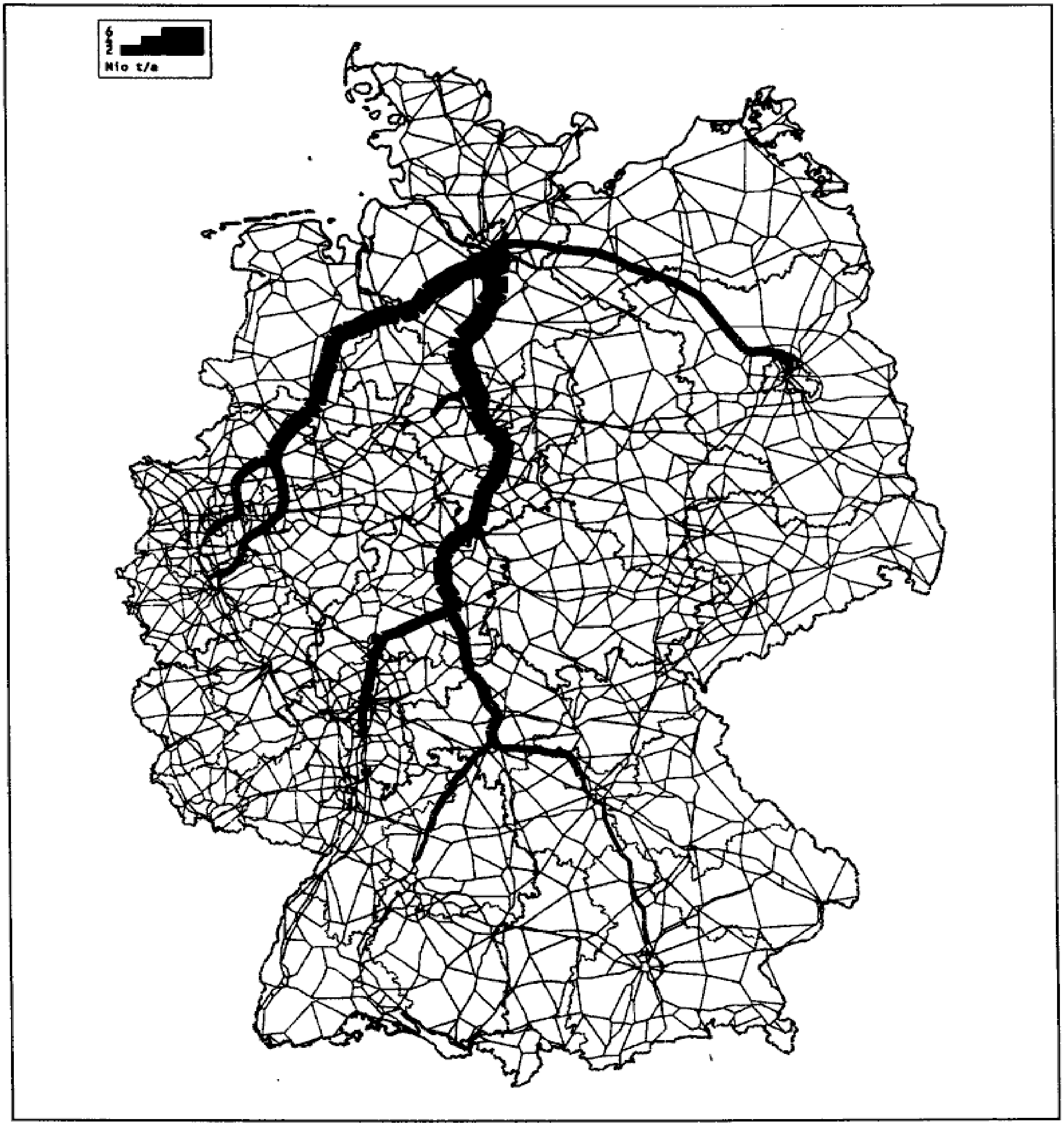



Figure 8. Long-distance freight transport to and from Hamburg 1986 Capable of daily bundling (at least two trucks per day)

Obviously, the potential of a super regional freight center is much higher than the average operation. Expressed in freight mileage, the daily potential for platoons of at least two trucks is

29% for Germany and 70% for Hamburg. Platooning of 5 trucks leads to a potential of 15% for Germany and 56% for Hamburg. With respect to an introduction strategy of platooning there is a higher probability of potential users in supra regional freight centers than in other areas.

#### 2.1.4. Introduction strategies

The results of the preceding investigations show, that the Terminal-composed platoons generate the highest operational benefit. Increasing platoon length decreases the potential. That is why it is recommended to use dynamic platooning for more than two trucks.

In a first step MIS should be introduced in closed test-networks (MIS-only-networks), e.g. night-time operated. After a successful test period it is possible to extend MIS-operations on reserved/opened networks or lanes of the public road network.

MIS-operations should start with planned (composed in terminals) two-truck-platoons and later on there is a possibility to extend the length of platoons dynamically (on the road) or to compose platoons of independent single MIS-trucks.

### 2.2. Simulation of Mixed AHS and Non-AHS Traffic

#### 2.2.1. Kernel of the micro simulation model

In figure 9 the headway between two cars following each other is outlined above their speed difference. The diagram is called "phase diagram". The phase diagram shows five regions of different behavior of the following car

- free driving
- following I
- following II
- closing in and

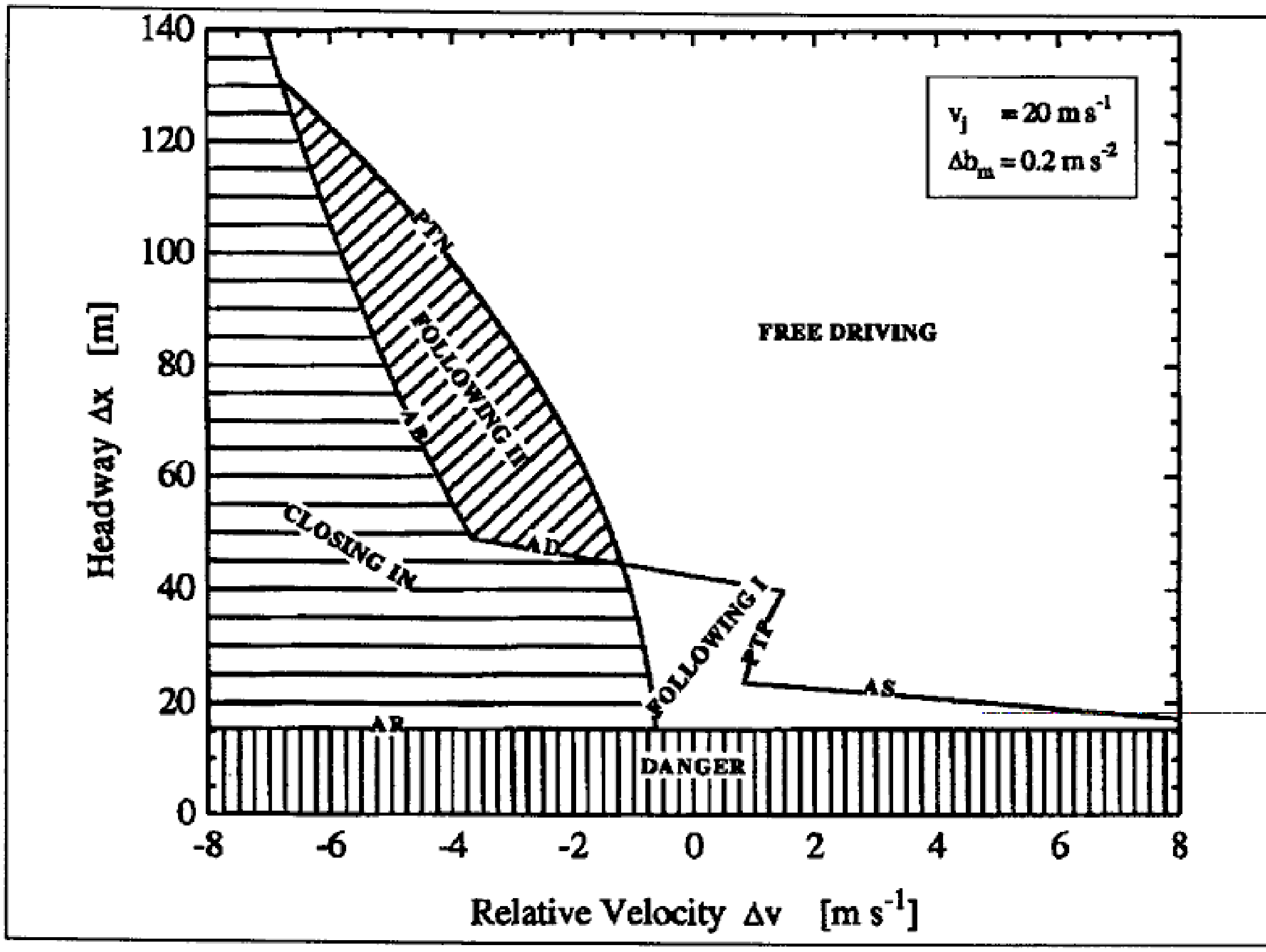



Figure 9. Car following phase diagram

These regions are determined by distinct borders. Two of them are the thresholds for perception of positive or negative speed differences by the driver in the following car against the leading car. These borders are shown as parabolas. Further, there are three straight lines representing the desired headway, the Safety headway, and the risk headway. Another parabola is shown as an emergency breaking headway, that means, the following driver has realized that he is in the closing-in-region but his speed is so high that he would fall below the desired headway. Then he chooses a deceleration which will lead right to the risk headway. This point is the vertex of the parabola.

If a following car has no chance but to follow the preceding car (no possibility for passing), then the headways follow some curves which are softly squeezed in by the perception borders. That means in the following-I region a driver is not able to realize whether his car goes slower or faster than the preceding car. If the following-I situation lasts for a longer period of time, then there may be a trend to longer headways over time (fig. 10).

Additionally, the model allows overtaking for non-MIS-vehicles. Overtaking is prohibited for MIS-vehicles. MIS-vehicles have to stay in the first lane.

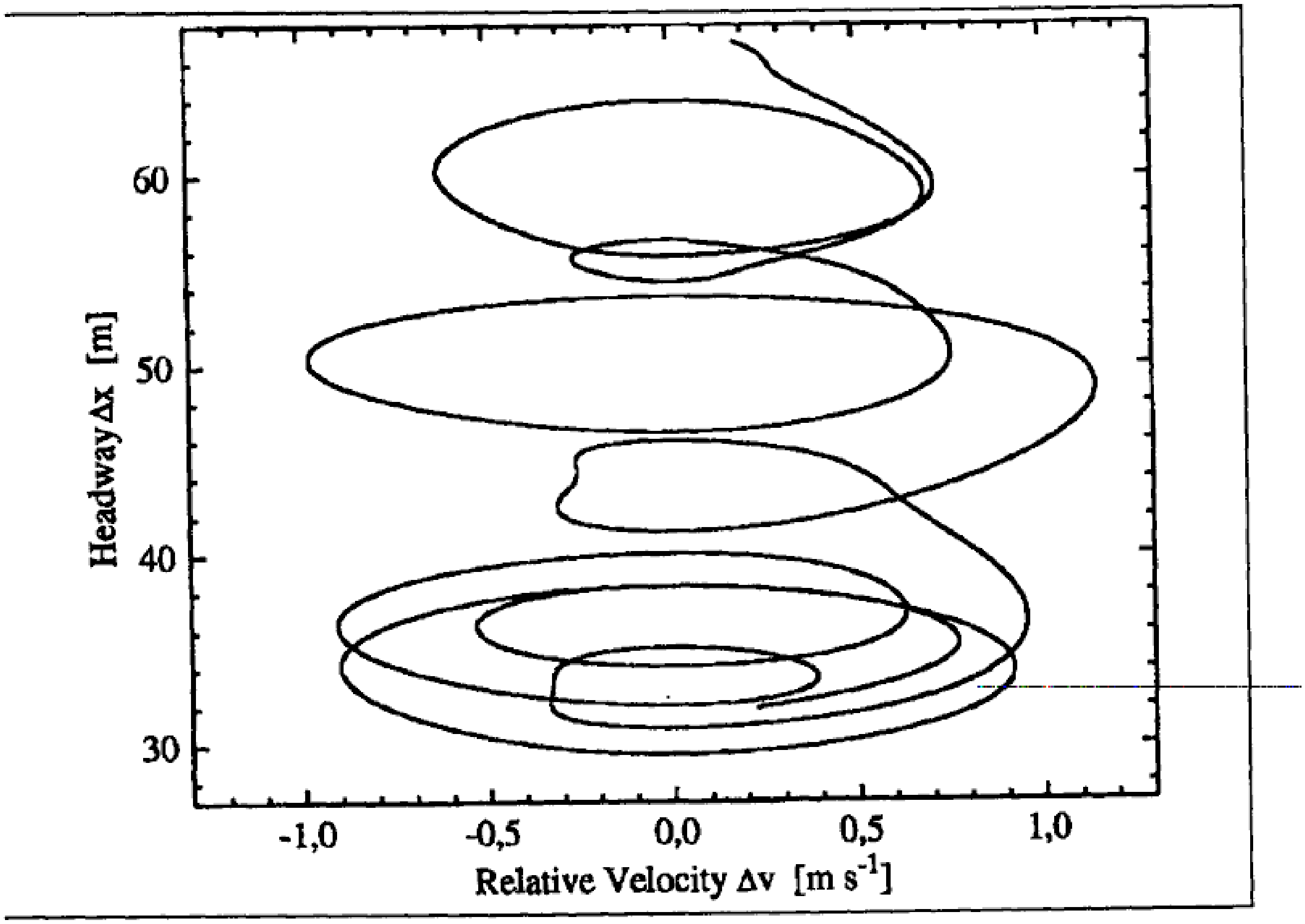



Figure 10. Car-following phase diagram
Example with trend to longer headway

### 2.2.2. Simulated situations

The simulations have been performed for a closed-loop highway section of the length of two kilometers. The section consists of a one-directional two-lane-carriageway. The advantage of a closed-loop-simulation consists in the possibility of catching all different traffic conditions (free driving, traffic jam, stop-and-go etc.) dependent on the prescribed density (vehicles/km), which is not possible on an open-end-section.

Simulations have been performed for free driving cars, free driving cars and trucks, and for free driving cars and clustered trucks on two-lane carriageways. For reasons of comparison, also simulations for clustered cars have been performed.

The proportion of trucks to all vehicles has been varied. Cars have been assumed a length of five meters, trucks a length of 18 meters, respectively. The minimum headways for the maximum density (all vehicles at a stand still) as well as the distance between clustered trucks have been assumed 1.5 meters each. The density has been varied from very small values to nearly maximum density in each case.
The simulation duration was 720 seconds in each case. The first 180 seconds were used for the consolidation of traffic flow in the sense of compensating small mistakes in determining the

starting conditions (spacing, speeds, accelerations) for all vehicles or platoons. The next three intervals of 180 seconds each were used for exploitation.

The flow was measured at a distinct cross-section in the middle of the road section as vehicles passing this cross section during the given period of time of 180 seconds but projected to hourly values, the speed was measured as instantaneous (time-weighted) speeds of all vehicles on the section, and the density was measured in vehicles on the whole section during the investigation interval weighted with the duration of simulation time steps and afterwards related to a unit length of one km.

### 2.2.3. Free driving vehicles

Looking at the results of the simulation for free driving cars especially in the flow-density diagram (fig. 11), two characteristics are immediately evident: The maximum for all functions representing different proportions of trucks to all vehicles lie in the same region of about 40 to 60 vehicles per kilometer, exactly the range, where traffic flow converts from stable to unstable. The corresponding speeds are between 80 and 55 km/h. But the end of the functions at the right hand side vary in a wide range. The maximum density for cars only (computed with the given figures) is 307 vehicles per kilometer, whereas for a ratio of 1:2 for trucks to cars the maximum density is only 184 vehicles per kilometer. The difference in the maxima can immediately be traced back to the length of the vehicles.

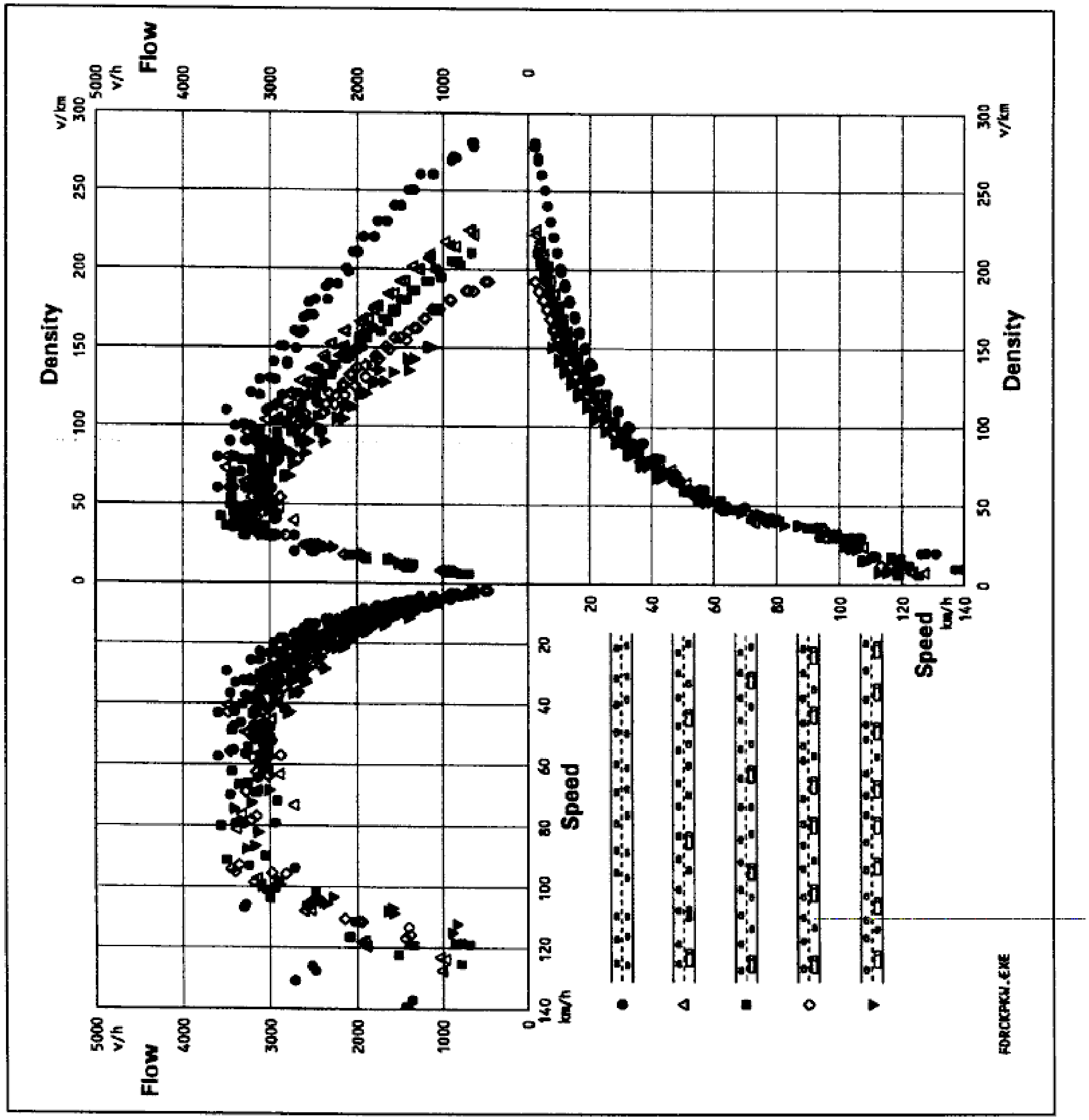


Figure 11. Simulation of non-MIS traffic on two-lane freeways

### 2.2.4. Ratio of 1:2 for trucks to cars

The next graph. shows the results for mixed MIS and non-MIS traffic with a ratio of 1:2 for trucks to cars (fig. 12). Declaring the maximum density of 184 vehicles per kilometer as pivot point, the straight lines can be drawn from there in the dots with different symbols standing for single operated trucks (filled triangles), clusters of two trucks each (diamonds), and clusters of five trucks each (filled circles). Measuring it against the line for single operated trucks, an increase of volume of about 15% for clusters of two trucks and of about 30% for clusters of five trucks may be noticed. Clustering is useful in order to increase traffic volume, or, m other words, the same density of vehicles in either case can be handled at a higher level of speed.

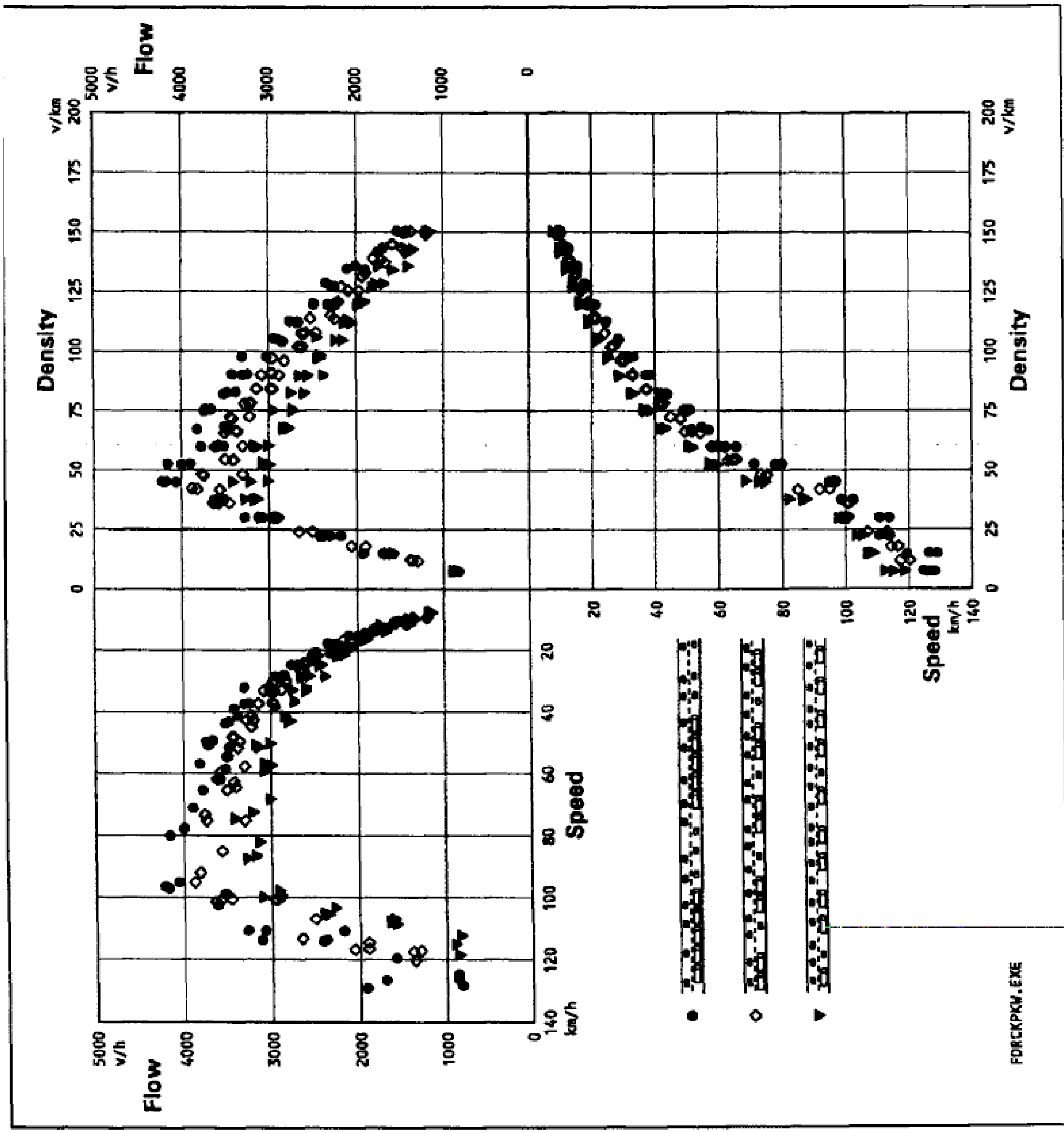


Figure 12. Simulation of mixed MIS and non-MIS traffic on two-lane freeways. Ratio of 1:2 for number of trucks to number of cars.

### 2.2.5 Other ratios for trucks to cars

Variation of the ratio for trucks to cars leads to the recognition that the increase of traffic volume by clustering trucks decreases with decreasing proportions of trucks. In the case of a ratio of 1:3 for trucks to cars (fig. 13), the increase of traffic volume by clusters of five trucks each is but about 28%. Reducing the ratio to 1:5 (fig. 14), the increase is only about 14%, and in the case of 1:7 (fig. 15) the increase is already reduced to about 10%.

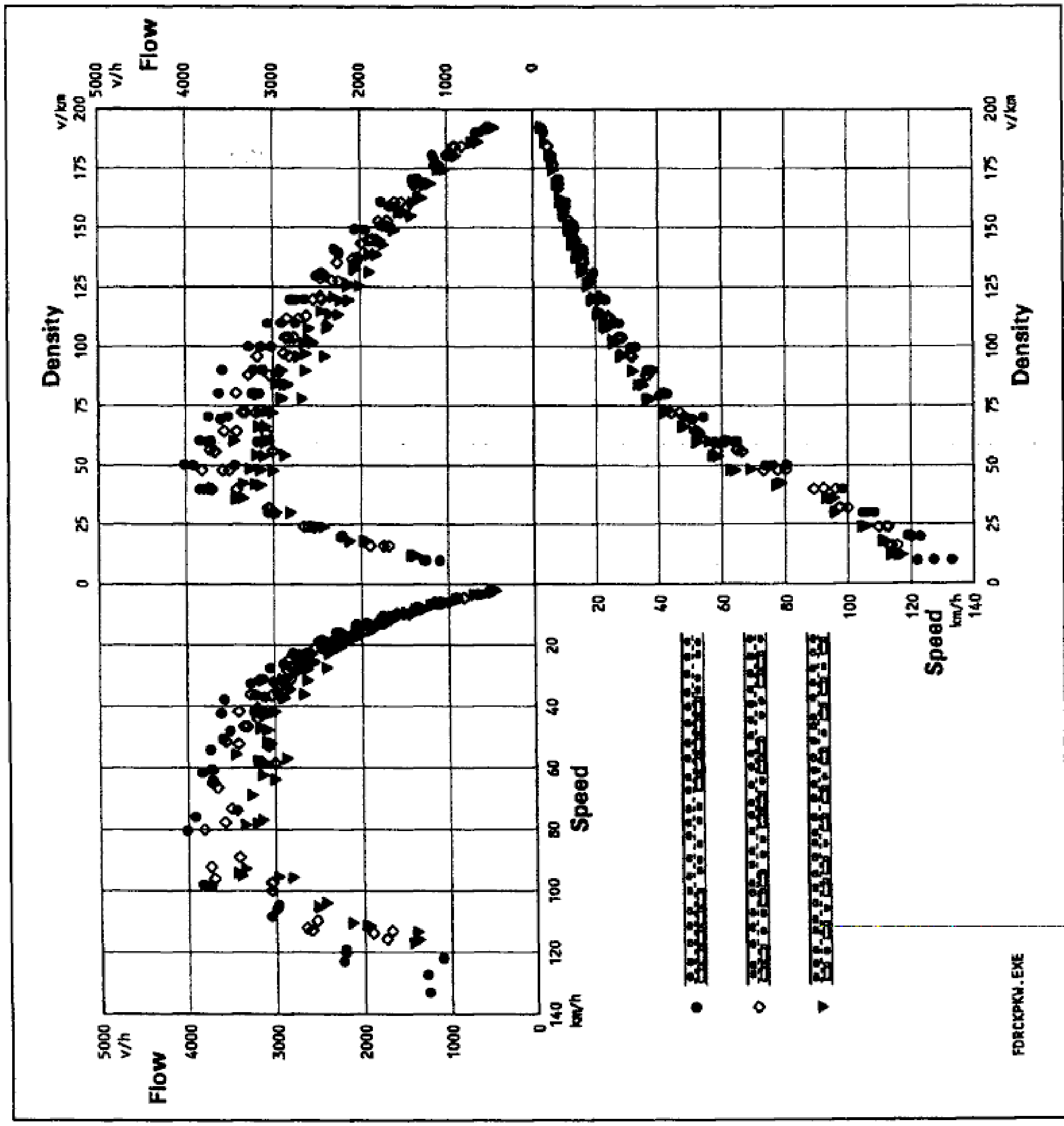



Figure 13. Simulation of mixed AHS and non-AHS traffic on two-lane freeways.
Ratio of 1:3 for number of trucks to number of cars

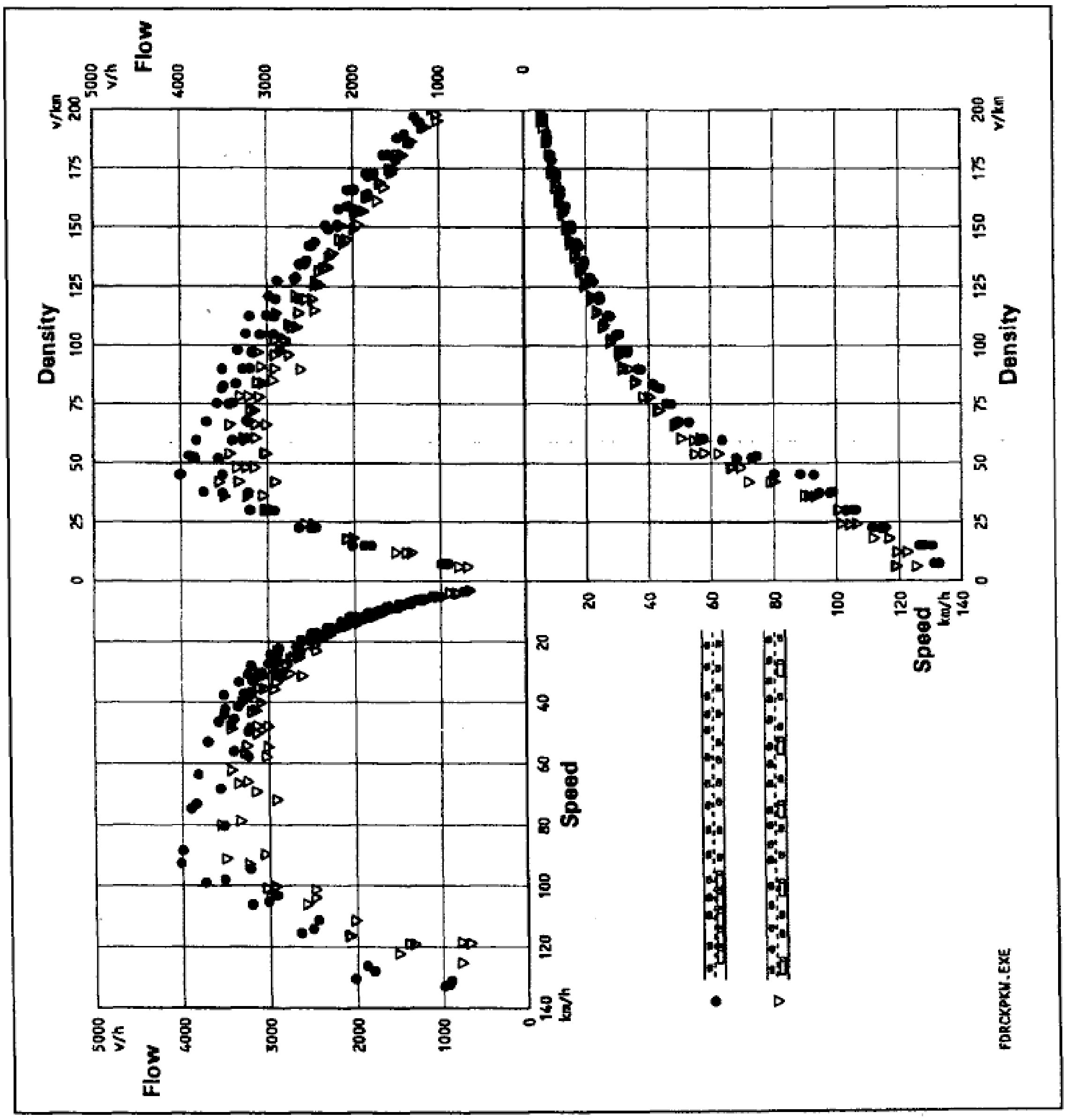



Figure 14. Simulation of mixed AHS and non-AHS traffic on two-lane freeways. Ratio of 1:5 for number of trucks to number of cars.

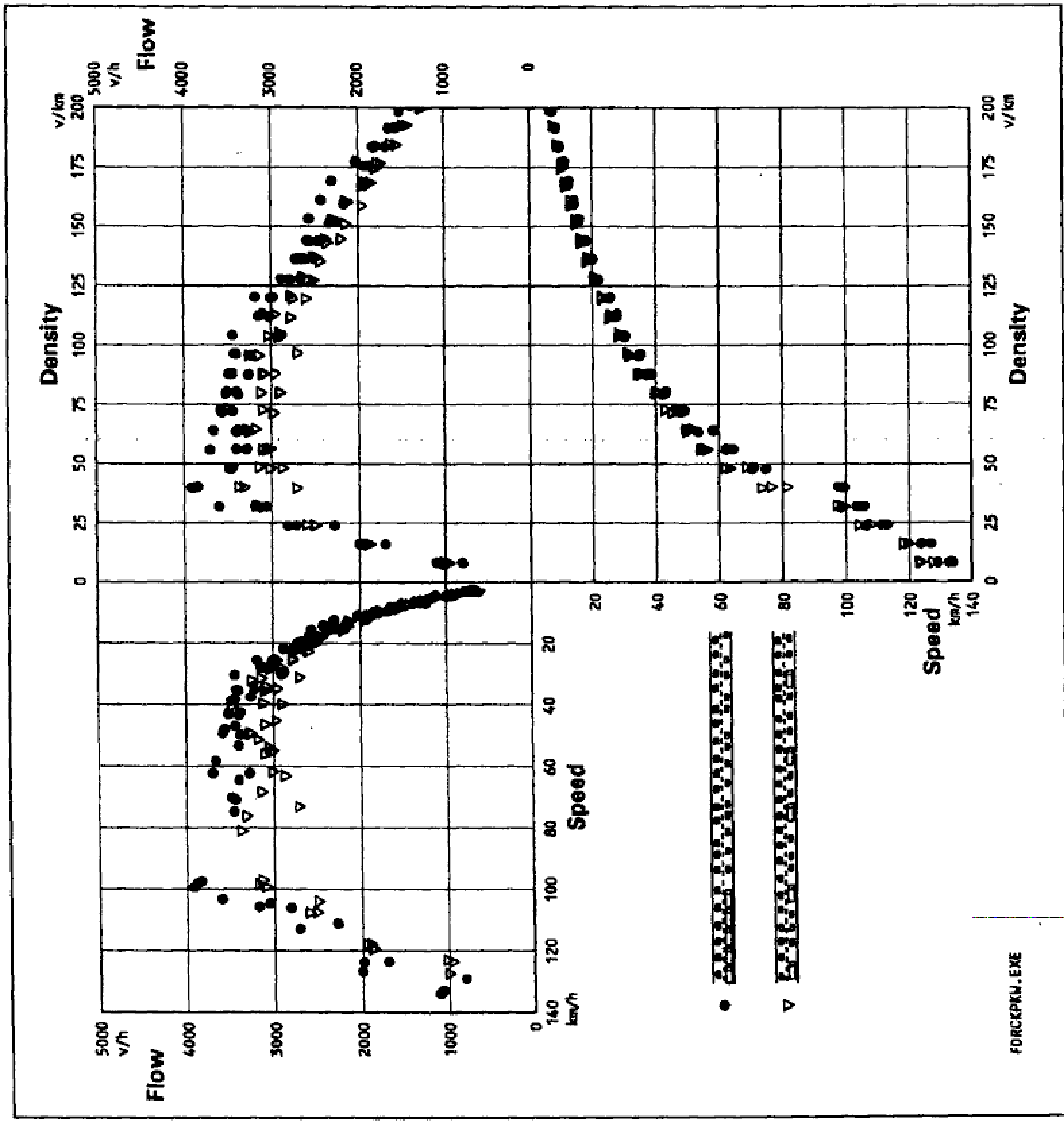



Figure 15. Simulation of mixed MIS and non-MIS traffic on two-lane freeways.
Ratio of 1:7 for number of trucks to number of cars.

### 2.2.6. Mixed AHS and non-AHS traffic with cars only

In comparison to the mixed traffic with MIS and non-MIS trucks, simulations of mixed traffic with MIS and non-MIS cars have been performed. The results of the simulations show that the increase of

throughput by clustering cars is bigger than with commercial vehicles. In addition, a greater proportion of vehicles may be clustered because of the majority of cars against trucks.
In the case of a ratio of 1:1 for MIS cars and non-MIS cars (fig. 16), the increase of throughput against single operated cars is already about more than 25% for clusters of two cars and about 67% for clusters of 10 cars.

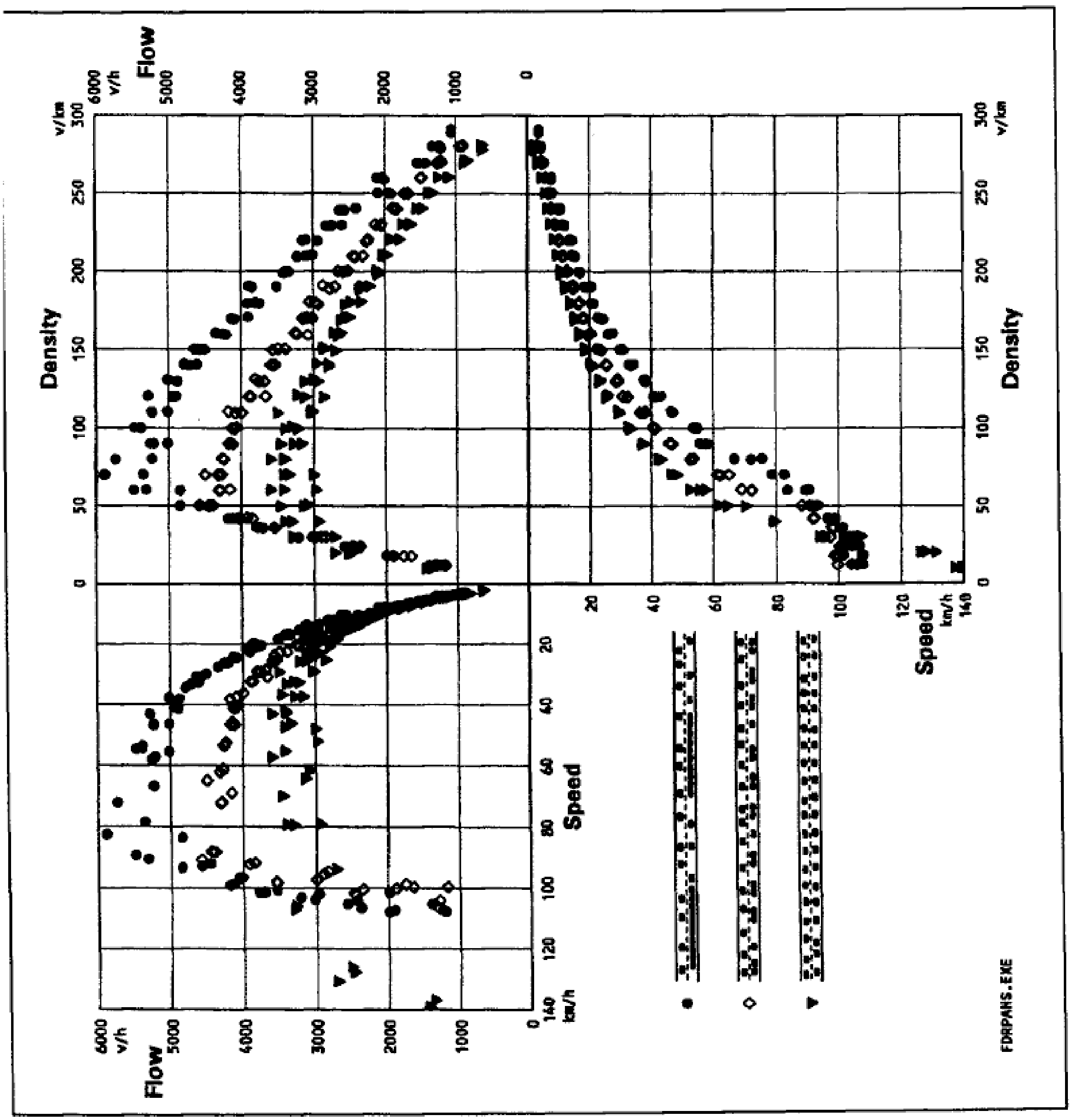



Figure 16. Simulation of mixed MIS and non-MIS traffic on two-lane freeways.
Ratio of 1:1 for MIS-cars to non-MIS cars.

### 2.2.7. Conclusions

Generally, increasing proportions of clustered vehicles of all vehicles lead to an increase of traffic volume. In case of clustering cars, the effect is greater than with clustering trucks. These effects are important for highway administrations, but not necessarily for users unless they can take advantage of much less travel time. It is a problem for users to evaluate travel time advantages. (Are the time savings worth to spend a certain amount of money for onboard devices?)

With respect to an acceptance of automated vehicles by users, the probability of realization with trucks may be higher. Carriers operating trucks for example, immediately realize an economic advantage, if they can operate clusters of trucks with only one driver in the first truck followed by automatically driven trucks. The costs for depreciation of the technical devices on the trucks must be less than the personnel cost.

## 2.3. Communication and Control Concepts for Commercial AHS

### 2.3.1. Control

In Automated Highway Systems, both longitudinal and lateral movements of vehicles must be controlled, depending on degree of automation. This control is a low-level function which receives reference values or reference trajectories from higher-level functions such as platoon control or lane control. Overall system performance and safety largely depend on the dynamic qualities of these basic control functions

Under normal operating conditions, longitudinal and lateral control can be regarded independent of each other. The tires operate in the linear region of their characteristics, and longitudinal and lateral forces do not significantly influence each other. Only in emergency situations there is a direct coupling between longitudinal and lateral movements, e.g. on hard braking in a bend. To handle such driving conditions, control design must take this coupling into account, and a complete non-linear drive-by-wire control concept should be applied. However, this is beyond of the scope of this paper.

Lateral control is also not considered here, since various control concepts have been developed in research on automated driving, both in Prometheus and in PATH programs. Lateral dynamics of vehicles is well covered by linear models, including the steering system. Control design is then straightforward with the vehicle speed used as a parameter. Even a design with constant parameters can yield good performance over the whole range of operating speed.

In contrast, longitudinal control has to deal with strong nonlinearities in the drive train, and large variations of the model parameters over the whole speed range. It is therefore useful to separate the problem into two parts. A basic acceleration or speed controller can virtually linearize the longitudinal dynamics. Distance control can then be designed based on a linear model.

#### 2.3.1.1. Vehicle Control

The design of longitudinal control is of great importance to Automated Highway Systems with respect to both performance (i.e. inter-vehicle spacing) and safety. It must cover the whole speed range from almost zero to maximum speed. The brakes must be controlled to a high degree of deceleration. Delays must be kept to a minimum, and dynamic response should be as fast possible. Also, static accuracy requirements are high. Standard cruise control systems do not meet these requirements, since they are designed only for speeds above 15 mph, and neither the brakes are applied, nor is the dynamic response of great importance in this application.

Longitudinal Dynamics Model

Regarding a block diagram of the drive train model depicted in figure 16, one can see the main components which are involved in longitudinal control.

The Electronic Throttle Actuator typically is a production version which is possibly modified to receive throttle commands from the vehicle control system via data link (e.g. CAN) or an analog signal. The standard actuator speed (full range within less than 100 ms) is sufficient, however additional delays due to filtering or plausibility checks of commands must be strictly avoided. Throttle commands generated by the vehicle control system are assumed to be smooth and valid. For simulation purposes, the throttle actuator can be represented by a first-order system.

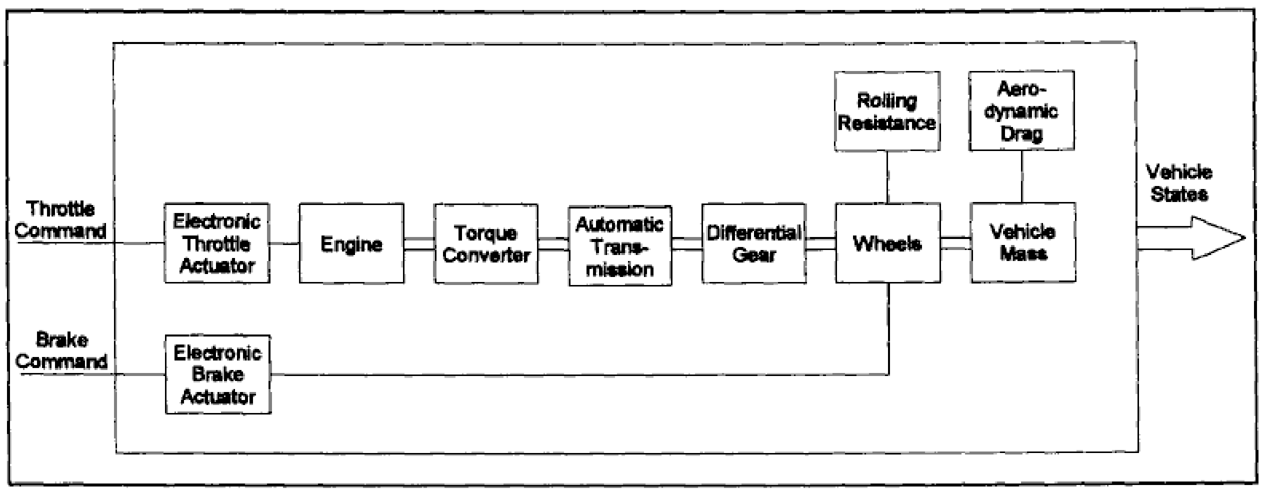



Figure 17. Basic components of a nonlinear model of vehicle longitudinal dynamics

The Engine is described by a two-dimensional torque characteristic depending on engine rpm and throttle position, the standard speed-torque graph. By depicting torque vs. throttle position with rpm as a parameter (Cf. fig. 18), the strong nonlinearity is obvious. The dynamic behavior of the engine can be neglected, except for the rotating mass connected to the pump wheel of the torque converter.

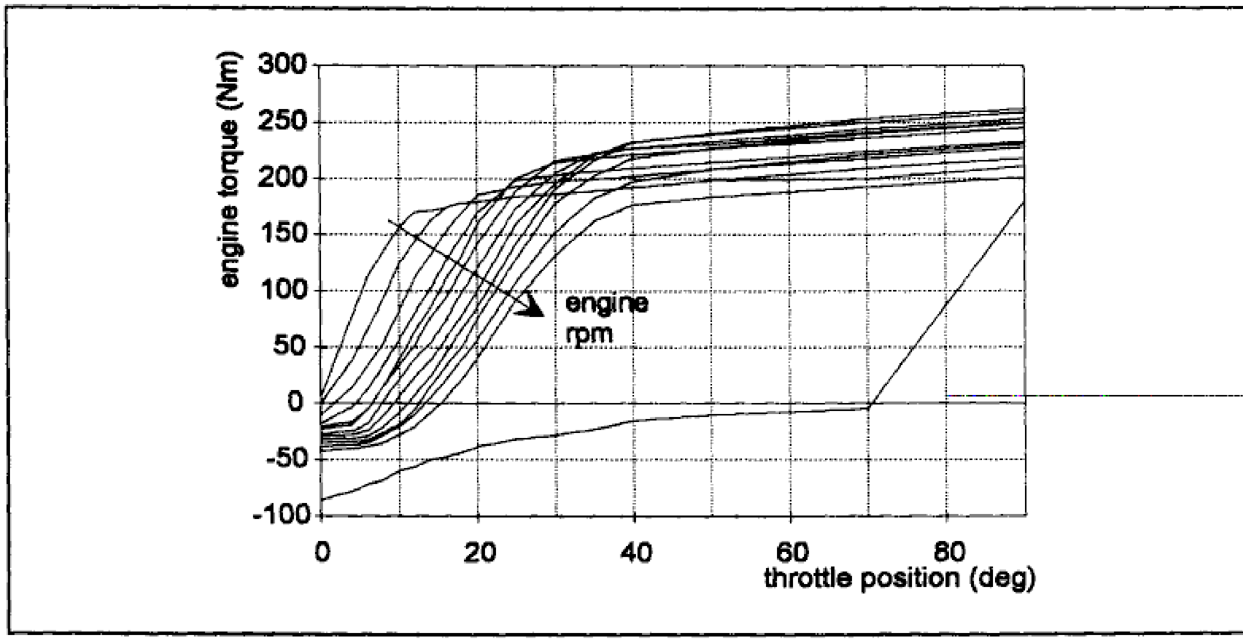



Figure 18. Typical engine characteristic showing torque vs. throttle position with engine rpm as a parameter

The Torque Converteralso is a nonlinear system. It is described by a set of characteristics depending on the ratio of input and output speeds. The torque both at the input and output shaft depends on this ratio. As long as there is no converter-lockup, the rotating mass of the engine and the vehicle mass are separated by the torque converter. When the lockup is engaged, this separation is suspended, which means a change in model structure.

The Automatic Transition and the Differential Gear must be taken into account for the overall gear ratio and for the efficiency. Gear ratio of the transmission - and hence overall gain - typically varies by a factor of four. Therefore the actual gear step must be known to the longitudinal controller. It can be estimated from the ratio of vehicle speed and engine speed, however the torque converter state should then also be estimated and taken into account.

The Electronic Brake Actuator generates brake pressure according to the brake command signal. Under normal conditions, vehicle deceleration is proportional to this value. Pressure rise time must be as small as possible, a value of less than 100 ms for maximum pressure being allowable.

Since pressure build-up speed is limited by the hardware, it cannot be influenced by any controller. A controller can only be used to achieve static accuracy. Even if brake pressure (or maximum deceleration) for longitudinal control is limited, the brakes must be equipped with an antilock system. Again, overall time delays must be kept to a minimum.

A simulation model of the described form has been implemented which can be used for a variety of vehicles including a light truck. It has been verified against measured data from open-loop tests as well as closed-loop tests with various longitudinal control schemes.

Because of the nonlinear and time-variant (or speed-dependent) nature of vehicle longitudinal dynamics it is advisable to use a subordinate control loop for acceleration or speed in order to simplify subsequent headway control design. An inner acceleration control loop is preferred, since acceleration is directly related to the torque generated by engine or brake to control vehicle movement. The headway controller would then generate acceleration commands. Even if this controller is tuned for fastest response to minimize headway without loss of safety, comfortable operation can be obtained by limiting the acceleration command in all but safety-critical situations.

In order to design an acceleration controller for the whole operation range of the vehicle, the knowledge about all nonlinearities should be used, i.e. a model-based approach is to be used.

In principle, the above model can be inverted, if all time constants are neglected. This means, from a given acceleration command, a corresponding throttle position or brake pressure can be calculated by inversion of the characteristics. The result is used as a feed forward control. In addition, a feedback controller of standard type is used to improve closed-loop response and to ensure static accuracy. The gain of this controller is adapted to the local system gain which can also be obtained from the characteristics. A controller of this type has been successfully implemented and tested on a station wagon as well as on a light truck.

This approach requires a good knowledge of all characteristics and parameters and is somewhat sensitive to parameter changes. However, this influence is small as compared to the limitations imposed by the time delays of throttle and brake subsystems. Closed-loop response quality is after all determined by such delays. Therefore, throttle and brake actuators with their local controllers must be optimized for fast response and zero delay in order to improve vehicle control and, finally, to achieve minimum inter-vehicle spacing.

#### 2.3.1.2. Simulation Tool

Daimler-Benz has developed a platoon simulation tool on the basis of the longitudinal dynamics model described in chapter 2.3.1.1. Since simulation time grows linearly with every additional vehicle in the platoon we decided to use a parallel computer system, so called transputers. This allows the parallel computation of the longitudinal dynamics of each member in the platoon instead of serial computation. Figure 19 shows the structure of the simulation of a controlled platoon on a Transputer system.

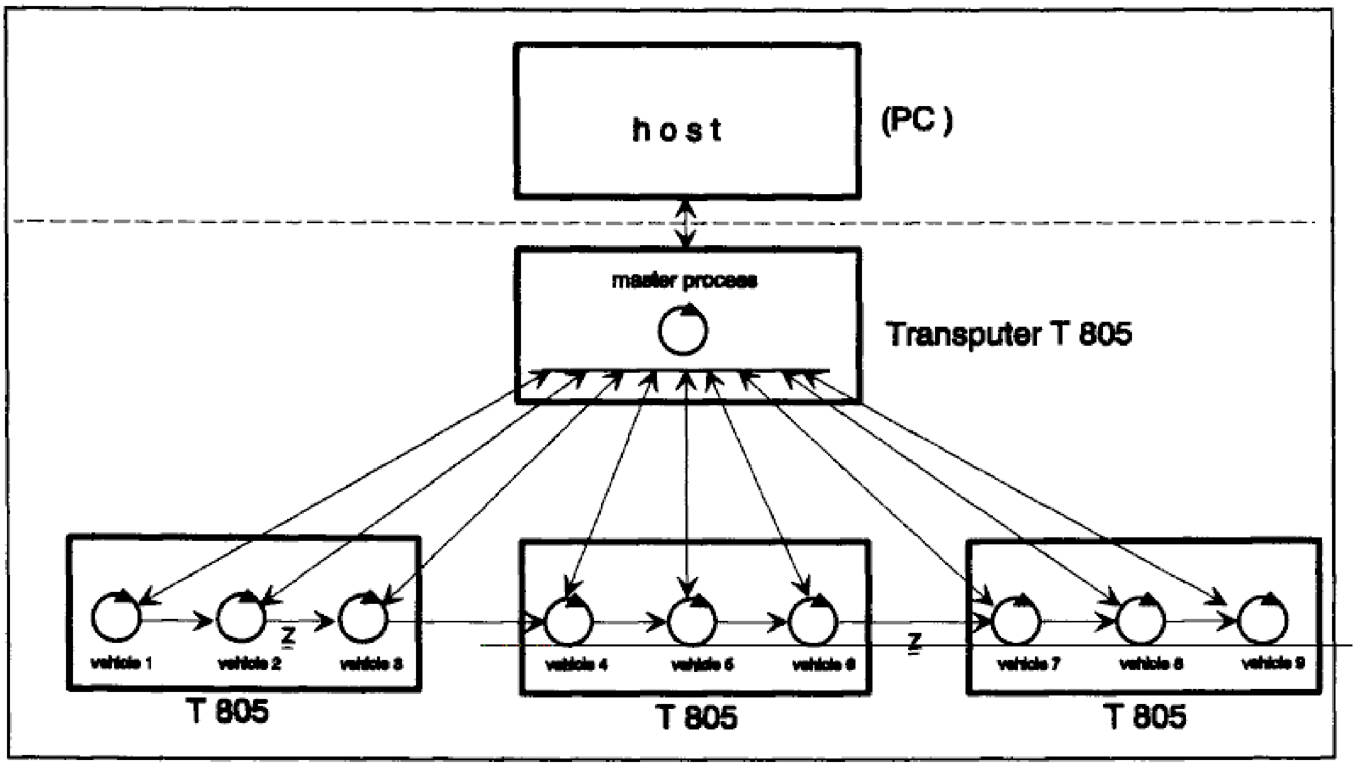



Figure 19. Platoon simulation on Transputer system

The master process manages the communication between the whole platoon simulation on the transputers and the host-PC. Each vehicle is represented as a process on a Transputer. A vehicle process integrates the model of the vehicle dynamics. This includes the underlying acceleration control and the distance control to the vehicles in front. The vehicle process also communicates with the master process and the neighboring vehicles. It receives information from the vehicle in front and sends information to the following vehicle.

The first vehicle in the platoon is a virtual vehicle included in the master process. Its acceleration and velocity profiles and therefore its covered distance are determined in advance. Vehicle number 1 in the platoon follows this virtual vehicle. In this way it is possible to test the vehicle controllers and the whole platoon control with standard test signals like a acceleration or speed step input.

### 2.3.1.3. Platoon Control

There are two principle ways of longitudinal control for road vehicles in a platoon: vehicle-follower (decentralized) and slot-follower (centralized, roadside communication needed) control. [SHL91A] reports a detailed comparison of the two longitudinal control approaches. The result is that the slot-follower control is simpler but not suitable for variable platoon length or for sudden demand shifts. Vehicle-follower control is more complicated but extremely flexible. Additionally, we want to use as little of the infrastructure as possible to keep costs low. Therefore we favorize the decentralized control without communication with the roadside. But of course with inter-vehicle communication. This concept also allows an evolutionary introduction of the system.

One objective of platoon control is minimizing inter-vehicle spacing. The minimum spacing depends on several parameters described in [IOA94]. One main parameter is the reaction time of the trailing vehicle, the time delay. This time delay can be minimized by inter-vehicle communication. So information about actual and target acceleration and speed of the vehicles in front are available in the trailing vehicles. Simulations also show that platoons with communication show greater stability than without.

Platoon control gets more difficult if the vehicles are big trucks rather than cars. This fact has a couple of reasons:

- greater time delays
- less deceleration capabilities
- larger differences in load

For this reason, platoon control with trucks is tested, since this is the more difficult task.

The distance control concept for the platoon is similar to that described in [SHL9 lB]: Every vehicle knows the speed and acceleration of the leading vehicle and of the one in front and the distance to the one in front. The difference between the concept introduced here and [SHL9 lB] is that here also the accumulated distance is communicated. The accumulated distance is the sum of the spacing of all vehicles in front. With this information each vehicle is able to calculate its longitudinal position in the platoon, that is, the distance to the leading vehicle. This allows a mixed concept of vehicle-follower control and a kind of slot-follower control. Each vehicle knows its slot in the platoon and follows the leading vehicle. Only in certain cases it switches to vehicle-follower control. This approach includes the advantages of slot-follower control (simple and stable) without the disadvantages (not suitable for platoon control).

Communication of speed, acceleration and status of the leading vehicle and the vehicles ahead is essential for a good and safe control. One possible control strategy could use a longitudinal position controller for all the vehicles in the row. Thereby distance control is within certain limits independent of the behavior of the vehicle in front. Only if control of this vehicle fails or if communication is incorrect a local distance controller (vehicle-follower control) without communication is taking over control as a backup safety flinction. In this case information is sent back to all vehicles in the chain that there is a failure and either the chain is driving with reduced capabilities or comes to a soft stop. The structure of the platoon control is shown in the figure 20 below.

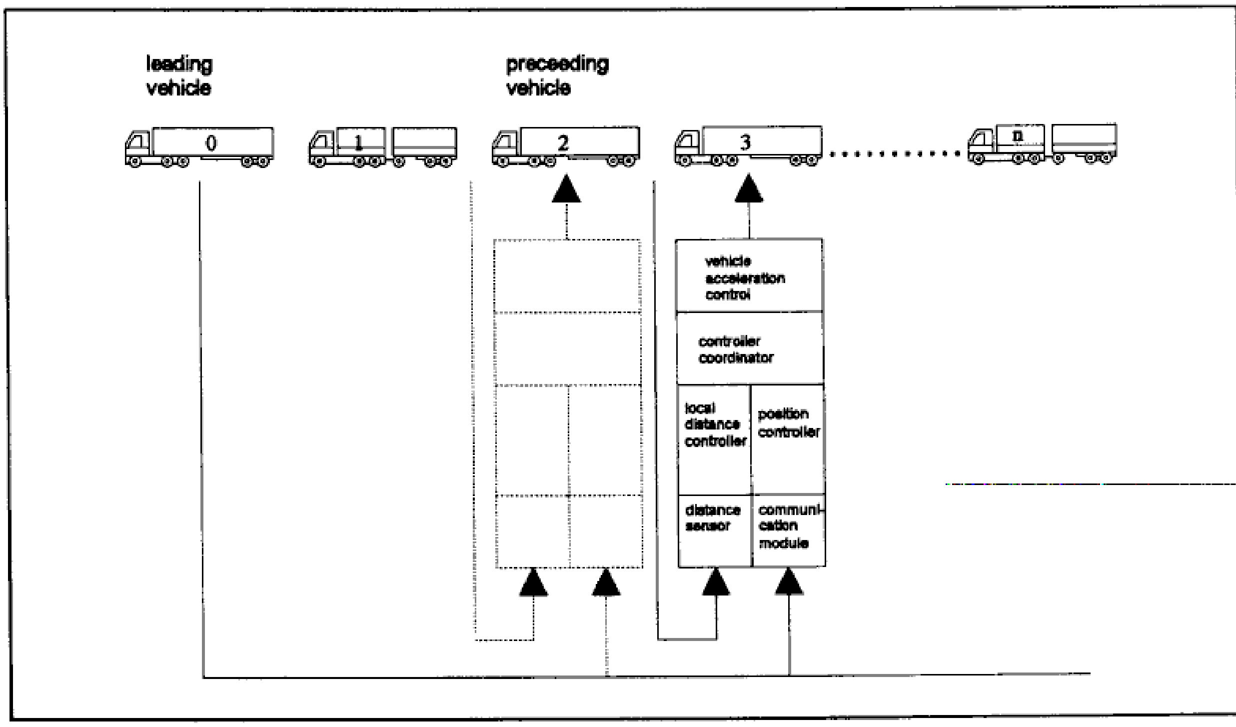
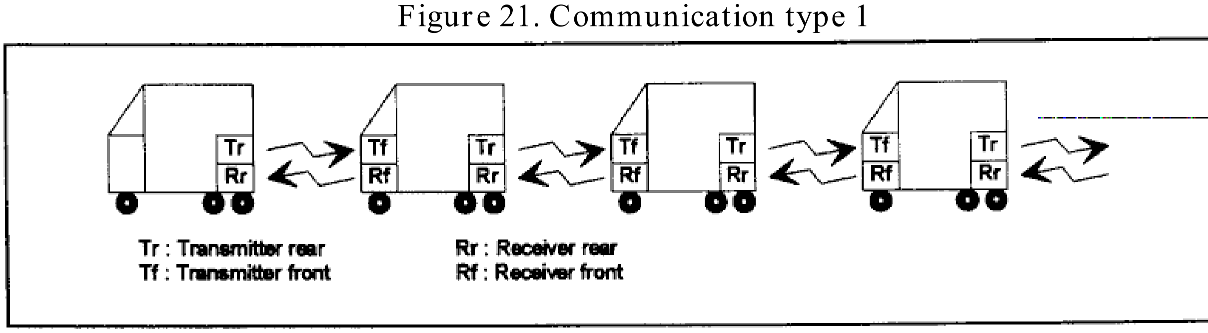



Figure 20. Controller structure

The local backup distance controller uses information measured in the vehicle and by the distance sensor. The position controller receives information of the leading vehicle and the accumulated distance via communication channel. Both controllers deliver nominal values for vehicle acceleration which are selected by a coordinator, taking care of safety with respect to communication quality. The output of the coordinator is input of the vehicle controller which is acting on throttle, brake and gear of the car.

A safety strategy for distance control depends strongly on the type of communication. The following sketches fig. 21 and fig. 22 show two types of communication, direct and indirect. Each vehicle has to know its position within the platoon and information of the communication status of all the vehicles must be available for the coordinators. A reduced capability flag is set when there is a communication failure.

Figure 21. Communication type 1



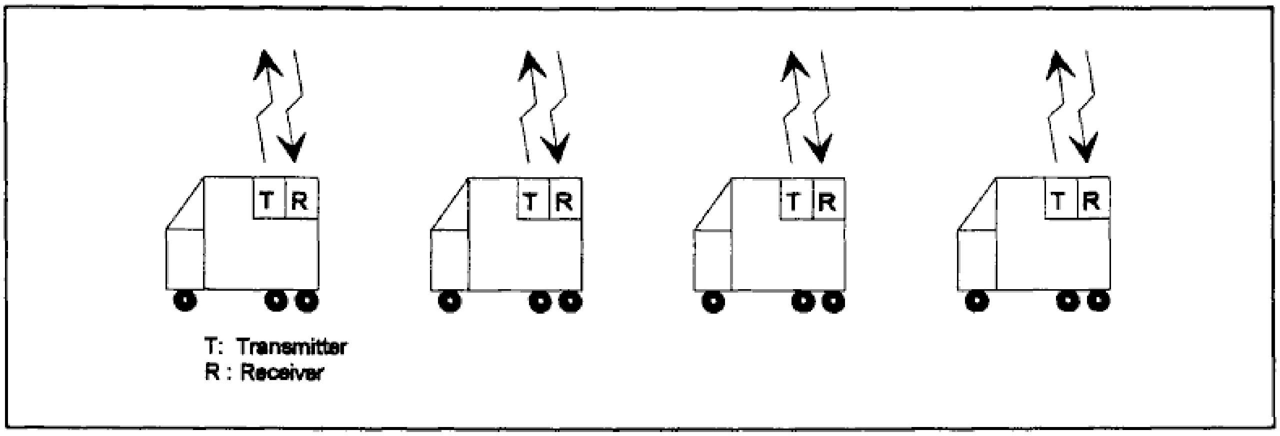



Figure 22. Communication type 2

A vehicle able of sending and receiving is ready for platoon control. If a vehicle is not able to receive but able to send it might become the leading vehicle for the rest of the chain while it is in the mode of local distance control. If a vehicle is not able to send but able to receive it can be under position control and the next vehicle will drive under local distance control and become the leading vehicle for the rest of the chain. A vehicle not able to send or receive must operate under local control. The following vehicle is also under local distance control and becomes leader of the rest of the platoon. Worst case is a total breakdown of communication causing a switch to local distance control for a safe stop or driving with reduced capability with larger spacing.

Platoon control has to be very comfortable for the passengers with respect to jerk and acceleration, because drivers are more sensitive to driving comfort than to safety. Uncomfortable control will not be accepted. Efficiency and throughput (vehicles/h) is therefor limited. Nevertheless an automatic system has to be safe because the responsibility is on the system and thereby on the car manufacturer. Real driving tests will lead to acceleration limits, speed limits and an appropriate distance for a good compromise between safe and comfortable driving. Safety strategies which rely on the driver in a case of emergency have no chance, because the driver is out of the loop and busy with other things or even not existing.

### 2.3.2. Communication

In an automated highway system with vehicle platoons different functions have to be accomplished by communication. First of all under consideration of safety aspects communication is required for the minimization of the distance between the vehicles of a platoon. Further on communication is required for the management of platoons like composition and decomposition of the vehicles and at least for the control and information of platoons.
For the first two functions we prefer an independent vehicle to vehicle communication system for each platoon. The advantage of this decentral solution is that no infrastructure along the highway is required like it would be with a vehicle-to-roadside communication system. The information and control functions can be done via already existing mobile and broadcast communication systems. Forwarding agencies use this possibilities already for routing and scheduling their vehicles. For broadcast services the future digital broadcast Systems will provide transparent data channels even for closed user groups e.g. for all platoons

of one highway system or only of one agency.

### 2.3.2.1. Vehicle-to-vehicle communication concept

The communication concept depends on the requirements of the system and on the type of technology, which will be used for the data transmission. First the requirements of the system. The first vehicle controls the platoon. On the forward channel each vehicle of a platoon should get information with a total delay of less than 10 ms and at a transmission interval of 40 ms. It is not required to have an error-free channel, but errors should be detected and reported to the control system. There should also be a backward channel to send information back to the first vehicle. The backward channel can be operated with lower reliability. The number of vehicles is limited to 10 and the distance between the vehicles can be between 1 and 30 m. The minimum amount of information to be transmitted on the forward channel is about 14 byte and on the backward channel about 4 byte.

Daimler-Benz' concept is based on bi-directional communication between the vehicles. Each vehicle has 2 transceiver, one placed in the front and one at the back. To avoid interference, only one vehicle of a platoon is sending at the same time. On the forward channel a message of the first vehicle is passed through to the last one and on the backward channel v.v.. In both directions the information is carried in a fixed message format. A message consist of an address field, one field for fixed and one field for variable information. While the fixed information field is maintained constant for the transmission through the whole platoon, the variable information part is updated in every vehicle. The address field is necessary to identify the source of the message, because of the possible reception of a message in the wrong succession and from neighboring vehicles of another platoon.

On the condition, that no error correction is required and that the receiving control system also makes a plausibility check, we assume that an error coding with the code rate 1/2 is sufficient for error detection. The actually required code rate depends on the transmission channel. On the base of the data presented in tab. I we can determine the required transmission rate. The strongest requirement is the total delay of less than 10 ms. For a platoon with 10 vehicles 9 transmissions of 240 bits in each case are required from the first to the last vehicle. Considering the delay in each vehicle a transmission rate of 279 kbit/s is required. A reduction of this transmission rate is a question of the realization. One possibility would be to start the transmission of a message while the reception is not finished, which means a reduction of the delay in the vehicles. Another possibility may arise by using a high quality transmission channel, which would allow a higher code rate.

Table 1. Parameter of the vehicle-to-vehicle communication

| | |
|---|---|
| max. number of vehicles | 10 |
| message length on the forward channel | 112 bit |
| message length on the backward channel | 32 bit |
| address field | 8 bit |
| transmission interval | 40 ms |
| max. total delay | 10 ms |
| code rate | 1/2 |
| delay in each vehicle | 250 us |
| transmission rate for 2 vehicles<br><br>transmission rate for 10 vehicles | 25 kbit/s<br><br>279 Kbit/s |

### 2.3.2.2. Communication technology

There are three potentially usable technologies for the vehicle to vehicle communication: ultrasonic, infrared and radio. Criterions for the choice of a technology are the communication characteristics such as transmission rate and delay, error-rate, cross-talk, the impact of the surroundings, the effect of motion and general aspects like the reliability, costs and compatibility or standardization respectively.

Ultrasonic is not proper for our application because of its limited transmission rate and constraints concerning the maximum distance of 30 m. Two alternatives remain. The communication can operate on the base of both alternative technologies.

Concerning the radio technology we have to distinguish between conventional radio transmission at usual radio frequencies, which is very unidirectional, and special solutions at very high frequencies of about 60 GHz, which allow a high directivity.

A solution at lower costs with a high directivity is the infrared communication. The advantage of the infrared communication is to have a solution with a high directivity at reasonable costs. But this directivity may cause a problem for the longer distances of the required transmission range, because then quality of the communication link is extremely sensitive to the alignment of transmitter and receiver. There are also some disadvantages of the infrared communication, which arise if the transmitter or the receiver gets dirty or if the sun shines directly on the receiver. Especially dirt or other kinds of precipitation caused by fog, rain or snow will influence the transmission range and quality.

For the required transmission range radio communication is independent of weather conditions and dirt. Another advantage of radio communication is the possibility of high transmission rates. In Europe a band of 1 Ghz from 63 to 64 Ghz is reserved only for vehicle communication. The standardization process is already started.

### 2.3.2.3. HF-Transmission Channel

For our first investigations we decided to realize a communication link on the base of commercially available radio modems produced by the Deutsche Aerospace AG. These modems operate at 2.45 GHz in a half-duplex mode with a transmission power of about 5 mW and a transmission rate up to 250 kbit/s. The transmission range depends on the transmission rate. Under stationary conditions we measured an error-free communication channel with a capacity of 250 kbit/s for a distance up to 90 m.

We made several tests under real conditions to investigate the feasibility of the communication channel. Therefor we constructed a prototype of a communication link for 2 vehicles. First we made bit error measurements and tried to find out, which situation caused bit errors by driving a route on a highway for several times. There had been some places where errors occur with a certain probability, but is hard to fix the observation. Only at the part of the route with a noise-protection-wall made of metal errors occur with a high probability. It may be, that reflection is the reason for this behavior. But on the other side the passing of other vehicles had never been a problem. We prepared a third vehicle with a transmitter to see, if this vehicle following our platoon has some influence on the quality of the communication channel. There was no difference measurable.

The measured bit error rate had been in the range of 3.0 E-4. On further investigations we determined the length of error bursts, to see if coding can improve the communication channel. The result of the burst error measurements is presented in figure 23.

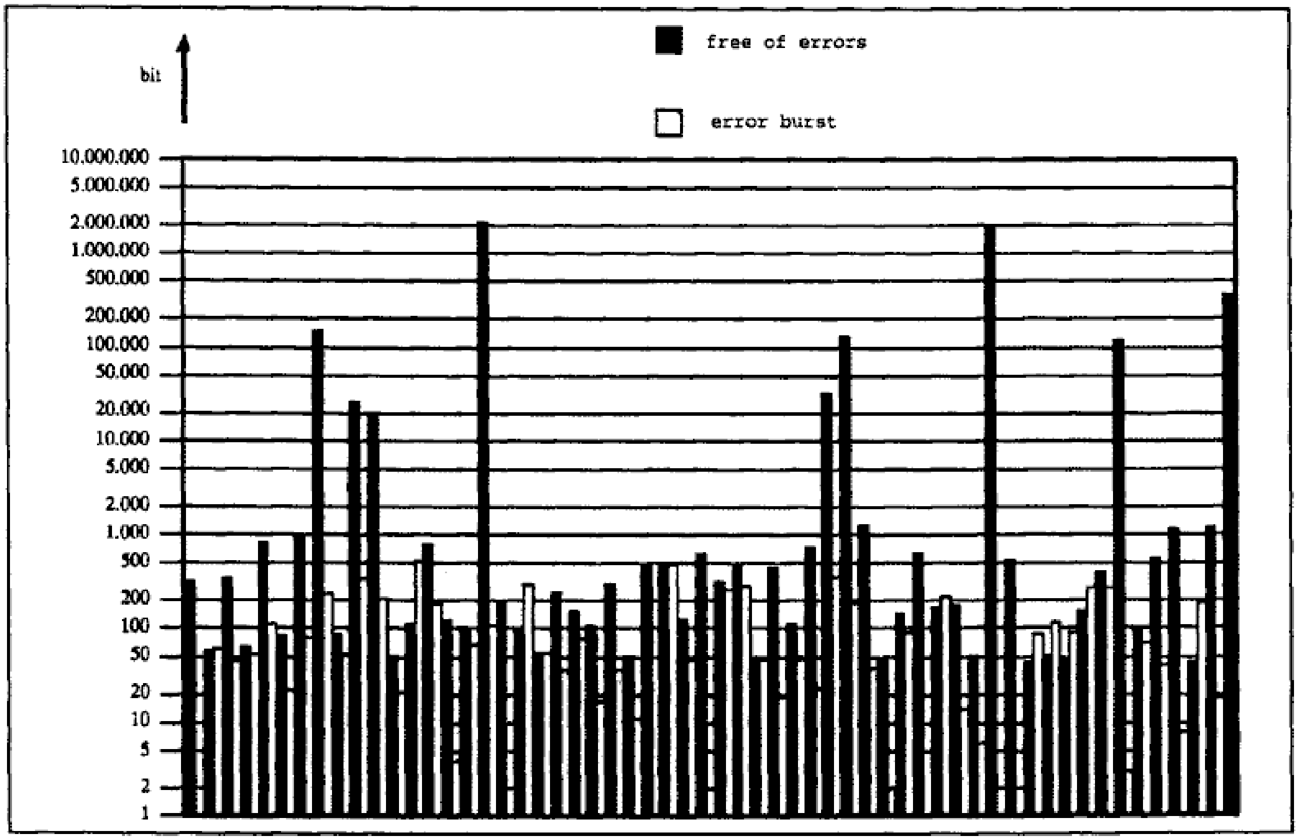



Figure 23. Error behavior on the communication channel

The black beams indicate the number of consecutive bits, transmitted without an error and the white beam indicate error bursts. Normally the burst length is below 200 bits. Transmitting with a rate of 230,4 kbit/s this means, that there is no transmission for about 870 ms. The communication channel is error-free or totally disturbed. Considering the relative short messages a method like interleaving will not be very effect, and because single errors are very seldom, coding will also not very effective. It is much better to follow a concept of retransmission and the most important information should be sent at the beginning of a message.

On the base of our experimental system we realized a communication system, which is successfully used for testing the vehicle control system.

### 2.3.3. Sensors for platoons

Platooning requires precise estimation of the distance to the leader for longitudinal control and the lateral offset relative to the desired position for lateral vehicle control. The first part of this chapter investigates sensors for distance measurement, the second part is concerned with sensing the lateral offset.

From our control investigations described above we conclude that precise but comfortable longitudinal vehicle control for platooning requires a distance sensor that fits the following specifications:

- minimum distance: <1m

- maximum distance:>15m
- relative error: <1%
- absolute error < 10 cm
- measurement rate: >20Hz.

It is evident that an appropriate sensor must work reliably under all standard weather conditions including rain, fog, snow, low sun etc.

These specifications can be reached by various sensing principles including radar, lidar, vision and, for smaller distances, ultrasonic. Independent of the favored approach, the distance measurement should be <u>cooperative</u> in order to make sure that the sensor really measures the distance to the very last point of the leader. For radar systems a corner reflector should be used. Lidar systems should track optical reflectors mounted on the leader. If the distance shall be measured by image processing, this task is significantly simplified if the leader is properly marked. Measuring the distance by means of ultrasonic can be made reliable and accurate if an active transponder is used. We like the idea to trigger such an ultrasonic transponder by an infrared or HF impulse and measure the traveling time of the acoustic wave sent back. At distances smaller than 15 meters such a system can work with a sufficient rate.

Advantages and problems of active sensors are well known. During the precursor study we investigated vision based distance measurement. In contrast to the active sensors vision allows estimation of distance and lateral position relative to the leader. Two approaches are equivalent in principle:

1. using two carefully calibrated cameras with known stereo base looking to a well visible structure of the leading vehicle or
2. using one camera looking to a structure of known size mounted at a known position on the back side of the leading vehicle.

Obviously, the second alternative is less costly and was chosen therefore. The leader was equipped with two markings 1 .2m apart. The structure of these markings were known to the follower. Determination of the positions of these markings in the image with sub-pixel accuracy and simple triangulation yields highly precise distance estimates. Fig. 1 shows the measured distance and the distance differences between adjacent measurements when the leader slowly moves away. It can be seen that the sensor shows extreme little noise. As expected, the relative precision increases linearly with distance. Closer investigations reveal a measurement accuracy of better than 0.5 cm at distances of about 10 m and 10 cm at distances of 30 m. Thus the vision sensor surpasses nearly all known active sensors.

Having such an accurate sensor at hand, the relative speed between the two vehicles can be estimated with very high precision, in particular if the acceleration of the leader is known from communication. In our tests the sensor worked reliably under various weather conditions. The estimates of distance and relative speed used in the experiments described in chapter 2.3.1. have been obtained with this image processing approach.

The measurement rate of this optical sensor depends on the used video norm. For standard NTSC one can realize 30Hz or 60 Hz, respectively. From the investigations concerning longitudinal control of real vehicles we conclude that 30 measurements per second are by far sufficient for this task, in particular if the relative speed can be estimated with the mentioned accuracy.

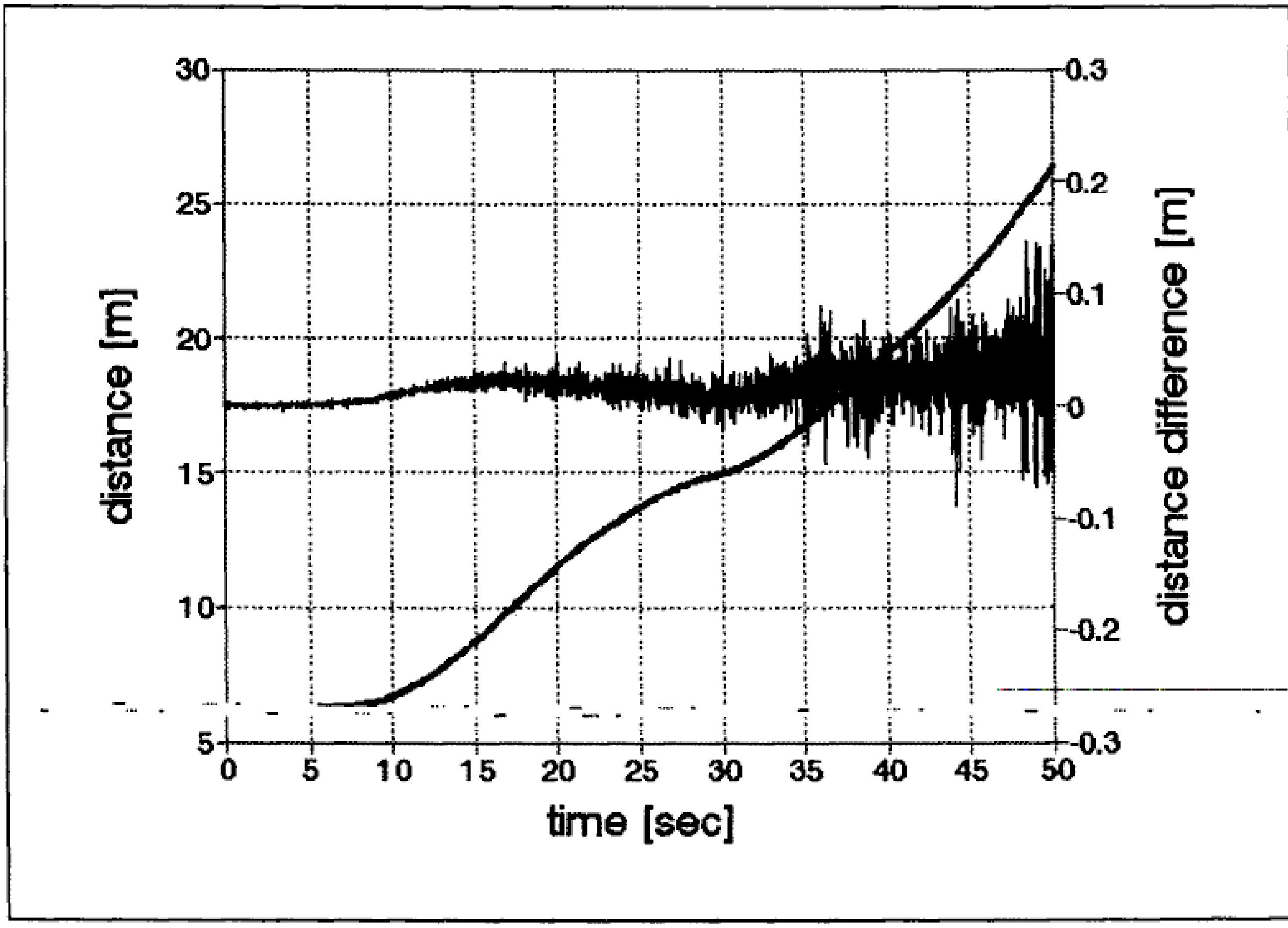



Figure 24. Measured distance (thick) and distance differences (thin) while the leader slowly moves away

A final MIS system must of course guarantee fault tolerant behavior. This requires a second redundant distance sensor. There are two possible approaches with vision:

1. One can double camera and image processing. Instead of purely comparing the results of both systems one can easily exploit the power of such a stereo system. We plan to investigate this approach in the near future.

2. Alternatively, an active sensor can be added. For MIS we suggest to study the fusion of the vision sensor with cooperative ultrasonic systems as described above, since they are inexpensive, robust and accurate in particular at the small distances aimed at in the MIS project.

### 2.3.3.2. Offset Measurement

Lateral vehicle guidance on narrow lanes requires precise measurement of the current offset relative to the desired position on the road. One can imagine many different approaches for this task. The most attractive for MIS are:

1. The inductive cable approach
2. Magnetic nails as proposed by PATH.
3. Image processing tracking an appropriate guard line.
4. Measuring the distance to a lateral guard rail by means of an appropriate distance sensor.
5. High precision differential GPS.

In the following, these approaches are discussed.

Ref 1: Vehicle guidance by inductive cable is a well developed technique and has already proven its reliability on the maintenance vehicles in the channel tunnel between Dover and Calais. At 80 km/h, the mean deviation from the optimal path is 3 cm, but never exceeds 7 cm.

Ref 2: In principle, the active inductive cable can be substituted by passive magnetic nails. From these nails the current offset can only be measured at discrete points. As a consequence, the measurement rate is directly proportional to the vehicle's speed. On the other hand, magnetic nails show the advantage of being passive and allow to encode a small amount of information, e.g. concerning the curvature ahead.

Ref 3: Image processing has proven to be a powerful approach for vehicle guidance. During the last 2 years, Daimler-Benz' test vehicle OSCAR Mercedes Benz station wagon 300 TE) has driven autonomously more than 3000 km on various German highways. Its maximum speed is 150 km in curves with radii of 500 m. The basics of this approach are described in [FRA92]. In this experiment, the camera is mounted nearly horizontally and measures offset, yaw angle difference between road and vehicle axis and curvature of the road. The precision of the sensor is in the range of ± 2 cm offset and ± 0.2 degree yaw angle on well marked roads. At v=120 km/h, the mean offset is in the range of ± 10 cm to ± 20 cm, depending on the road conditions and the used controller.

For MIS, we suggest to mount a camera under a depression angle of 60 to 70 degree and to track an appropriate guard line. This guard line can be a white or colored line as well as reflective markers. In contrast to the two principles discussed above, this approach allows to precisely measure offset and yaw angle difference. Our practical investigations using a white marking reveal an accuracy in the range from 1...10 mm for the offset and 0.1...0.2 degree for the yaw angle, depending on camera height, focal length and depression angle. A test vehicle equipped with this sensor could be successfully guided with an accuracy of ± 3 cm on a standard road.
The approach has been successfully tested under various weather conditions including heavy rain. However, snow will cause problems to such an image processing approach. If one really decides to allow autonomous traffic on snow and ice, one has to look for additional measures to overcome these

deficiency. It should be pointed out that snow and ice will cause serious control problems. It must be argued that system safety can only be guaranteed at intolerable low speeds if the friction coefficient falls below a critical value.

Ref. 4: Lateral guidance is also possible by measuring the distance to a guard rail mounted beside the lane. For example, Paccar has realized such a system for test automatization using a radar sensor and appropriately shaped guard rails [131S93). Alternatively, one could use a lidar together with an reflective rail to determine the current lateral positions. This approach is simple and effective at least for one lane. It can be extended to multiple autonomous lanes if these lanes are separated by barriers that can act as guard rails.

Ref. 5: High precision differential GPS is under development at various places. An accuracy in the range of some centimeter is reported from practical investigation. This means that GPS is suited for MIS lateral guidance if the initialization time necessary for resolving the carrier cycle ambiguities can be limited to a sufficient short time and the problems caused by bad receiving conditions (tunnels, foliage, buildings) can be fully and reliably overcome. Cohen et. al [C0H93J describe a promising approach using so called pseudolites pseudo satellites). The idea described in this paper for autonomous landing can be transferred to an MIS system. In any case, high precision GPS can play an important role in a redundant fault tolerant system.

Finally, the key features of the mentioned sensors are summarized in the following table.

Columns have been added that indicate the information that is delivered from the specific sensors. A sensor that only measures the lateral offset requires much stronger and less comfortable controllers than a sensor that gives additional information on the yaw angle difference.

Table 2. Key features of lateral offset sensors

| Sensor | accuracy | range | active/ passive | offset | yaw angle | curvature | current state |
|---|---|---|---|---|---|---|---|
| inductive cable | 1 cm | ± 15cm | a | x | - | - | already running |
| magn. nails | | ± 7 cm | p | x | - | - | research |
| image proc. | 1..10 mm | 0.3...1 m | p | x | x | (x) | research |
| lateral distance | | | a | x | | | research |
| high prec GPS | . 2 cm | no limit | a | x | x | | research |

## 2.4. Analysis of an Existing Transit AHS System

The O-Bahn is a transportation system using normal buses that are modified for lateral guidance operation. They can be operated in two modes:

1. as a conventional bus that drives on existent roads, steered by a driver

2. automatically laterally guided and running in instrumented lanes.

A lateral control can guide a bus with a precision of a few centimeters. Guided operation has therefore several advantages:

- Additional space to the right and the left in the lane can be reduced to little more than the vehicle width.
- Cost benefits can be achieved by smaller and lighter roadway constructions. This is of special importance with bridges and tunnels.
- Running in a guided track results in greater riding quality and passenger comfort.
- High safety comparable to railway systems is possible.

Since the buses can also be steered manually on ordinary roads, no change of transport medium is required between suburb (manual bus) and center of the city (guided bus) and traveling times can be shortened. They are an ideal transportation system for cities where the traffic volume does not justify installation of a subway.

Automatic lateral guidance can be achieved either mechanically or electronically. Both solutions measure the desired course and modify the steering of the bus in the right direction. The front wheels keep their role of supplying the lateral forces for cornering.

Buses are normally driven by Diesel engines. Guided operation suggests to use electrical power trains and to use overhead wires for power supply. Furthermore exhaust problems in tunnels can be avoided. Buses are in use that are driven by both types of propulsion.

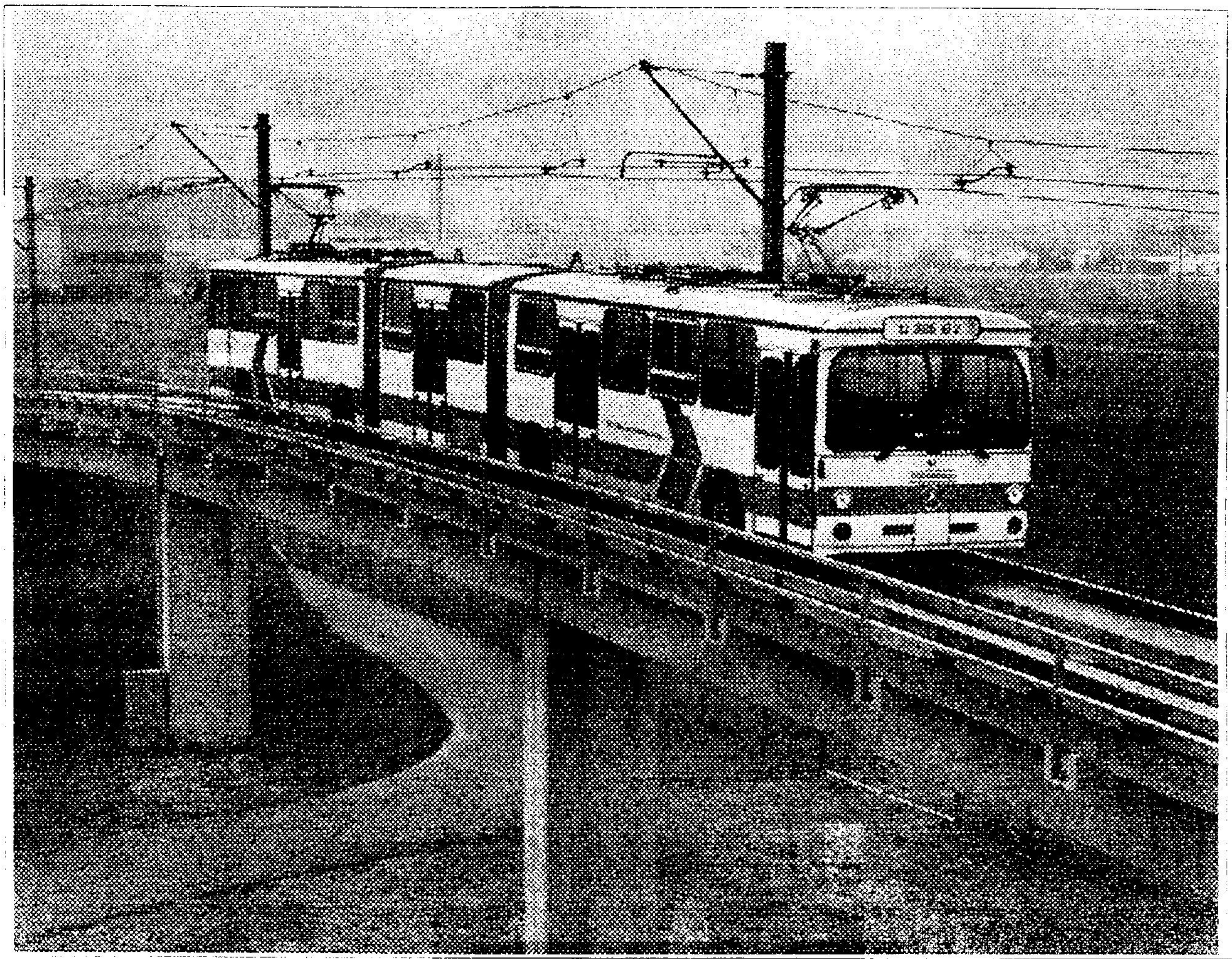


Figure 25. O-Bahn

The report describes the components of the system and the operational data and experiences with the system so far, covering also the acceptance of the system by customers and practical experience in every days operation.

### 2.4.1. Mechanical Lateral Guidance

#### 2.4.1.1. Mechanical modifications to steering

With the mechanical lateral control lateral deviations of the vehicle are detected by feeling a distance to a guide rail. These deviations are then converted to a rotation of the steering wheels either directly or indirectly with or without the aid of a power steering. The guide rail has only a pure mechanical role.

There are two possible guide rails: Using the mechanical limits on both sides of the guideway that otherwise are used for emergency reasons, or using a separate rail in the center of the lane. Advantages of a separate rail is that an additional degree of freedom permits to design the curve ride by its geometric design.

In the simplest case the forces necessary to operate the steering come directly from the connection with the guide rails. Guide rollers run on vertical guide rails and are directly connected to the steering knuckle of the front axle of the guided bus. No additional auxiliary power is needed. The control is stable and damped in all velocity ranges. This system was chosen for the 0-Balm.

#### 2.4.1.2. O-Bahn Roadway Design

Dimensions of a standard transit bus (length 1 lm, width 2.50) and minimum distances to buildings and stationary objects determine the space requirements for the roadway of a guided bus system.

Performance of lateral guidance would require a minimum lane width of 2,60 m. Additional space requirements of 15 cm to each side result in a minimum additional free space of 20 cm on each side with respect to the vehicle border. Modifications are necessary in curves due to incoming rear axle and corbelling.

Due to lateral control the 0-Balm drives exactly in a track. Therefore no road substructure is necessary for the whole lane width. Prefabricated 1-shaped concrete parts are used instead. Figure 26 shows the roadway dimensions of a typical 0-Balm realization.

Figure 26. 0-Bahn roadway configuration

The concrete elements are 1-shaped and have a length of 10 meter. The vertical leg serves as a guide-rail for the guide-wheels. Its width and height are 15 and 18.5 cm respectively. The running surface has a width of 72 cm and a thickness of l cm. The complete roadway is made of concrete, only in entry sections steel surfaces are used for the guiderails. The inside width is 2.60 m, the width of one lane is 2.90 m, and the complete roadway has a width of 6.20 m.

Figure 27 shows the parts and construction work. The advantages of that type of roadway construction are that the parts can be easily exchanged, precisely adjusted and have a good surface that guaranties low wear.

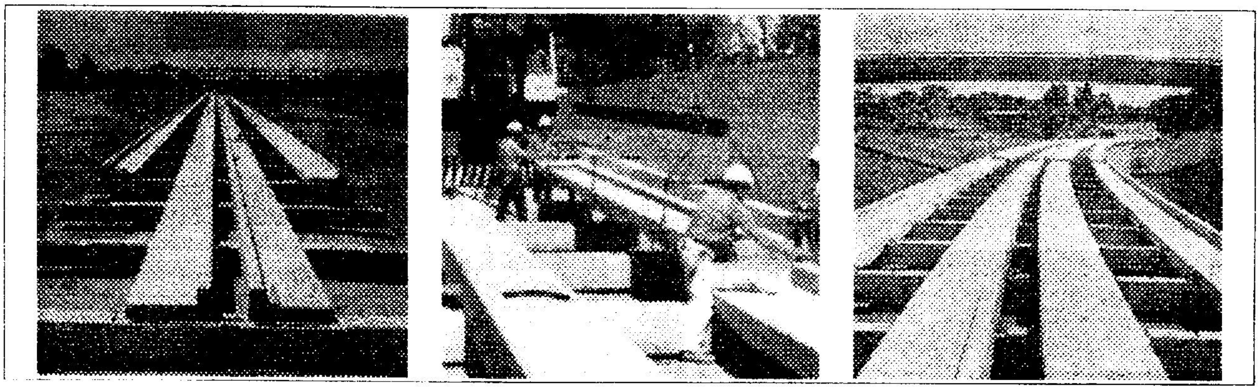


Figure 27. O-Bahn roadway construction

The easy entry and exit of 0-Bahn buses to the guideway permits design of intersections with short interruptions of guided operation. Normally not even resumption of manual control is necessary for this. Nevertheless switches were designed. They are in use where manual entry and exit is not possible, e.g. in concurrent operation with light rail. Figure 28 shows two examples of switches.

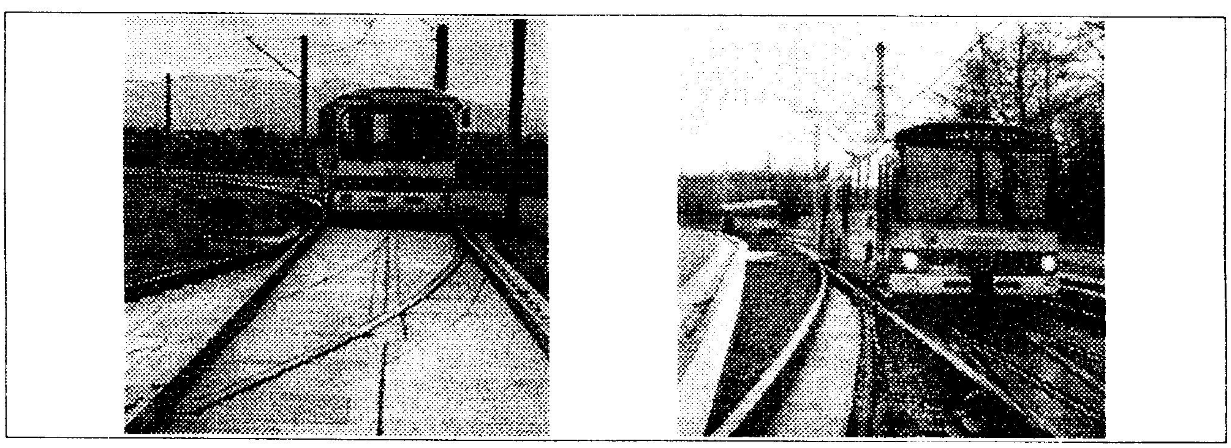


Figure 28. Examples of O-Bahn switches

Figure 29 shows an example of en entry/exit design for guided buses. At this entry/exit the buses enter the guided busway on a bridge. The busway itself runs between the lanes of a freeway. The space was used for light rail before.

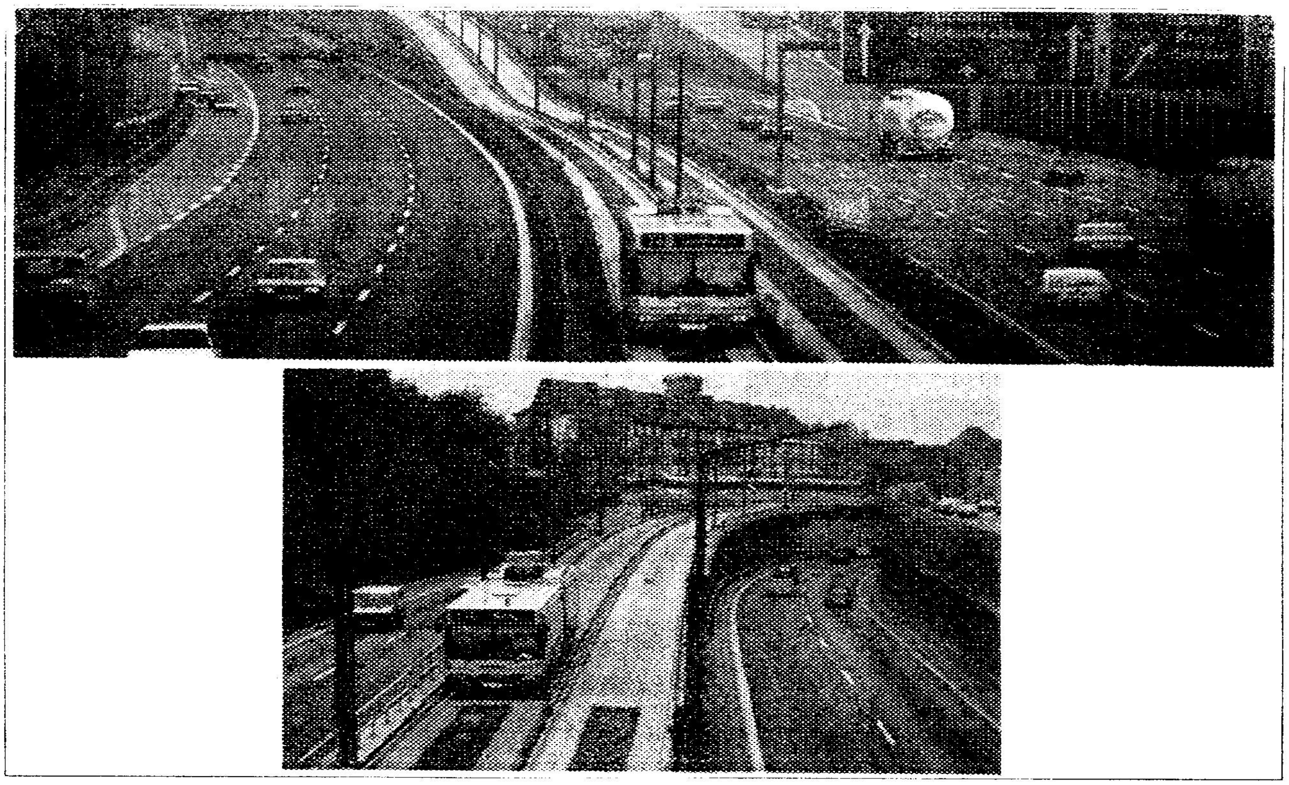


Figure 29. O-Bahn entry/exit example

Narrow tunnel design is possible. For radiuses greater than 200 m a diameter of 4.40 m is sufficient. A tunnel section was constructed as part of the test site in Rastatt. Part of the tunnel demonstration was a tunnel exhaust system (fig. 30).

Figure 30. O-Bahn tunnel solution

#### 2.4.1.3. O-Bahn Application Essen

Public transit in Essen is based on a light rail system of 81 kin and on bus traffic with a total line length of 310 km. The number of passengers on both systems is roughly the same.

Whereas light rail runs in tunnel systems and on own roadbeds in downtown, the buses are forced to share public road with individual traffic and are hindered especially during rush hour. The goal of introduction of the 0-Balm system in Essen was to share the tunnel and roadbed systems between light rail and bus. A feasibility study in 1979 proved the principal realizability.

Several development phases studied individual components on different sections of the road system. The different sections were selected in a way that they could be chained later for the whole system. Table 3 gives an overview of the phases and their development tasks.

Table 3. Development phases of busway Essen

| | |
|---|---|
| Phase I 1980- 1983<br>•Mechanical guidance<br>•Guided busway<br>•Stops<br>•Protection system | Phase II 1981-1984<br>•Shared roadway/railway<br>•Switch for guided bus<br>•Dual mode buses<br>•Catenary system |
| Phase III/1 1985- 1986<br>•Mechanical guidance<br>•Guided busway<br>•Stops | Phase III/2 1986 - 1987<br>•Catenary system<br>•Power supply<br>•Dual mode buses |
| Phase III/1 1987 - 1988<br>•Shared roadway/railway<br>•Catenary system<br>•Protection system<br>•Switches<br>•Dual mode buses | |

Operating experience refers to 49 guided vehicles. Significant problems during operation did not occur. Some problems with the guide-wheels in normal operation could be solved.

Three different shared roadway/railway systems were tested: two steel-concrete systems and a steel-wood system. One steel-concrete substructure and the wood-concrete substructure proved suitability. The wood-concrete system had to be coated to reach a sufficient friction coefficient, but proved to attain the best driving comfort.

Two switching systems were tested: A lifting switch with vertical motion of the switch blade and a bending switch with horizontal motion of the switch blade. The lifting switch is faster but more complicated and more expensive due to its mechanical interaction with rail switches. The bending switch avoids that disadvantage. Longer setting times could be tolerated.

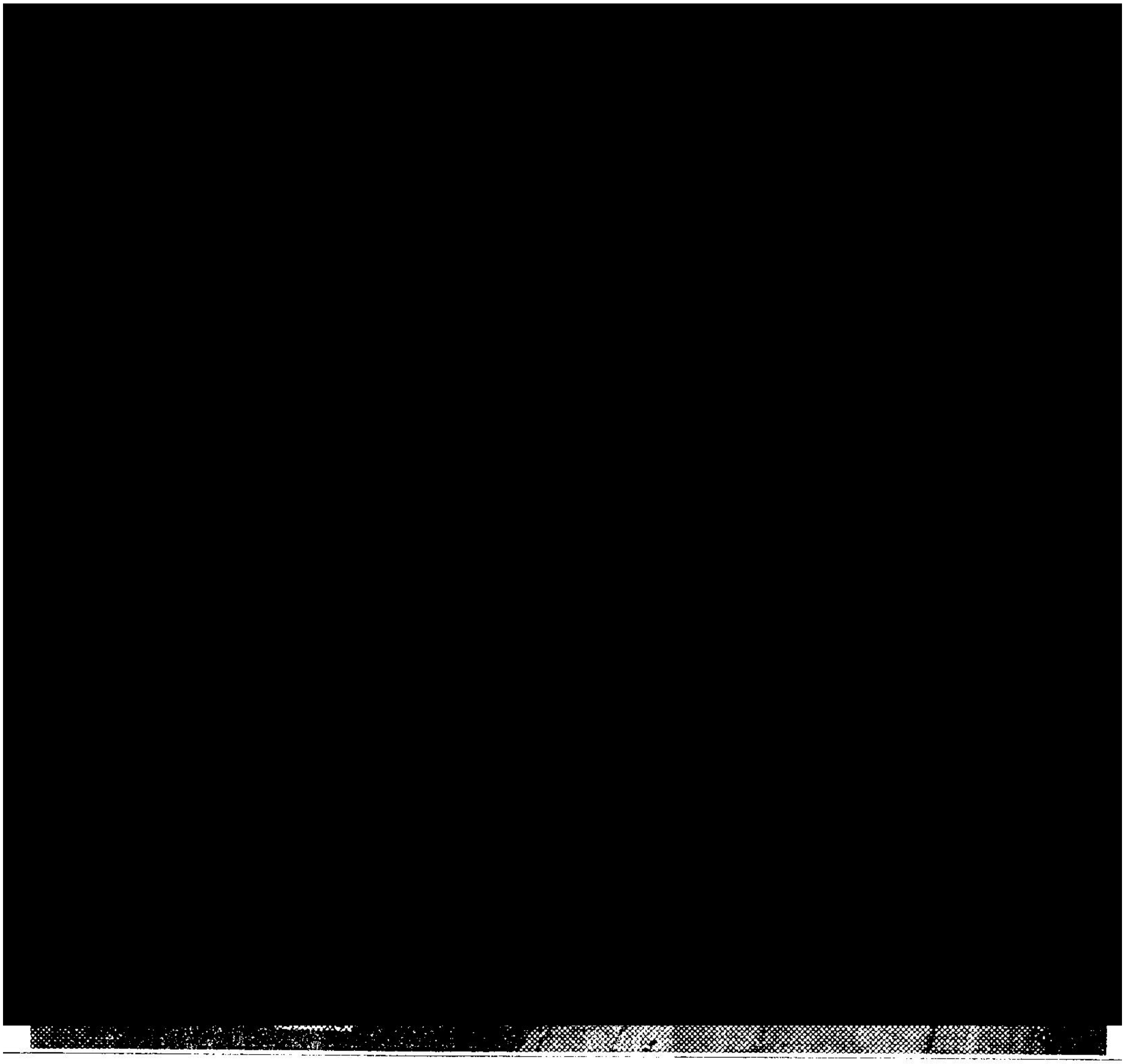


Figure 31. 0-Bahn Essen

Beginning in 1983 buses with dual drivetrain - electrical and Diesel - were tested and later introduced in normal operation. The buses were driven by Diesel engines in manual operation and by electrical engines supplied by trolley lines in guided operation.

Mixed operation with light rail required use of a route protection system. Compatibility with the already existing system and easy installation in the buses could be achieved.

Winter operation of the system is possible and so far without major problems. An all-wheel-drive truck with salt and sand distribution and a detachable snowplow is used.

The system is suited for operation without restriction. Opinion polls show that passengers and drivers are satisfied with the system's capabilities.

In Adelaide, Australia the northeastern suburb region had to be linked with the city center. Of the two realistic alternatives under consideration - light rail and O-Bahn - eventually the 0-Bahn was chosen. The reasons for selection were:

Compared to light rail the 0-Balm:

- had much lower capital cost.
- had lower operating cost.
- was more convenient for passengers because there is no need to change vehicles to reach the desired destination.

Compared with a conventional busway the 0-Bahn

- provided a higher riding comfort for passengers.
- is safer because of the automatic steering.
- occupied less space because 6 the narrow track.
- had lower maintenance costs due to the rigid concrete construction.

was less environmentally intrusive because of its lesser width and lower noise levels.

The total track length is 12 km and was opened in two stages. Each section has a length of6 km and opened in 1986 and 1989 respectively.

The busway operates successfiil, both technological and operational. Between 1986 and 1989 public travel to the city center increased by 40%, resulting in transport of more passengers to the City than with the other railway lines. Major technical problems did not occur. Accidents and breakdowns were not directly related to the guidance technology. Major observed problems and their solutions were:

- The guidance system is vulnerable to unintentional collision with the curb during normal street operation. Resulting damage of the guide wheels can be corrected by mobile maintenance teams.
- Due to the high operating speed of 100 km/h excessive wear of tire side walls occurred in narrower curves. Experiments with pushing rollers at the rear axle were not satisfactory. The problem was mainly solved by reducing the operating speed in those sections.
- Bus breakdown on track stops immediately operation in that section to prevent accidents. A special guided maintenance vehicle that can travel in both directions is in use to recover such buses.

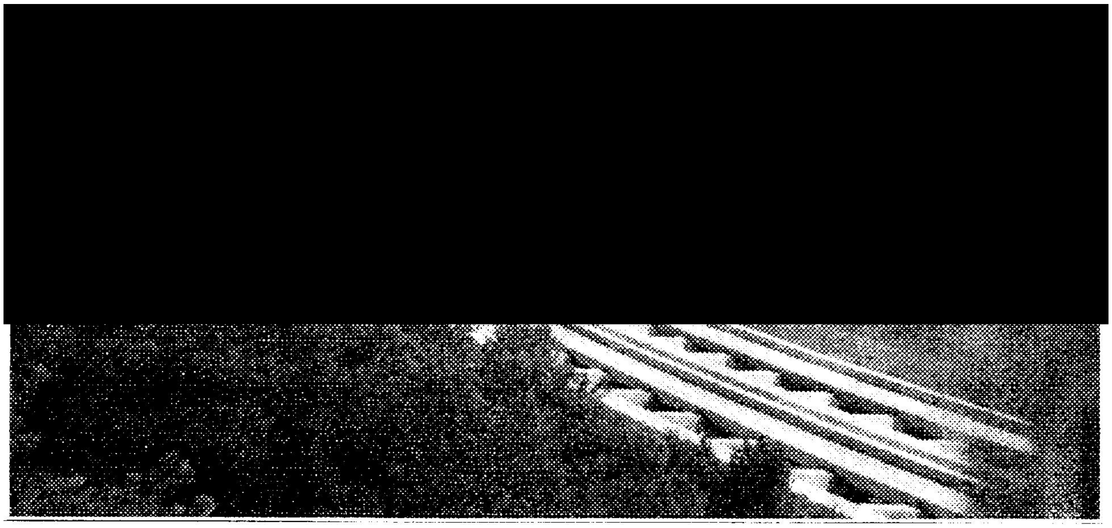


Figure 32. 0-Bahn Adelaide

Table 4 shows total system cost as of 1988.

Table 4. 0-Bahn Adelaide System Cost 1988

| Item | Estimated Total Cost A$m |
|---|---|
| Structures | 17.3 |
| Civil Works | 12.4 |
| Guided Track | 13.4 |
| Stations | 5.6 |
| Land Acquisition | 6.3 |
| Busway Landscaping | 4.2 |
| River Landscaping | 5.8 |
| Vehicles | 24.0 |
| Utility service alteration | 3.2 |
| Preliminary design | 1.3 |
| Administration & Supervision | 4.5 |
| Total | 98.5 |

### 2.4.2. Electronical lateral guidance

The desired course is defined by a guide-cable laid below the surface of the pavement. A low-frequency current of about 200 mA and a frequency of approximately 10 khz generates a concentric electromagnetic field around the cable. A cross coil measures the horizontal and vertical components of the magnetic field. Antennas mounted at bow and stern of the guided vehicle measure the deviation to the cable.

From these deviations and the velocity of the vehicle, an electronic controller computes a steering signal which is set by a hydraulic steering system. The quality of the controller determines the deviation of the vehicle during the ride. Stationary accuracy and good dynamic response in the presence of disturbances like side-wind and unequal brake forces are criteria for the controller design. Switches and crossings are relatively easily achievable by using different frequencies in two cables.

A typical antenna mount height is 50 cm for a bus and it is limited on one side by the ground clearance of the vehicle and on the other side by the signal to noise ratio of the measured signals.

When the magnetic filed can build up without disturbances the magnetic field lines are concentric circles around the cable. In practice this is only seldom the case. Magnetic materials in the environment such as steel reinforcements in concrete road surfaces deform the lines of flux and hereby introduce virtual locations of the cable and deviation errors. Since the controller tries to follow that virtual cable, the vehicle steers with steering disturbances.

Several arrangements of multiple coils were studied to compensate for possible disturbances of the magnetic field caused by concrete reinforcements in the pavement. Figure 33 show possible antenna arrangements. The optimum found is a crossed coils in the second arrangement. Maximum possible deviation from the cable in which the signal is still usable is +J5 cm.

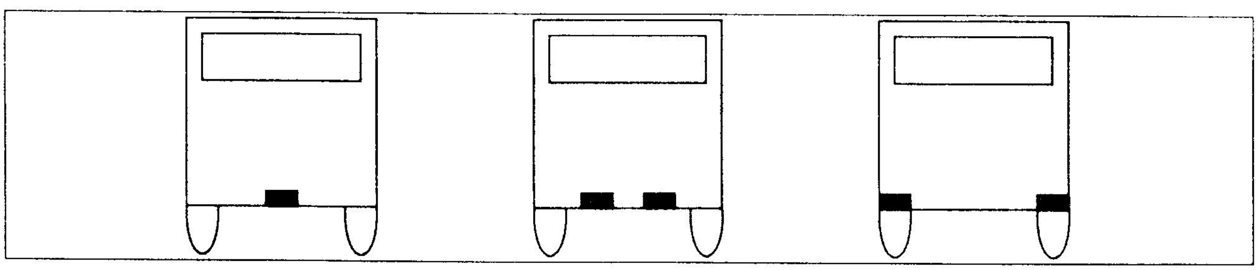


Figure 33. Antenna arrangements for electronic lateral control

2.4.2.1. Modifications to steering

For influencing front-wheel steering two different modifications of the steering assembly were carried out:

- An additional steering cylinder can be linked to the idler arm of the steering at the right side of the vehicle. The normal power steering acts on the pitman arm on the left side as before.

- For safety reasons two steering cylinders on both sides of the steering assembly can be used. Advantage of this system is the inherent redundancy, disadvantage is the possibility of counteracting forces of the two cylinders. This system (cf. fig. 34) was tested by Daimler-Benz in Furth and is in use for the Tunnel Service Vehicle.

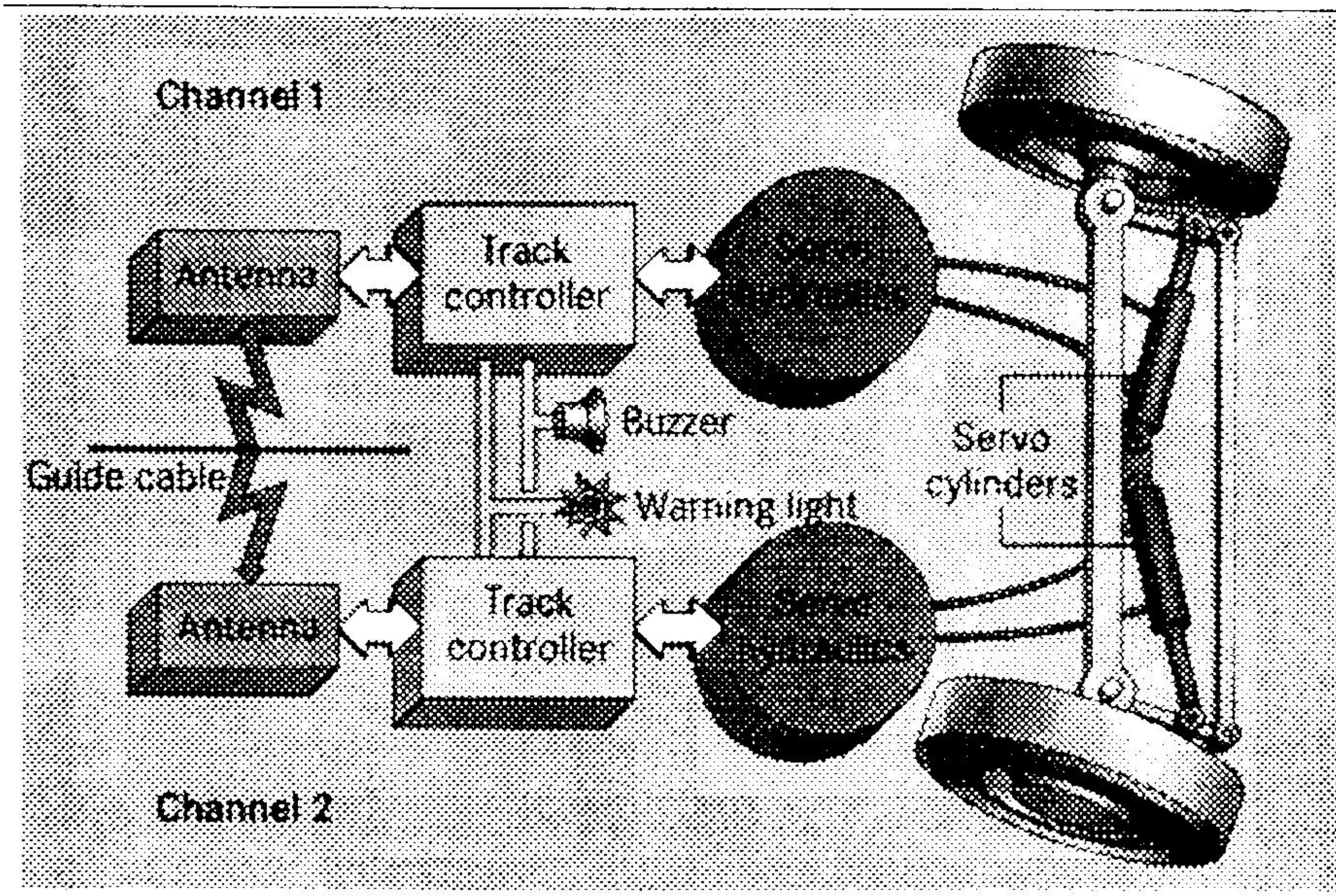



Figure 34. Electronic track guidance

Both systems allow a conventional steering by the driver in case of a system failure. Two variants of safety concepts were in use:

One control circuit is active. The second controls itself and supervises the active control. The role of the supervisor is periodically interchanged. By comparing typical performance criteria of control circuits and by self-diagnosis, a failure of a control circuit can be detected very fast.

- Both circuits are completely independent and active. They are designed in a may that each circuit can control the system on its own. Each circuit controls itself and withdraws if an error is detected.

In case of a failure the driver is informed and advised to take corrective actions, e.g. decrease velocity or switch to manual operation.

2.4.2.2. Roadside Equipment

The guide-cable lies in a cut groove of the pavement. The laying is easy and non-expensive. The lateral position of the cable is determined by aspects of vehicle dynamics. The cable is fed from a central site with an alternating current of 0.2 Ampere. Vehicles can enter and leave the instrumented roadway at any point at their convenience. other vehicles can cross or drive on the instrumented lane without restrictions.

Switches can be realized by using two different frequencies for the antenna signal in the branching cables.

Since in an automated operation a higher density of vehicles can be achieved, additional measures are necessary to guarantee a safe and smooth operation.

Busses were demonstrated at test sites that could operate in three different modes characterized by the degree of automation:

1. Manual operation
   The vehicles &e completely manually driven according to the orders of traffic operations center. A safety system is subordinated to the dispatching system and interferes only if instructions of the dispatch center are disregarded.

2. Partly automated operation
   Within certain limits it makes sense to automate recurring procedures such as starting, acceleration to target speed or precision braking. The driver starts and supervises all actions and has the chance to step in at his discretion and - if necessary - drive manually.

3. Fully automated operation
   Fully automated operation only makes sense when significant savings in personnel costs are hereby made possible. Prerequisite is a high reliability of all vehicle functions. This means having redundant systems that are constantly controlled and supervised. if malfunctions are detected a forced braking occurs.

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