Freeway Control Using a Dynamic Traffic Flow Model and Vehicle Reidentification Techniques

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Freeway traffic flow is described in terms of control theory. The detecting elements of millimeter-wave radar sensors, which detect speed and occupancy time by a 61-GHz continuous-wave doppler radar, are used. The regulating unit consists of variable traffic signs for traffic-dependent speed limit and alternative route guidance. The control unit consists of a local computer and a control center. The control strategy is based on a continuum theory of traffic flow, which takes into account characteristics of the speed distribution for different traffic states. For incident detection and early warning criteria, the model yields the traffic density as a crucial stability parameter. For measuring the traffic density, a correlation technique is presented that for dense traffic uses the radar reflection signals as fingerprints for reidentification of vehicles.

To avoid congestion, freeway traffic control systems are designed that detect traffic flow and influence traffic by display of variable traffic signs for speed reduction or for alternative route guidance.

The acceptance of such systems and the improvement potential increases with a good adaptive control strategy. A proper control strategy needs data from accurate traffic detectors as well as an advanced modeling of traffic flow. For this aim, new millimeter-wave radar detectors are developed that measure vehicle speed by doppler frequency shift of the transmitted 61-GHz radar beam within an accuracy of ±2 km/hr. The detectors can easily be mounted in overhead position on a traffic sign bridge. No interruption of traffic is necessary as in the case of inductive loop installation. Advanced modeling of traffic flow is possible on the basis of a continuum description. This continuum description contains a relaxation to the static equilibrium speed-density relation and an anticipation of traffic conditions downstream.

In this way, the premises of a well-adapted traffic control system are fulfilled. The proper control unit to transform this traffic detector data and traffic model into a control strategy is a hierarchical control architecture. This architecture consists of local control units, which handle nearly autonomously the traffic data and threshold values derived from the traffic model.

It consists of a control center that coordinates the local displays of the variable traffic signs within a harmonizing strategy also considering external weather influences. Figure 1 shows the elements of the control circuit for a line control setup.

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Besides the traffic detectors (with millimeter-wave radar detectors used advantageously as detecting elements), visibility detectors and rain detectors are installed. The local control unit is in the cabinet at the street border, and the control center is in a control room within the traffic agency. The changeable traffic signs form the regulating units in the sense of a control circuit and indicate not only traffic-dependent speed limits but also Keep in Lane, No Passing for Trucks, or Lane Blocked, because the displays have universal contents. A famous example of a freeway network used for alternative route guidance is the New York Integrated Motorist Information System (IMIS) corridor (*1*). Such network control systems need sensors for travel time detection and a forecasting strategy for traffic demand on main and alternative routes.

For this purpose, vehicle reidentification techniques, which classify the radar reflection patterns by pattern recognition methods, are developed. In this sense, each vehicle produces a fingerprint that can be compared at neighboring measurement sites with preceding fingerprints. If two fingerprints are in accordance, travel time and traffic density can easily be derived.

CONTINUUM DESCRIPTION OF TRAFFIC FLOW

A macroscopic description of freeway traffic uses the variables traffic flow q (in vehicles per hour), traffic density ρ (in vehicles per kilometer), and mean speed v (average speed over an interval such as 5 min). (Throughout this paper ρ is used as density symbol rather than k, which is used by other authors.) The relation

$$q = \rho v \tag{1}$$

and the empirical speed-density relation

$$v = V(\rho) \tag{2}$$

always hold. The latter can be transformed directly to the fundamental diagram $q = Q(\rho)$. (The capital letters V and Q denote functional relations, and the lowercase letters v and q refer to actual variables.)

For a dynamic description, the continuum limit of a general car-following behavior is considered. The speed v_n of the nth car in a line of cars reacts with a time lag τ on the change of

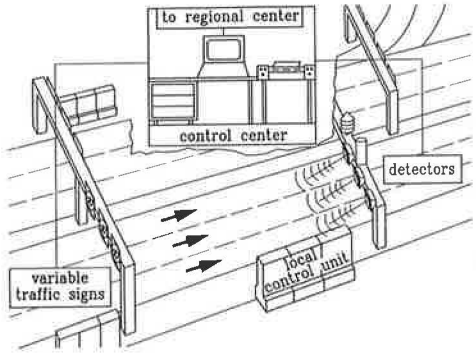

FIGURE 1 Elements of the control circuit.

headway h_n of the subject car relative to that of the preceding car:

$$v_n(t + \tau) = F(h_n) \tag{3}$$

In this relation, a general headway function $F(h_n)$ is used. Introducing differentiable functions $v(x,t)$ for speed and $\rho(x,t) = 1/h$ for density leads to the acceleration equation [compare with that of Kühne (*2*)] with a general speed-density relation instead of the general headway function $V(\rho) = F(1/\rho)$:

$$\frac{dv}{dt} = v_t + vv_x = \frac{1}{\tau}[V(\rho) - v] - c_0^2 \frac{\rho x}{\rho} + v_0 v_{xx} \tag{4}$$

In Equation 4, subscripts t and x denote partial derivatives with respect to time and space coordinates, respectively. The acceleration equation contains a relaxation to the empirically fitted equilibrium speed-density relation $V(\rho)$ and an anticipation of traffic conditions downstream. The first-order derivative (pressure term) leads to a deceleration (acceleration) when traffic density grows (decreases), and the second-order derivative leads to temporal speed change when the spatial density trend changes (viscosity term). The relaxation time τ, the "sound" velocity c_0, and the dynamic viscosity v_0 (in the limit $v_0 \rightarrow 0$) are constants. The relaxation time τ denotes the response time of a vehicle collective for compensation of a speed difference. The "sound" velocity results from the spreading velocity of disturbances in the absence of relaxation and viscosity. Finally, the dynamic viscosity introduces a small shear layer to smear out sharp shocks. The viscosity term even in the limit $v_0 \rightarrow 0$ guarantees a continuous description of roll waves and other traffic patterns for unstable traffic flow.

Besides this, the equation of continuity holds,

$$\rho_t + q_x = 0$$

which states that a temporal change in density takes place only if a spatial change of net flow occurs.

One possibility is to use the model for spatial or temporal forecasting by integrating the equations given traffic volume and mean speed time series as boundary conditions. In this way, time series of traffic volume or mean speed for cross sections downstream or at later times can be predicted (*3*).

The traffic flow model also is a powerful tool for explaining general properties of traffic flow such as stability regimes, stop-start waves, and critical fluctuations. Stability analysis of the homogeneous solution $[\rho_0, V(\rho_0)]$ yields stability when the traffic parameter is negative. When

$$a \equiv -1 - \frac{\rho_0}{c_0}\frac{dV(\rho_0)}{d\rho} < 0$$

traffic waves decay to the static speed-density relation $V(\rho)$. When

$$a \equiv -1 - \frac{\rho_0}{c_0}\frac{dV(\rho_0)}{d\rho} > 0$$

the static flow $\rho = \rho_0$ and $v = V(\rho_0)$ are no longer stable. The traffic parameter reflects the small-signal performance and not only the speed-density relation itself. The quantity $a(\rho_0)$ contains the operating point density ρ_0, the slope of the speed-density relation, and the "sound" velocity c_0. These are the crucial dynamic parameters of traffic flow besides the relaxation time τ.

The critical density ρ_c at which the change from stable traffic flow to unstable traffic with jams and stop-start waves is given by

$$-1 - \frac{\rho_c}{c_0}\frac{dV(\rho_c)}{d\rho} = 0$$

To estimate the slope of the speed-density relation $v = V(\rho_c)$, a proper fit of the measurement data with restriction to data from noncongested traffic flow is necessary. The fit procedure described by Kühne (*4*) yields, for West German autobahns under normal conditions,

$$\rho_c = 25 \text{ veh/km per lane}$$

The speed-density relation and its critical density depend on street curvature, light, and weather conditions.

TRAFFIC PATTERNS FOR UNSTABLE TRAFFIC FLOW

Far beyond the critical density at which traffic flow nearly breaks down completely, stop-start waves occur. These stop-start waves can be derived from the traffic flow model when the equations are transformed to the collective coordinate

$$z = x - v_g t$$

as the only independent variable. This transformation means that only running profiles with stable shapes are considered. The group velocity v_g of the profile motion will be determined by proper boundary conditions. Integration of the continuity equation yields

$$\rho(v - v_g) = Q_0$$

This equation means density and speed in a frame running with group velocity v_g must always serve as supplements. Wave solutions with a profile moving along the highway are only possible if the density at one site increases in the same proportion as the mean speed with respect to the group velocity v_g decreases, and vice versa. The constant Q_0 has the meaning of an external given flow.

The remaining acceleration equation

$$\nu v_{zz} + F'(v)v_z + H(v) = 0$$

has the form of a nonlinear wave equation with an amplitude-dependent damping term and an unharmonic force (*5,6*). In the limit of vanishing viscosity, $\nu \rightarrow 0$, sawtooth oscillations occur.

Figure 2 shows the stop-start wave solutions together with measurements from West German autobahns. The oscillations are strongly asymmetric. Decreases of speed occur much more quickly than increases of speed. This asymmetry was pointed out early by Gazis et al. (*7*). It is a consequence of nonlinearities caused by convection and indicates again the power of the traffic flow model. Even such details of traffic behavior as the difference between deceleration and acceleration behavior coincide with observation. It is therefore not necessary to discriminate in the relaxation time between relaxation from high speed levels downward or from low speed levels upward.

In the vanishing viscosity limit, a simple relation between the amplitude $A = v_{\max} - v_{\min}$ of the stop-start waves and the oscillation time T of these waves can be derived (*2*).

$$T = \frac{1}{|v_g|a} \oint dz \approx \frac{2\tau}{|v_g|a} \sim A$$

The amplitude A describes the difference between the maximum speed $v_{\max}$ and the minimum speed $v_{\min}$ during an oscillation. The oscillation time T defines the repeating time of the start-stop waves.

The approximate proportionality between amplitude and oscillation time is significant for nonlinear oscillations. In contrast for harmonic oscillations, amplitude and oscillation time are independent and are only fixed by geometrical dimensions. In Figure 3, four measurements of German autobahn stop-start waves are shown in which each measurement had a duration of several hours with continuous stop-start wave conditions. The theoretical predictions are well fulfilled. This again is an example for the capacity of the traffic flow model under consideration.

Stop-start wave propagation is not the only possible solution in the congested traffic regime. The premise for such an oscillatory solution is the existence of a limit cycle for the nonlinear wave equation.

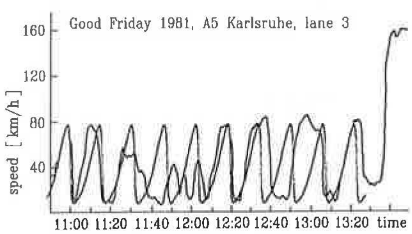

FIGURE 2 Sawtooth oscillations of mean speed for stop-start traffic together with measurements from Autobahn A5 near Karlsruhe, West Germany (*6*).

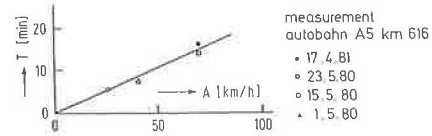

FIGURE 3 Oscillation time *T* and stop-start wave amplitude *A* from four measurements of stop-start traffic each of several hours duration (*8*).

A limit cycle occurs if an unstable-focus fixed point has a neighboring saddle point. Analyzing the fix points of the nonlinear wave equation by examination of the vicinity of the zeros of the force term $H(v)$ indicates that the only fixed point that can form an unstable focus is the fixed point corresponding to the operating point $\rho = \rho_0$, $v = V(\rho_0)$. When this operating point is also a saddle point, only shock front spreading occurs and no oscillatory solution is possible. The shock front jumps between the two equilibrium solutions corresponding to the zeros of $H(v)$, one corresponding to the operating point and the other lying in the creeping regime or in the nearly free condensed-traffic regime. The propagation (group) velocity v_g of such shock waves is given by

$$v_g = V(\rho_0) - c_0$$

in which $V(\rho_0)$ is the equilibrium speed of the operating point from the speed-density relation and $c_0 = 65$ km/hr, the "sound" velocity of disturbances spreading in the absence of relaxation and viscosity terms (*3,8,9*). As a typical value for dense traffic operation, $V(\rho_0) = 50$ km/hr leads to a negative group velocity

$$v_g \approx -15 \text{ km/hr}$$

which means backward spreading of traffic stops. The propagation velocity differs clearly from the "sound" velocity c_0. The "sound" velocity would be the disturbance propagation velocity in the absence of the relaxation term and viscosity. An artificial separation of anticipation and relaxation is not possible, because the two effects are coupled.

Besides the dynamics, which are described by convection, anticipation, and continuity equations, the form of the speed-density relation $v = V(\rho)$ and the position of the operating point determine which of the possible solutions in the congested traffic flow regime will occur. The speed-density relation is derived from local measurements of speed and traffic volume $v = V(\rho)$. Such measurements are shown in Figure 4 from West German autobahns and from a field survey of parkways in the New York area (*10*). The latter data are early measurements reported by Roess et al. (*10*) under truly ideal conditions—no trucks or buses, lane width of 3.60 m, and adequate lateral clearance.

The speed-volume relation can be transformed to a volume-density relation (fundamental diagram) using the relation $q = \rho v$. A fundamental diagram produced from Figure 4 is shown in Figure 5 together with different traffic state regimes in the unstable traffic regime derived from the traffic flow model. In contrast to the level of service subdivision, where the unstable traffic regime is not further subdivided, the traffic

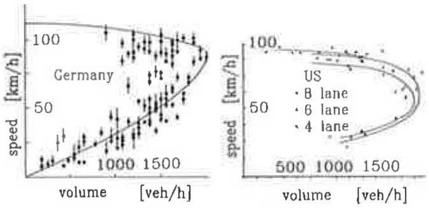

FIGURE 4 Speed-volume relation for West German (*left*) and U.S. (*right*) freeways from local measurements (*9,10*).

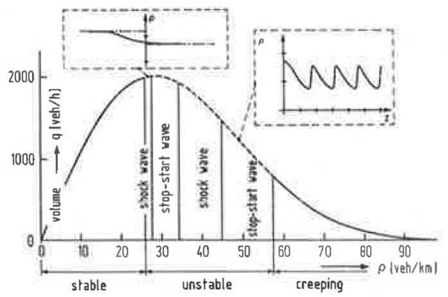

FIGURE 5 Fundamental diagram corresponding to speed-flow characteristics of Figure 4. The unstable traffic regime is subdivided into several regimes of different traffic behavior on the basis of the traffic flow model (*11*).

flow model yields in that specific case various different traffic behaviors such as regular stop-start waves or spreading of single shock waves. Because there are many different neighboring traffic states, under nearly the same congestion conditions on a given day, regular stop-start waves occur, and on another day sticky traffic with irregular perturbation spreading occurs.

Shock wave spreading is described within the kinematic wave theory (*11–13*). The propagation velocity of these shock waves can simply be calculated from the corresponding volume and density jumps. The only promise for such shock wave solutions is the existence of two fixed points between which the jump occurs. The proper statement of Figure 5 is the coexistence of shock waves and stop-start waves in the unstable regime. To derive the oscillating solutions, drivers' reactions not only to the amount of density or speed variations but also to the tendency of these variations must be taken into account. A large deviation justifies the introduction of the viscosity term together with the general feedback mechanisms, which establish the nonlinearities. This driver behavior leads to a change of topology as the control parameters [for instance, the position of the operating point ρ_0, $V(\rho_0)$] are changed.

As a particularly interesting example of stop-start waves, Figure 6 shows a control parameter configuration in which the stop-start wave solution surrounds a stable fixed point and an unstable limit cycle. This subcritical bifurcation leads to bistability: a stop-start wave solution and a homogeneous solution (divided by an unstable limit cycle) exist at the same time. The change from one to the other is connected with hysteresis effects. For presentation, a $v_z - v$-phase portrait was chosen. The amplitude depends on the external given

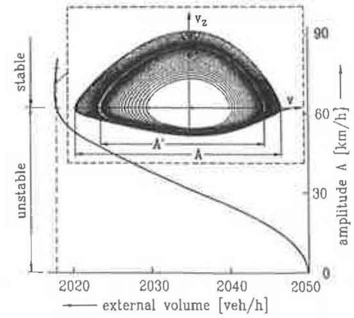

FIGURE 6 Bistability of stop-start wave solution, homogenous solution as $v_z - v$–phase portrait, and subcritical amplitude dependence with respect to the external given flow Q_0 (c_0 = 60 km/hr, ρ_0 = 34 veh/km) (*4,5*).

flow for the complete subcritical case, which is also indicated in the same figure.

TRAFFIC FLOW MODEL AND CONTROL STRATEGY

The basis for the traffic control strategy is operating level of service (LOS) derived from idealized speed flow characteristics and field measurements as reported in Figure 4. From such measurements, LOS standards are deduced that define regimes of free, nearly free, or unstable traffic flow. The classification is shown in Figure 7. The draft is transformed from the 1985 *Highway Capacity Manual* (HCM) (*14*) to West Germany autobahn conditions; additionally a polygon approximation is shown that is used in the control center of the traffic area of Bavaria North (*15*).

The traffic flow model allows the derivation of a dynamic traffic state classification and appropriate early warning criteria. Because the traffic flow model describes traffic flow in terms of fluid motion, one expects that (as in hydrodynamics in which the change from steady flow to turbulent flow is connected with critical fluctuations and strongly irregular motions in the turbulent regime) the change from steady traffic to traffic with jams and stop-start waves is indicated by large fluctuations. The fluid analogy points out the reason for the strong spreading of the measurement values in the unstable regime; in fluid motion the convection nonlinearity serves as a feedback circuit. Beyond a certain feedback strength, the fluid motion is characterized by turbulence irregularities. Large eddies are diminished because the nonlinearity describes saturation; the following limited motions are increased because the nonlinearity amplifies more than proportionally. Also, in traffic flow, besides the ever-present random influences (e.g., bumps, irregularities in street guidance, and fluctuations in driver attention), the nonlinearity stochastics caused by feedback by convection motion produce critical fluctuations. The influence of the omnipresent fluctuations was investigated by Kühne (*2,4,16*). The irregularities and dynamic fundamental diagram have also been interpreted in the sense of chaos theory (*17–20*).

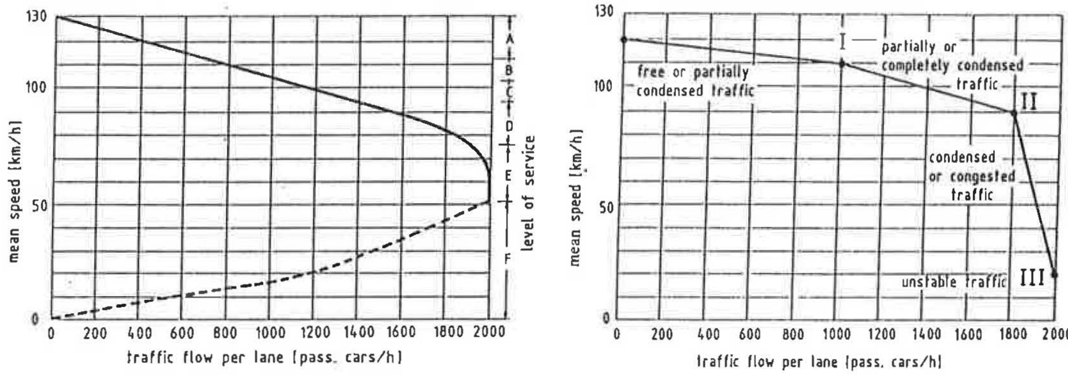

FIGURE 7 Highway capacity and LOS—transformation from HCM to West German conditions (*left*) together with a simplified polygon approximation used in the traffic control area Bavaria North (*right*) (*15*).

The essential result of all these investigations is that the speed distribution of traffic flow broadens before traffic breaks down. The standard deviation of the speed distribution as a measure of the broadness of the speed variety is therefore an early warning criterion of impending congestion and turbulent flow.

In Figure 8, the speed distribution is shown including the standard deviation for traffic with several traffic breakdowns from German Autobahn A5 near Karlsruhe. In each case, the standard deviation crosses the threshold of 18 km/hr before the mean speed sags. This provides the basis for an early warning strategy by detecting the broadening of the speed distribution. On the basis of the derived early warning strategy, a control logic was derived that is shown in Figure 9. It

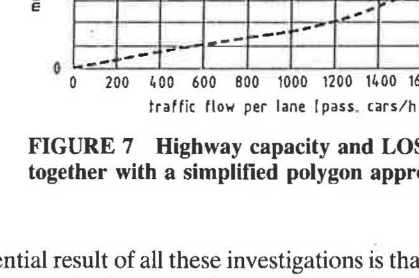

FIGURE 8 Speed distribution, standard deviation, and early warning principle (*6*).

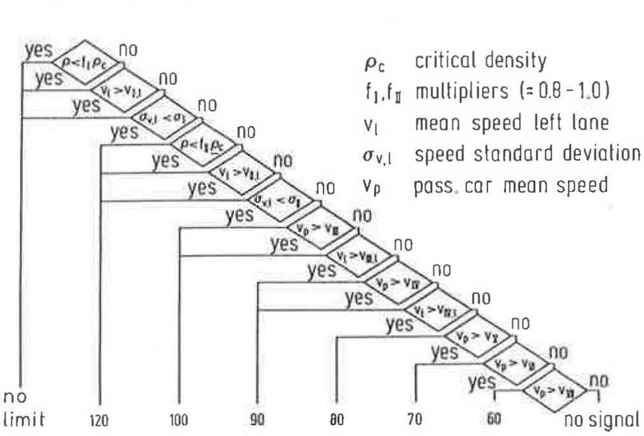

FIGURE 9 Control strategy derived from early warning principles by evaluating speed distribution.

will be implemented in the control center of the Bavaria North control area in West Germany.

The control logic presented in the flow chart uses a combination of several threshold values. The decision whether a specific speed limit is switched is made on the basis of the actual traffic density. As the traffic flow model indicates, this traffic density determines the appearing traffic patterns. The traffic density is a variable that is related to traffic conditions of a complete street segment in contrast to local variables such as traffic volume or mean speed, which refer only to a local point. As threshold value for density comparison, a first value can be derived from the traffic flow model condition $a(\rho_c) = 0$ with a proper speed-density fit stemming from free traffic flow conditions. In practical cases, a lane with low proportion of trucks (and therefore uniform vehicle composition) can be taken as a measurement reference. As an additional parameter for threshold comparison, the mean speed is taken. Because the calculated and measured traffic densities for heavy traffic exhibit strong fluctuations, an additional criterion is needed for a safer decision. As a third decision variable, the standard deviation of the speed distribution is used. As a speed distribution characteristic, the standard deviation measures the erratic character of the traffic flow. The more worriment in heavy traffic, the more danger of traffic breakdown exists. Readings taken on the broadness of the speed distribution yield an early warning. This criterion therefore is used on rather high speed levels.

The flow chart is designed for six different speed limits and two neutral states: no limit, 120 km/hr, 100 km/hr, 90 km/hr, 80 km/hr, 70 km/hr, 60 km/hr, and traffic jam. Translated to U.S. conditions, these values would lead to speed limits of 60, 55, 50, 45, 40, and 35 mph. The basis for the decision chart is static and stretched under practical aspects. Using a complex objective function for a dynamic decision logic makes no sense because there is no traffic diversion by a speed-influencing system.

The control strategy based on main-line control by speed limitation, temporal prohibition of passing trucks, lane keeping, or general warning homogenizes traffic flow, suppresses critical fluctuations and stabilizes traffic in a situation where without provisions traffic would have broken down. The success of such measurements is shown in Figure 10 in which the standard deviations of 2-min speed distributions are plotted against the mean speed with and without the working speed-

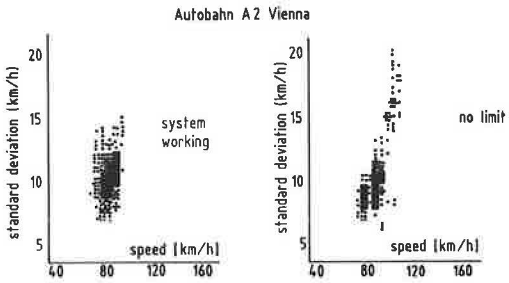

FIGURE 10 Standard deviation of speed distribution and mean speed with and without working line control system (*21*). The standard deviation is clearly reduced, impressively demonstrating the homogenizing effect.

influencing system. The data are taken from the Südautobahn A2 near Vienna, Austria (*21*). By application of the control strategy, the fluctuations are significantly suppressed.

Details of the speed distribution have proven to be an excellent tool for both assessment of traffic control provisions and early warning. To guarantee that the speed distribution has been sufficiently updated and the regarded ensemble is sufficiently stationary, the Sturges rule of thumb (*4*) is applied for speed class width estimation. In order to divide the speed distribution into a proper number of classes, this rule of thumb states that for the class width,

$$\Delta v = \frac{v_{max} - v_{min}}{\mathrm{ld}(2q_m t)}$$

where

ld = logarithmus dualis, and
q_m = average volume.

which means a ratio of speed range $v_{max} - v_{min}$ and average information content of the measurement events. For a 2-min interval and a maximum traffic flow of q_m = 2,000 veh/hr, the class width is (*4*)

$$\Delta v = 10 \text{ km/hr}$$

The speed distribution in this case is built up by speed classes each of width 10 km/hr. A finer subdivision would make no sense because of the strong fluctuations and a rougher subdivision would blur unnecessary details. The speed detection must therefore be done within an accuracy of less than 5 km/hr. This accuracy is easily obtained by millimeter-wave Doppler radar detectors described in the previous section. Meanwhile, the stated class width subdivision is standard for a modern traffic control center (*15*).

VEHICLE REIDENTIFICATION FOR TRAFFIC DATA ACQUISITION

The traffic flow model and the derived control strategy use traffic density as the crucial parameter. If stable or unstable traffic flow discrimination is performed, traffic in the unstable regime will be characterized by shock wave spreading or stop-start wave propagation, even if the speed distribution is used as an early warning criterion when the critical density is approached. In any case, the position of the operating point on the speed-density relation (and so the density itself) is the crucial traffic parameter. Traffic variables like traffic volume or mean speed are local variables. They are measured at a given location during a distinct time interval. Because of the discrete character of the traffic measurements, especially for short measurement intervals, large fluctuations occur. Likewise, large fluctuations occur in unstable traffic flow with shock front spreading and stop-start wave formation. The quotient $\rho = q/v$ has the dimensions of traffic density, but in the case of strong fluctuations it refers to the density only in the vicinity of the measurement site. In this case, there is a large difference between the calculated density and the overall density or lane occupancy of vehicles along the main-line facility. An extrapolation of $\rho = q/v$ for the complete main-line segment is not allowed. The correct determination of density takes into account the nonlocal character of traffic density. Traffic density, in contrast to traffic volume and mean speed, is a segment-related variable. It is by definition (strongly speaking) only measurable by aerial photo evaluation.

In practice, correlation techniques are applied for density determination. If two or more neighboring measurement sites are correlated, traffic variables with respect to street segments can be deduced. The most sophisticated method is the vehicle reidentification method by inductive loop pattern analysis (*22*). The impedance change of an inductive loop buried in the road surface when a vehicle passes the loop of several windings of wire is analyzed by pattern recognition methods (*23*) and used as a fingerprint. At the next measurement site, this finger print is compared with the passing finger prints. In the case of coincidence, the number of passed vehicles yields the traffic density (= number of passed vehicles within the subject main-line segment) and the waiting time until coincidence occurs gives the travel time. To avoid failures by artificial coincidence, thresholds for reidentification are regarded as well as reidentification windows for vehicle platoon reidentification. In this way, density and travel time as mean values for traffic engineering purposes are derived. Meanwhile, the traffic density and travel time detection based on inductive loops are commercially available (*24*).

Inductive loops have numerous disadvantages. They must be buried in the street pavement. Therefore on the occasions of installation, maintenance, and repair the traffic flow has to be interrupted. Under heavy truck traffic, pavement and inductive loops are damaged. Inductive loops need a metal-free environment which does not occur on bridges, steel-reinforced concrete pavement, or in tunnels. Millimeter-wave radar detectors mounted in overhead position are oblivious to these disadvantages.

After an extensive test phase, it is now possible to apply the vehicle reidentification technique also with millimeter-wave radar as traffic detectors (*25,26*). The finger print radar reflection signature is scattered back from the vehicle to the radar transmitter-receiver unit. Figure 11 shows the experimental set-up for radar signature collection. Some 1,000 signatures are collected in several measurement cycles to obtain a proper data base. Parallel to radar signature recording, the traffic scenes were stored by video to obtain the vehicle class and to reidentify vehicles using optical impressions. To sim-

FIGURE 11 Measurement test setup for radar signature recording with parallel video recording. Small size and easy ambulant installation of the millimeter-wave radar detector are clearly recognizable.

ulate the various detector conditions, a group of test vehicles was detected more than 600 times under defined conditions by the same detector set-up.

The radar signature processing is based on envelope detection with a sampling rate of 32 kHz at a dynamic range of 60 dB. Figure 12 shows the power spectra of the same vehicle from six different measurements. The spectra vary because of different orientation of the vehicles with respect to the radar sensors. The Doppler frequency, which is determined by means of fast Fourier transformation (FFT), serves for normalizing the spectra as well as the power content. As in the simple case of only local traffic data determination (restricted to speed, signal duration, and length), the maximum spectral amplitude of the averaged power spectrum is obtained from the Doppler frequency (*27*).

For pattern extraction, front and tail ends of the vehicle reflection patterns are determined by proper thresholds. These thresholds are periodically adapted to react on the noise level fluctuations. Short-time amplitude breakdowns caused by interferences or radar beam deflections while the vehicle passes may be taken into consideration by controlling the time of breakdown. Beyond time control, the end threshold has been reduced to one-half of the start threshold, to avoid having to specify as an end what is actually an intermediate amplitude

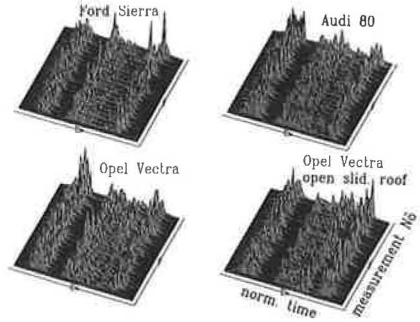

FIGURE 12 Power spectra of millimeter-wave radar reflection patterns from different measurements. The resemblance of the different patterns is recognizable, as well as the difficulty of similarity quantification.

breakdown. After begin and end determination, the signal contour is smoothed and then coarse grained by a restriction to 100 scanning points. Mean value subtraction and covariance matrix formation finally lead to an eigenvector description of the radar signature, which can be restricted to seven eigenfunctions. This number is sufficient for accurate pattern extraction and reidentification and reduces the data amount for correlation data exchange to a data value of 1,200 bits/sec. This data rate on an additional direct data link is standard for traffic data transmission. Higher data rates press the limits of existing data transmission hardware.

In a correlation unit, the extracted finger print is compared with the finger prints of the neighboring measuring site similar to vehicle reidentification techniques using an inductive loop pattern. The correlation unit detects traffic density and travel time with respect to the preceding street section like the local traffic variables speed and volume. The complete set of data relevant to local and street sections is sent by a control module to the control center. Figure 13 shows the conception of local control stations with data acquisition relevant to street sec-

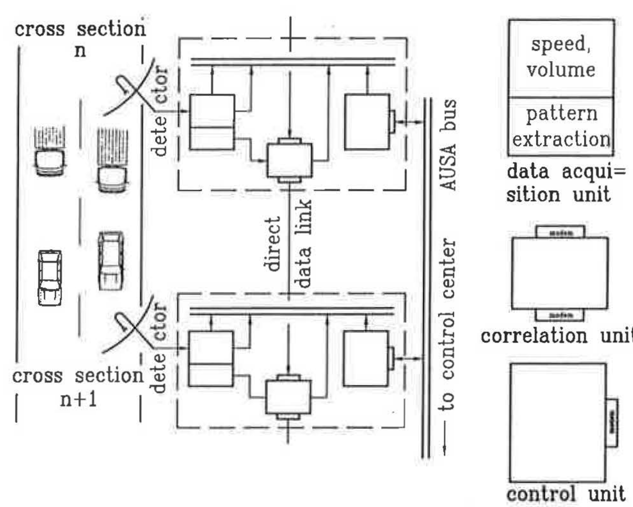

FIGURE 13 Local control stations with acquisition of traffic data relevant to street sections. Local traffic data are speed and volume; nonlocal data as determined by correlation techniques are travel time and traffic density.

tions. The data acquisition unit is the normal radar signal processing unit for local traffic data (*27*) enlarged by a pattern extraction processor. Both are installed on one European-sized board including the ECB-bus interface, the analyzing filter, and the A/D converter.

The functional architecture of the local control centers comes up to the modular set up required by the transportation authorities (*27*). With this modular concept, it is possible to use units from several suppliers, which is of great advantage in traffic control systems.

DESIGN OF A FREEWAY CONTROL SYSTEM

Traffic flow model and vehicle reidentification techniques enable the design of freeway control systems in which emphasis is put on new technologies in traffic engineering. As components of such freeway control systems, millimeter-wave radar detectors as speed and volume detectors have sufficient accuracy. These detectors can be mounted advantageously in overhead positions. For collective driver information and speed influencing, variable traffic signs are used. These signs are built up with a matrix technique; optical fibers with a pin-up lens for magnifying the light spot end in a matrix such that regular traffic signs are displayed. The fibers are collected in a bundle, which is illuminated by a halogen lamp via a coupler.

Traffic detector and variable traffic signs as well as meterological sensors are connected over a local data bus with the control unit in a local controller forming the local control station. The local control station is nearly autonomous and is responsible for the control of a street segment of 0.5 to 5 km in length. For mainline control, several such local control stations are put together. To avoid implausible jumps in the speed displays at the local control sections, the local control stations are connected by modems over a special data bus (AUSA-bus). At the end of this chain, which can take a length up to 50 km or more, is the control center where a Sun workstation is implemented. The complete control concept is shown in Figure 14. It is typical for a freeway control system in Western Europe (*28*).

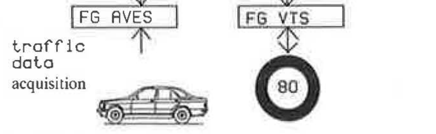

FIGURE 14 Traffic computer concept for freeway control systems. The local control stations contain a local bus connection between control unit, traffic detector (AVES), variable traffic signs (VTS).

CONCLUSION

Freeway control systems with line control and alternative route guidance in most cases use a speed-volume relation derived from local traffic data measurements as the basis of the control strategy. Traffic flow with a great variety of observable traffic patterns can be described by the dynamic traffic flow model, which uses traffic density as the crucial traffic parameter. Traffic density determines whether stable traffic flow occurs—stability conditions can be derived from the traffic flow model—or unstable traffic flow occurs with stop-start wave propagation or shock wave spreading. The density decides if nonlinearities caused by convection lead to irregularities that—together with the ever-present fluctuations—form critical fluctuations as an early warning criterion. From all these model ideas, a control system can be designed that controls traffic flow in the sense of a control circuit and that uses traffic density as the crucial control parameter. Turning away from only local traffic data affords new concepts for detection of traffic variables such as traffic density and travel time. For these, a correlation measurement concept is derived from vehicle reidentification techniques (previously used with inductive loop pattern recognition), which uses the radar reflection signature as a fingerprint from each vehicle. A satisfying concept is presented for a freeway control system based on the proposed ideas. This concept is partially realized in West German traffic control areas and can stimulate further traffic control systems.

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