# Foundations of Traffic Flow Theory I: Greenshields' Legacy – Highway Traffic

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## 1. History

The first beginnings for traffic flow descriptions on a highway are derived from observations by Greenshields, firstly shown to the public exactly 75 years ago (Proc. of the 13th Annual Meeting of the Highway Research Board, Dec. 1933). He carried out tests to measure traffic flow, traffic density and speed using photographic measurement methods for the first time. A short look on his CV shows that Greenshields started his career as traffic engineering scientist with this publication which leads to a PhD-thesis at the University of Michigan in 1934.

**Bruce D. Greenshields**

- born in Winfield, Kansas; grew up in Blackwell, Oklahoma
- graduate of University of Oklahoma; earned Masters Degree in Civil Engineering Univ. of Michigan
- 1934 Doctorate in Civil Engineering from University of Michigan
- taught at different Universities
- wrote numerous articles on traffic behavior and highway safety
- pioneer in the use of photography relating to traffic matters and in applying mathematics to traffic flow
- invented the „Drivometer"
- 1956 joined the University of Michigan faculty and was Acting Director of the Transportation Institute there
- 1966 retirement
- then returned to Washington and was a traffic consultant to various federal agencies
- Dr. Greenshields received the Matson Memorial Award in 1976

Fig. 1.: CV of Bruce Douglas Greenshields

How Greenshields performed the measurements is shown in the attached figure 2. From his original paper we read: "The field method of securing data was quite simple. A 16mm simplex movie camera was used to take pictures. An electric motor driven by an automobile storage battery operated the camera with a constant time interval between exposures. Figure 1 shows the camera with the motor attachment. Varying the voltage by changing the battery terminals controlled the time interval, which might be varied from one-half to two seconds. This method was found better than rheostat control. The time interval was carefully measured with a stop watch over a period of 40 to 100 exposures and checked by the sweep hand of a photographic timer included in the pictures. In order that moving cars might appear in at least two consecutive pictures a field of twice the space travelled per time interval was required.

To avoid photographic blur due to motion, a moving car had to be at least 300 feet from the camera. In this case the length of road included in a picture was about 125 feet. The blur might have been lessened by using a faster shutter.

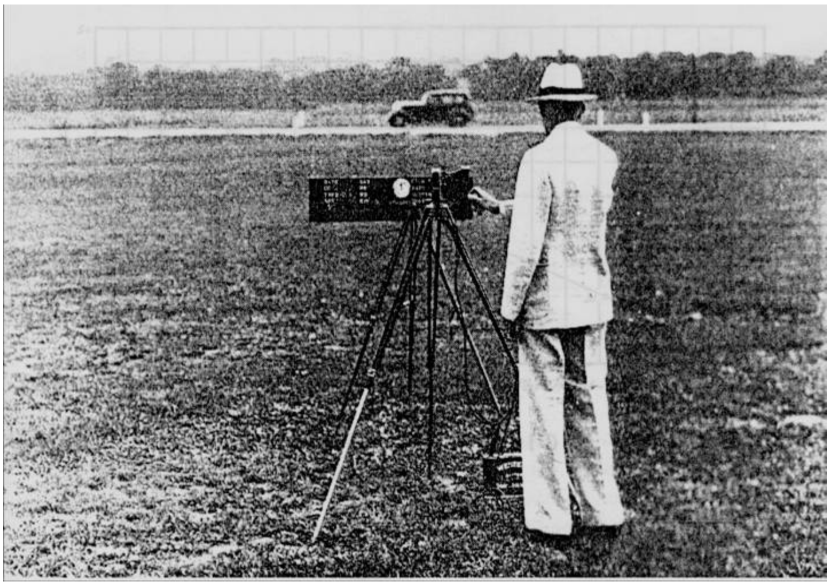

Fig. 2: Greenshields measurement set up for the reported 75 years ago

At the beginning of each film, and hourly during a run, there was included a photograph of a bulletin board giving the location date, hour, time interval, shutter opening and other pertinent information. The white cloth stretched along the opposite side of the road was used to keep the vehicles from fading into the dark background. Figure 3 shows three frames of pictures taken with the movie camera at this station.

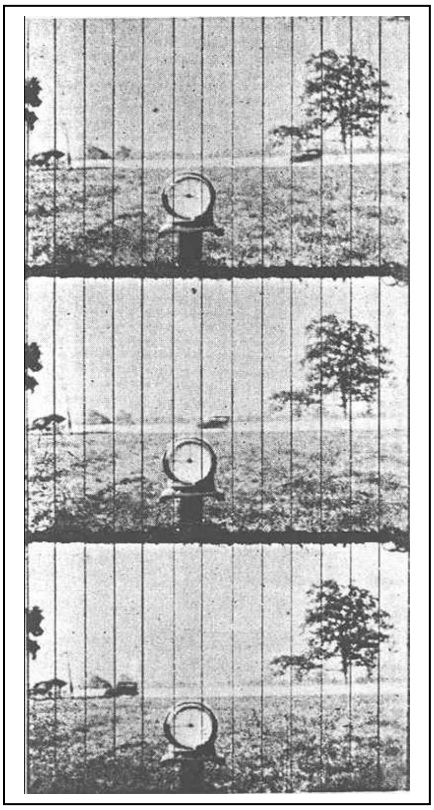

Fig. 3: Three frames pictures taken with the movie camera

The vertical lines are added to show how the pictures look when projected upon a screen with lines drawn upon it for scaling distance. The measured distance from the camera to the road together with the camera characteristics suffices to give the scale of dimensions which are more accurately determined if the camera is set at right angles to the road. As a cheek, however, a complete plan of the section of the roadway studied is recorded giving the distances from the camera and between objects in the pictures such as fence posts or poles. Where no identification exists a 100 foot tape is laid along the pavement and at every 10 foot interval a marker is held over the point and photographed. There is thus obtains a definite scale for the picture.

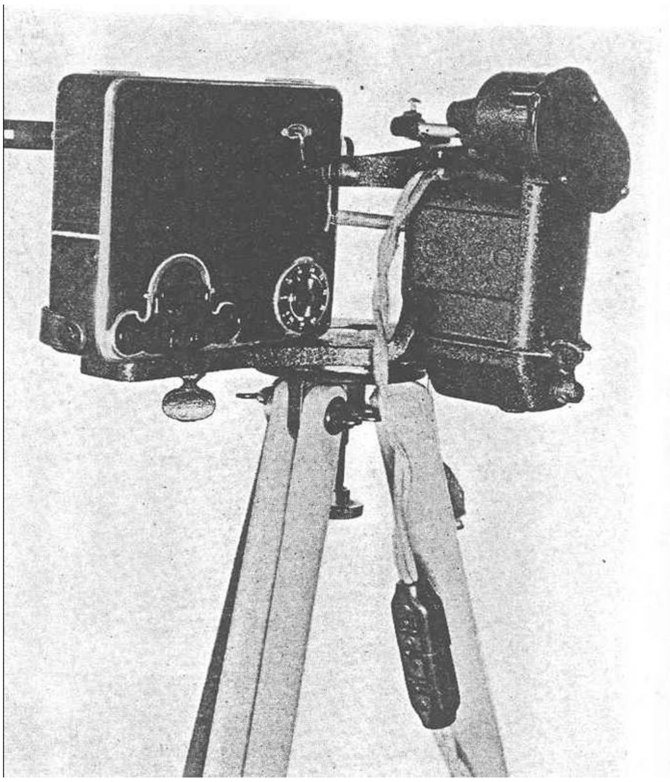

Fig. 4: Camera with Motor Attachment used by Greenshields

## 2. The linear speed-density relation

Greenshields postulated a linear relationship between speed and traffic density, as shown in Figure 5. When using the relation

flow= density * speed

the linear speed-density relation converts into a parabolic relation between speed and traffic flow (Fig. 6). Increasingly  even the term “flow” was not known 75 years ago and Greenshield called that term “Density-vehicles per Hour” or density of the second kind.

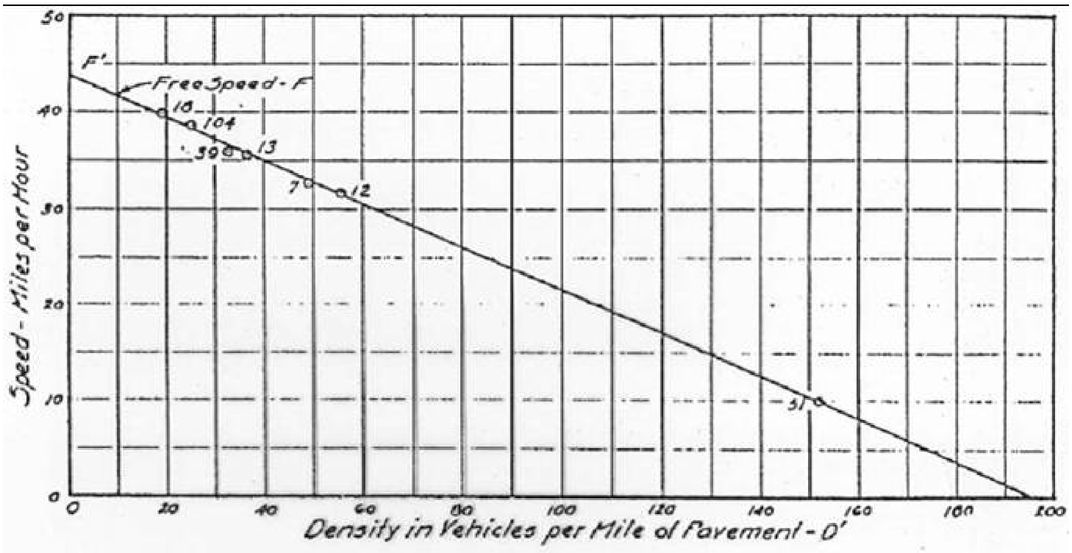


Fig. 5: Speed Density Relation V (Greenshield 1934)

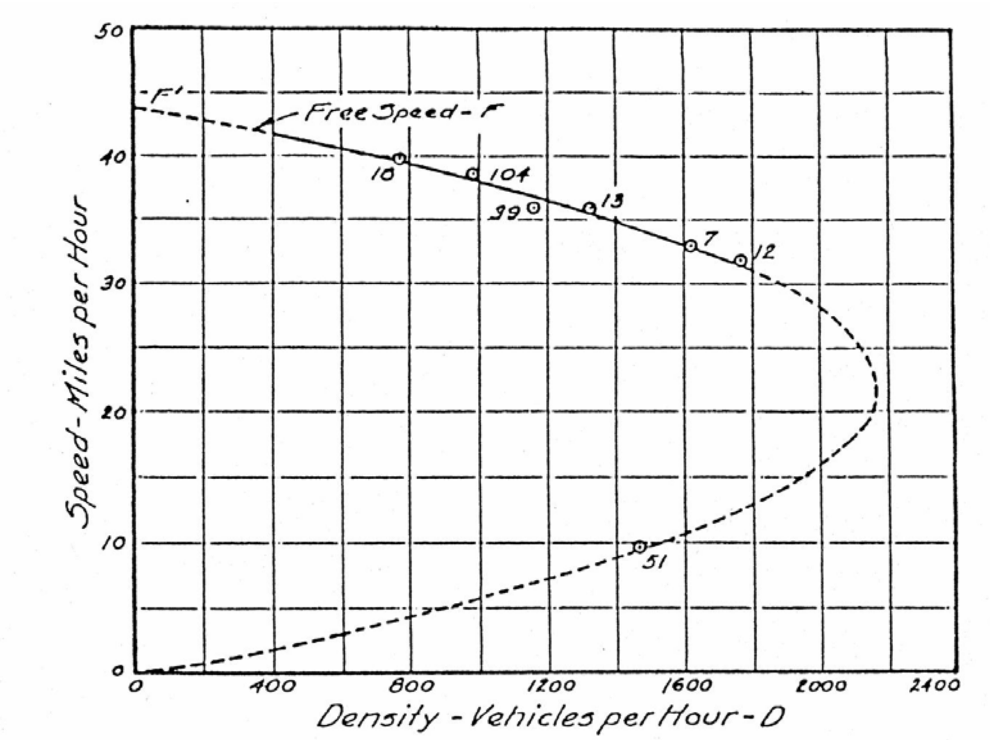


Fig. 6: The first Fundamental Diagram as v-q Diagram

In this model some traffic flow characteristics are expressed well. It shows a maximal traffic flow with the related optimal traffic density. In the q-v-diagram exist two regimes, that means it's possible to have two speeds at the same traffic flow. By this the traffic flow is classified in a stable and an unstable regime. Greenshields linear relation would be called an univariate model, because both regimes are calculated with the same formula.

Early Studies at traffic capacity of motorways had two different approaches. On the one side speed-traffic density relations were analysed. Here a constant (free) speed was implied $q=v_f*k$.

On the other side distance phenomenon at high traffic density were analysed and as easiest approach a constant reaction time $t_r$ was implied, which brings you to the gross headway $l=l_0+v*t_r$ with $k= 1/l$

$$q=-\frac{l_0}{t_r}(k-k_{max}) \;,\; k_{max}=\frac{1}{l_0}$$

Also a linear relationship between q and k – but with a negative congestion broadening speed $-l_0/t_r$ as proportionality constant. If you summarise both regimes you get a triangle function as traffic flow-traffic density relation. Lighthill and Whitham as well as Richards preached this triangle function as flow-density-curve and the use of the cinematic wave theory on road traffic as instrument to combine both fields and to explain the dispersion of shock waves as revertive going congestion front (LWR theory).

Also the q-k-relation established by Lighthill and Whitham has a parabolic curve progression and it's an one field model too. The maximum stands for the expected road capacity of a motorway section. The insights of Greenshields inspired the development of two and multiple-regime models in the aftermath.

# 3 Two-variate models

Edie showed as one of the first that at the empiric q-k data often in the area of the maximum traffic flow and he suggested to describe the q-k-relation with discontinuous curvature. 1961 he shows the first two-variate model approach for the Fundamental diagram. Here he discriminates the regime of the free traffic and the jammed traffic. His suggestions caused a series of analysis specially made by May, which aim was to specify strenghtly the characteristics and parameters of this two field models. May and Keller developed a two field traffic flow model, which based on the vehicle-sequence-model of Gazis. In the process emerged that the traffic flow in the field of instable traffic is better shown by a hyperbolic function that by a parabolic one. Parallel to these developments Prigogine and others established a traffic flow analogy for the kinetic gas theory. They showed a dependency of the velocity distribution of the traffic density and indirect of the overhauling probability. Model tests by means of measurement data showed that the curves q(k) only brings a realistic description at low traffic and burst off before the capacity limit was achieve. The model was also critically judged concerning the description of the effects of a speed impact. After that Prigogine and Herman tested an analogy of the traffic flow phases compared to the phase changes on the condition of aggregation of water (gas-fluid).
Two field models were edited for the practical use of alternative route control with changing directing signs. Assuming that there are time and route sector homogeneous conditions the traffic situation could be modellised by density waves and shown for the optimization of controlling the necessary effects of traffic flow in one end function.

## 4. Follow ups of Areal Photogramentry Techniques

Treiterer and Myers made first tests about hysteresis in traffic flow, where the connection of two variables depends on the previous history, if one variable grows or falls in relation to the other.

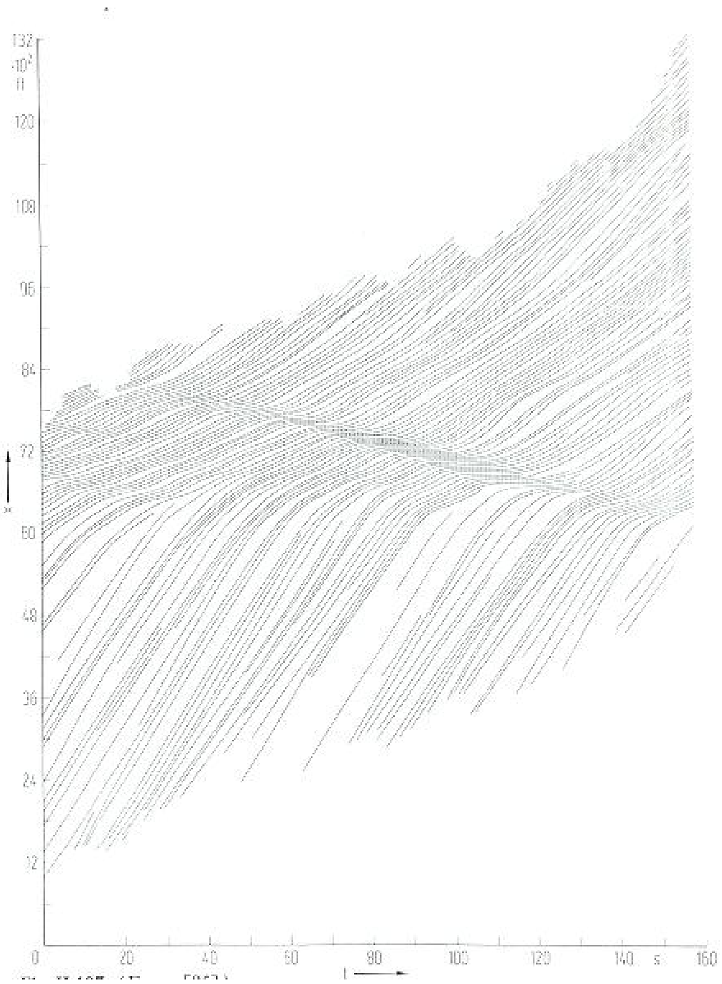


Fig 7: Description of the States of Traffic

Thereby a convey of vehicles airborne observed in an interval of 4 minutes on a route of 5,3km. 70 vehicles were analysed, which due to an upstream interference passed through an backwards running shock wave. The measurements show an asymmetry in driving behaviour at delay and speed up as resultet in tests of Treiterer and Myers. After they run through the shock wave the vehicle convoy speeded up from 40 to 60km/h and the traffic flow increased from 1800 vehicles per hour to nearly 3000 vehicles per hour. The traffic density didn't change significant.

## 5. Influence of Greenshields to European and Japanese Research Work

Greenshields influenced traffic engineers and researchers around the world. Cremer calculated the influence of dynamic traffic flow effects on the result of the fundamental diagram on a basis of a macroscopic traffic model. Through Analysis of traffic data on highways in Japan, Koshi postulates that the curve for the field of the free and dammed traffic is not constant concave in the q-k-diagram, but rather similar to a mirrored lambda. A classification of vehicles for free traffic in two groups “only following vehicles” and “leading and following vehicles” followed.

Kühne and Kerner introduced a phase transition model about the traffic flow in the field of capacity and the appropriate parameter for identification of interferences in time. Banks studied the traffic flow on the Interstate 8 east of San Diego in view of a capacity drop. By a combination of video recordings and traffic data of measurement loops he analysed the traffic flow over 9 days. The measurement loops provided traffic volume and assignment data in 30 seconds intervals. With the video recording the congestion start could be specified chronological accurate and periods of 12 minutes each pre-queue as well as queue discharge could be chosen. Via these data the existence of a two capacity phenomenon for this route section could be proved. Hall and Agyemang-Duah studied the traffic flow on the Queen Elisabeth Way west of Toronto over several days. The traffic data existed for a 30 seconds interval. The calculated capacity drop was 5-6%. Inquiries of Brilon and Ponzlet on German motorways showed data between 4 and 12%.

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