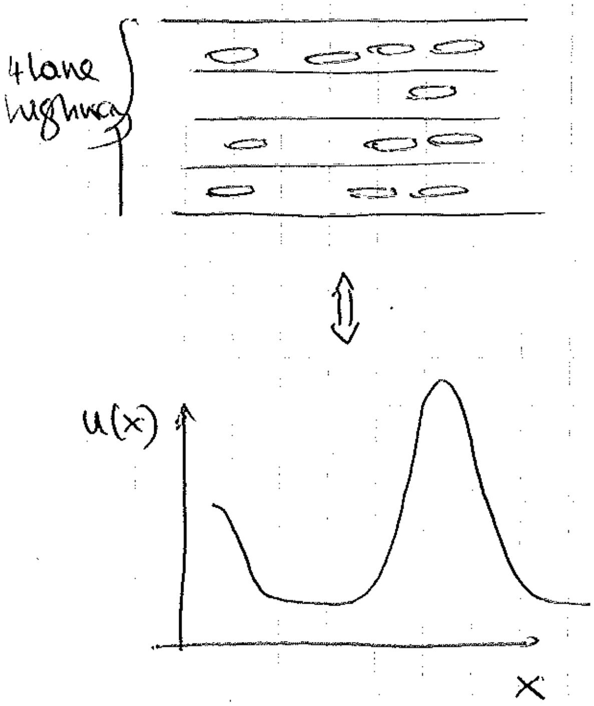
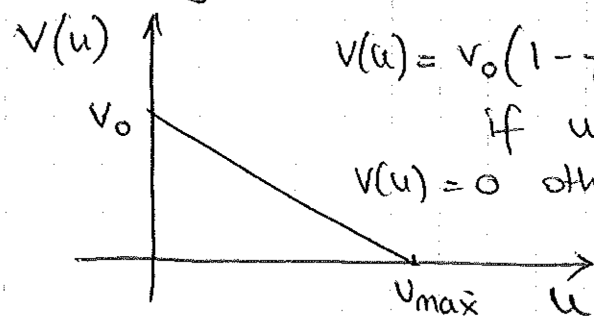
2.4.4 Traffic flow

The study of traffic flow is an attempt at modelling (for example) the flow of cars on a road/highway, but also for example of information on a network, etc..

Idea: ① Model the road/network as a 1D line, with some density $u(x,t)$ of traffic (cars/information packets) at time t, position x.



② Model the velocity of the traffic flow as a function of the traffic density:



$V(u) = v_0\left(1 - \frac{u}{U_{max}}\right)$ if $u \in [0, U_{max}]$

$V(u) = 0$ otherwise

→ Flowing traffic has optimal velocity v_0 when u is small, and stalls when $u > U_{max}$

The conservation law for the car density $u(x,t)$ is simply

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\left(u V(u)\right) = 0$$

$$\Leftrightarrow \quad \frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\left[V_0 u \left(1 - \frac{u}{U_{max}}\right)\right] = 0$$

So here we have a conservation law with

$$F(u) = V_0 u\left(1 - \frac{u}{U_{max}}\right) \quad \text{if } 0 < u < U_{max}$$
$$= 0 \quad \text{otherwise}$$

$$\Rightarrow \quad F'(u) = V_0\left(1 - \frac{u}{U_{max}}\right) - \frac{V_0 u}{U_{max}}$$

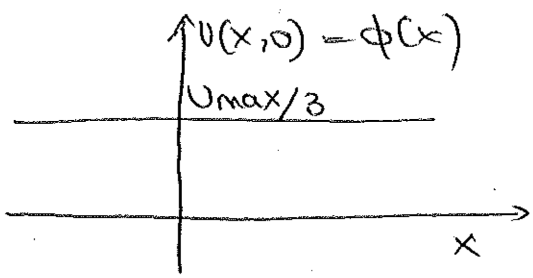
$$F'(u) \begin{cases} = V_0\left(1 - \frac{2u}{U_{max}}\right) & \text{if} \quad u \in [0, U_{max}] \\ = 0 & \text{otherwise} \end{cases}$$

- The solution to any initial traffic condition $u(x,0) = \phi(x)$ is given by the algebraic equation

$$u(x,t) = \phi\left(x - F'(u)t\right).$$

- The solution $u(x,t)$ is constant along characteristics, which are straight lines with slope $\dfrac{1}{F'(\phi(s))}$

<u>Example 1</u> Suppose we start with a uniform density of cars $u(x,0) = \frac{U_{max}}{3}$ $\forall x$.



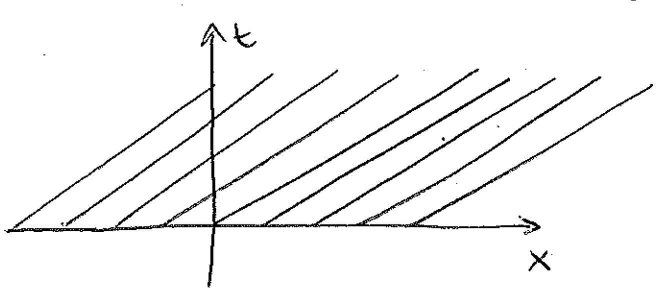
so $\phi(s) = \frac{U_{max}}{3}$ $\forall s$.

The characteristics are straight lines with equation

$$x = F'(\phi(s))t + s$$

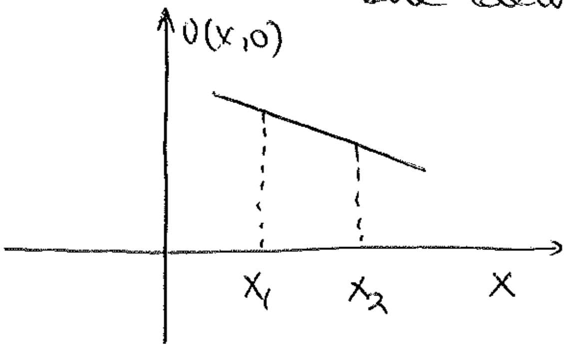
$$\Leftrightarrow \quad x = F'\left(\frac{U_{max}}{3}\right)t + s$$

$$\Leftrightarrow \quad x = \frac{V_0}{3}t + s$$

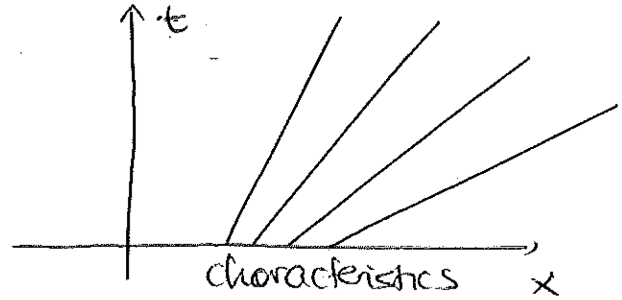


$\rightarrow$ since u is constant along a characteristic, we see that traffic is smoothly flowing at velocity $\frac{V_0}{3}$ and $u(x,t) = \frac{U_{max}}{3}$ is always constant

Example 2 Suppose there is a local decrease in the density of cars with x $\left(v(x,0) < \frac{v_{max}}{2} \right)$



$\Rightarrow$

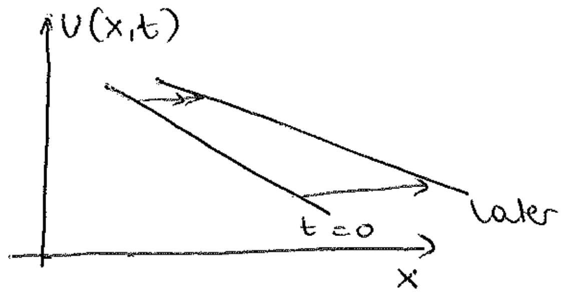


$$v(x_2,0) < v(x_1,0)$$

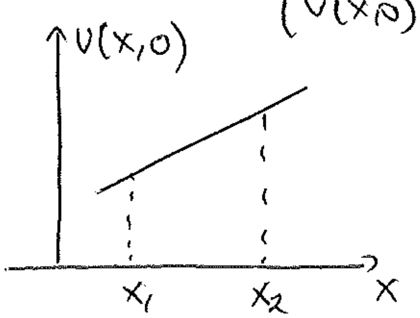
then $\phi(s_2) < \phi(s_1)$

$\Rightarrow \quad F'(s_2) > F'(s_1)$ $\rightarrow$ the slope of the characteristics in the (x,t) plane decreases

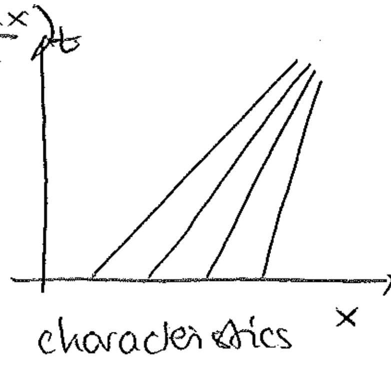
$\Rightarrow \quad \dfrac{1}{F'(s_2)} < \dfrac{1}{F'(s_1)}$ regions of less dense traffic move faster



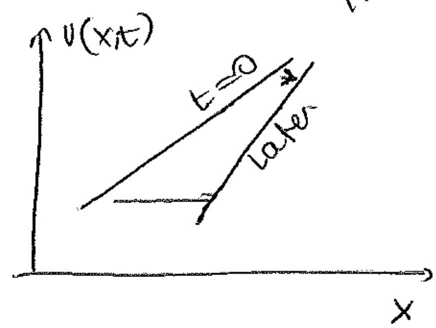
Example 3 Suppose there is a local increase in traffic $\left(v(x,0) < \frac{v_{max}}{2} \right)$



$\rightarrow$



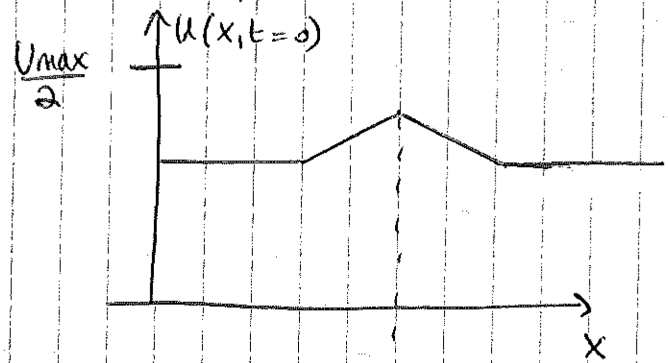
$\rightarrow$

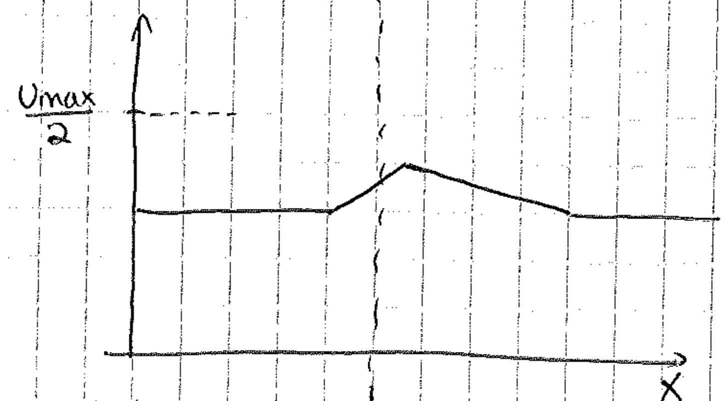


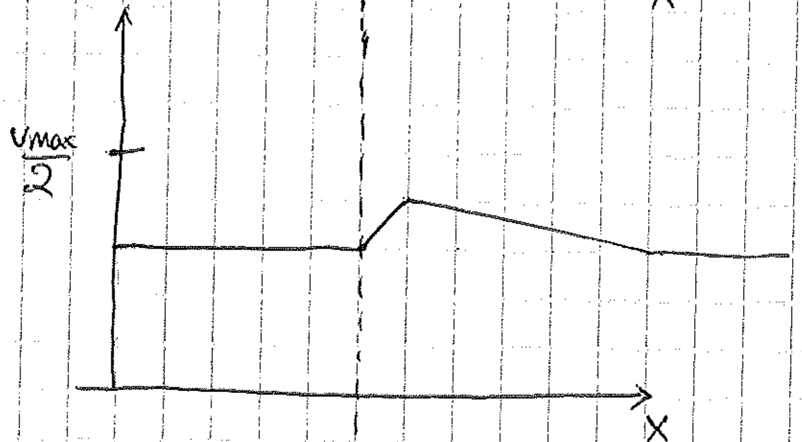
$\Rightarrow$ This behavior leads to the emergence of traffic waves spontaneously.

The traffic wave moves forward or backward depending on the density of traffic compared with $\frac{v_{max}}{2}$.

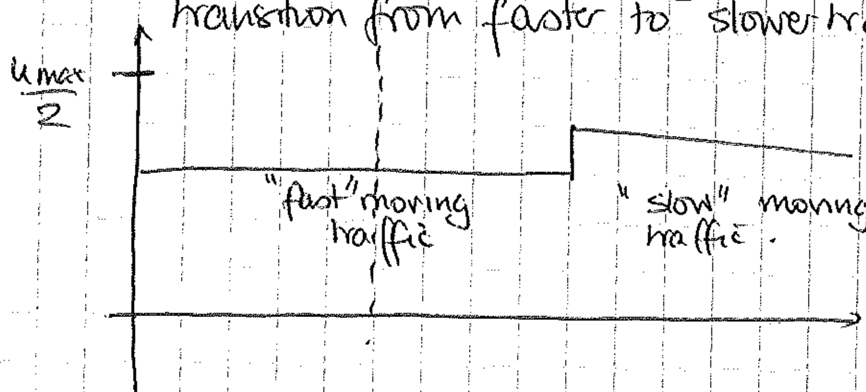
So if there is initially a small perturbation in the traffic density (but with $u(x,t=0) < \frac{u_{max}}{2}$ for all x)





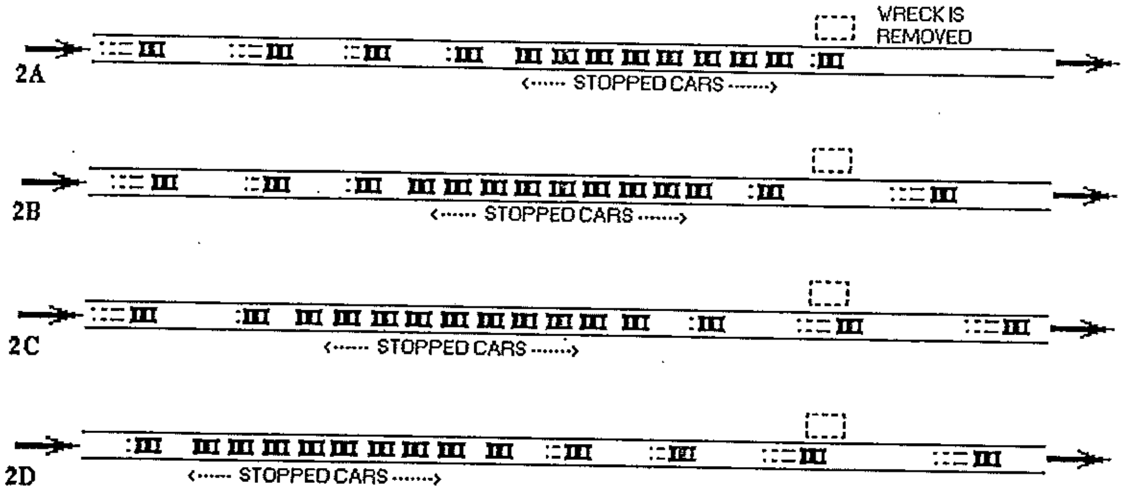


until eventually a discontinuity forms with a transition from faster to slower traffic.



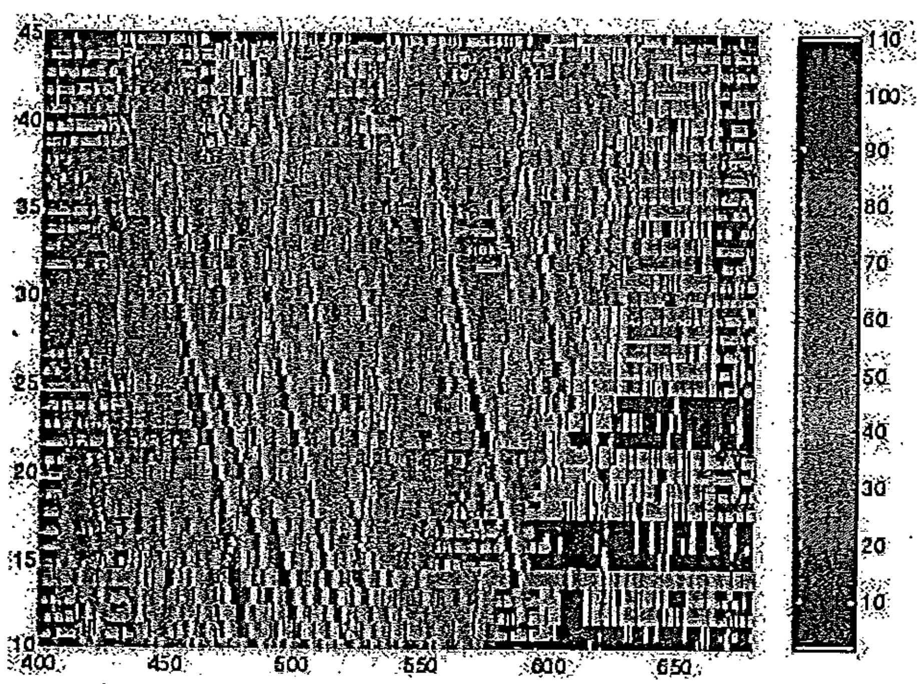
<u>HOMEWORK</u> What happens if $u(x,t=0)$ exceeds $\frac{u_{max}}{2}$ locally?

Illustration of the cause of traffic waves



M25 data (London) of traffic density vs space & time

time



distance