Traffic Modelling and Flow Rates from Floating Vehicle data

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Summary

Almost every vehicle carries a mobile phone, (not forgetting eCall) the whereabouts of which is known to the service provider. We can buy in that data to learn about traffic movements anywhere. No need for loops, CCTV, or manual counting.
At busy times there is a theoretical and demonstrable mathematical relation between speed and flow rate, which allows the construction of a Fourier representation of that flow into the future, enhanced by AI. More usefully it allows calculation of road capacity today, how near to maximum it is, and what it is likely to tomorrow.
A case study of M6 Jcn 19 shows how the technique is used to safely and easily validate junction design, but it also shows the power of the technique in making future predictions, spotting traffic problems in real time, and, when combined with weather forecasts, monitoring when fog actually exists on the road.
In summary, a powerful and easy way of understanding traffic patterns, and hence how to strategically plan to reduce, and avoid, congestion.

The problem

Traffic counting is fundamental to modelling, and doing it over a period of time is expensive (and carries an element of risk). However, it is a necessary process to validate new road layouts, and to improve signal timings at junctions. Although if they are fed with sufficient data, traffic signal controllers should be capable of re-adjusting themselves, making the task of 'tweaking MOVA' obsolete.
A possible solution comes from the wealth of unseen communication which occurs between a mobile phone and its network, and also the plethora of data sent from a vehicle by means of the eCall system. No need for loops, magnetometers, or CCTV, although it must be said that CCTV, supported by AI, is a powerful alternative idea.
The same data can also give great insights to the public for journey planning and congestion avoidance, thus helping the environmental concerns.

The second half of the problem relates to only being able to get an accurate determination of speed. Obviously we don't know how many mobile devices are in the vehicle, so numbers are difficult to establish. (We are reminded of the guy who borrowed a whole collection of mobile phones, put them in a bag, and walked round the centre of Berlin. The authorities believed they had a traffic problem similar to that shown in the 'Italian Job' film!)

The Theory – Flow Rate

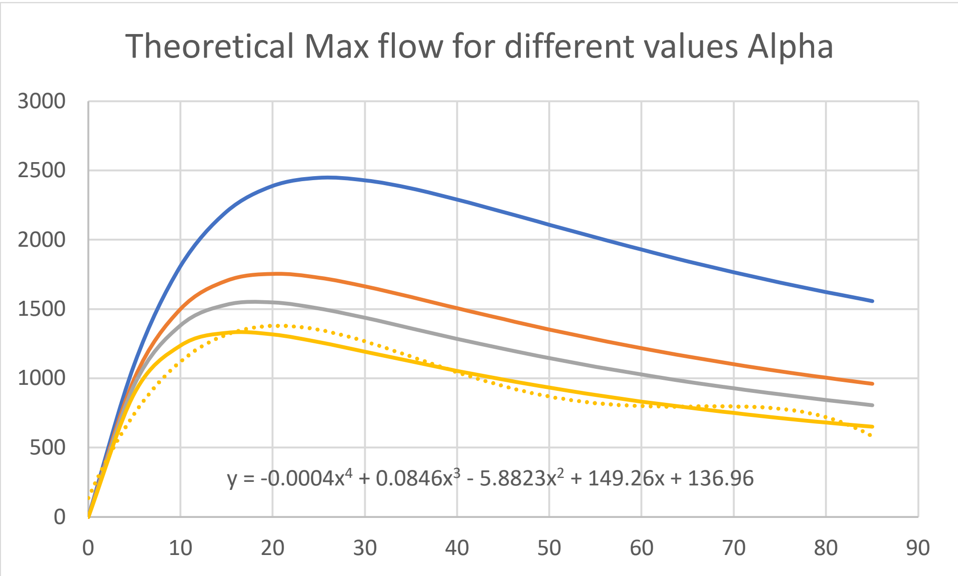
Consider a line of traffic on a busy road. Each driver is following the guy in front, and leaving a 'reasonable' stopping distance according to Highway Code guidance, speed, and weather conditions.

It is demonstrated in Appendix 1 that flow rate is given by:-

Vehicles / hour = 3600 / { L/V + 0.7626 α V + 0.681804 α }

Where L is vehicle length in metres, V is speed in metres / sec,
and α is dimensionless average fraction of stopping distance used on the day.

The value of α (alpha) will depend on many factors, such as weather, and even cultural attitude of the driver. Hence it is a similar problem to measuring the sizes of people. No matter how many measurements you make, you will still get a probability density function covering a range of sizes, and things like building design (or clothes) must take account of the range. In a similar way, so must traffic modellers.



The chart shows flow rate for different speeds (MPH) for values of α (alpha) being 0.6 (blue), 1 (red), 1.2 (grey) and 1.5 (yellow). The dotted yellow is a 'best fit' quartic curve for the case of α = 1.5

This gives a link between speed and flow rate, which has been validated against data provided by loops in the motorway. The Pearson Correlation Coefficient test against real speed / flow data giving a value (0.85) way in excess of that required for a statistically significant result at the 1% level (0.684). Therefore it is reasonable to assume that the matching of loop data and the above equation has not occurred by chance.

The Theory – Flow Patterns

To show a recurring daily pattern, we will use Fourier series.

$F(\omega) = \int_{-\infty}^{\infty} f(t) \; e^{j\omega t} \; dt$ where j = √ -1

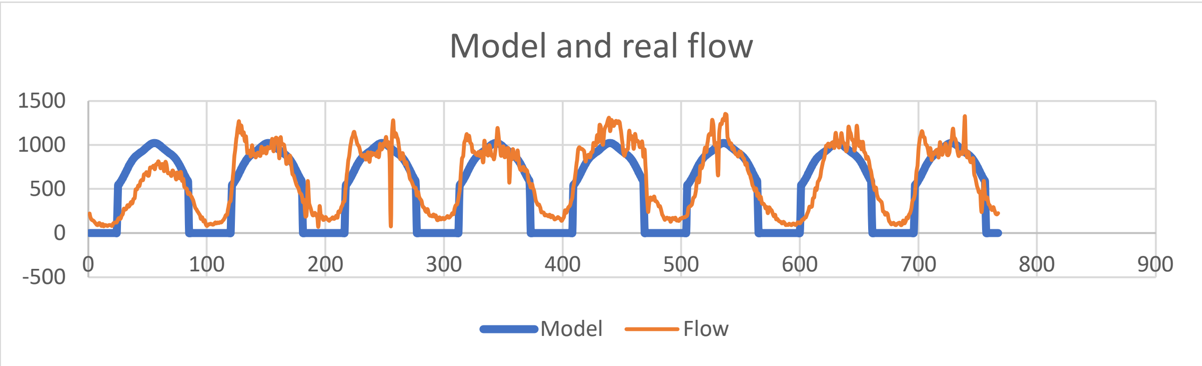
More helpful if used with Euler's formula,

$e^{j\theta} = \cos\theta + j\sin\theta$ and $\cos\theta = \sin(90 - \theta)$

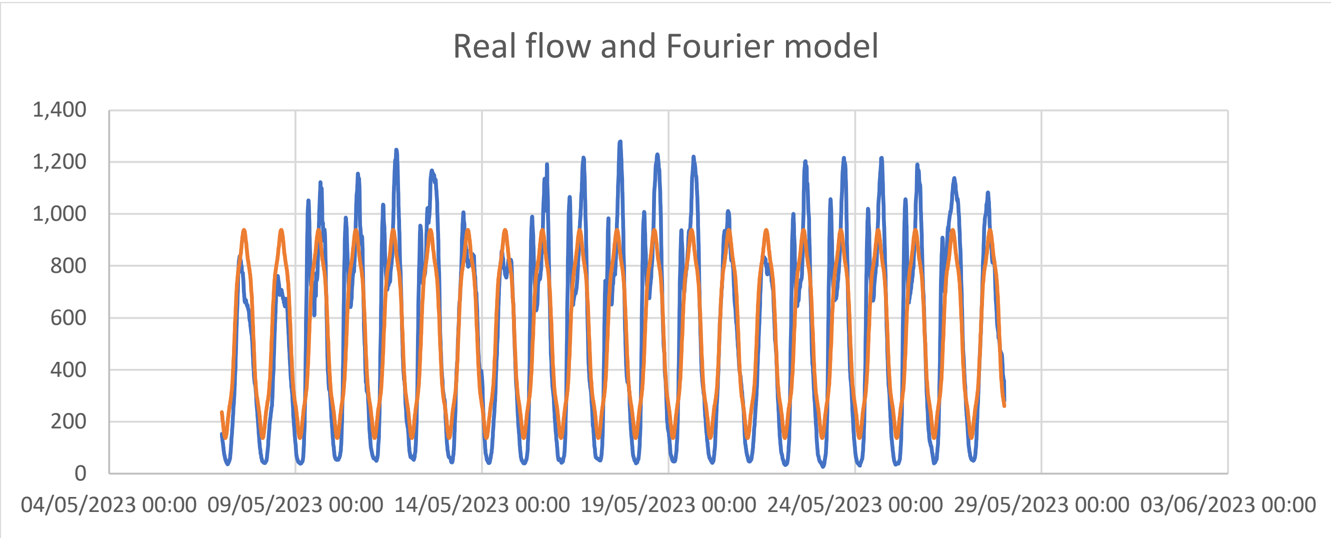
Which then yields a set of harmonics of the fundamental. (ie how much of each frequency). To help the analysis, we can disregard the night time hours, as traffic volumes are so low they do not cause any issues or interest. It would be possible to add a 1/7 sub harmonic to cover weekends if the traffic volumes were high.

To this we can add a linear term to show traffic growth over the years, and some AI / machine learning to allow for special cases such as holidays, sporting events, etc.

This is from the M6, jcn 19 'J' slip road



And this one from A1(M) jcn 6 NB approach



Remember that 8 May 2024 was a public holiday for the coronation of King Charles.

Floating Vehicle Data

Floating vehicle data is anonymised, timestamped geolocation and speed data collected directly from moving vehicles. Advantages include:

- No roadside infrastructure
- No special vehicular hardware
- Significantly greater coverage and detail
- Rapid set-up and zero maintenance (all remote)

4way have partnered with Mooven to access this data in the UK. Mooven quantifies Google traffic data – likely the largest and most used aggregation of crowd-sourced traffic data.

Case study – M6 J19

This is a junction Improvement scheme comprising two new ‘throughabout’ overbridges, new traffic signals, and associated signal plans, which was completed and opened in 2022.

Two key scheme requirements were:

1) Journey times between the M6 NB and A556 NB do not exceed 87 seconds
2) That traffic exiting at J19 does not queue and back-up onto the M6 mainline

A monitoring trial was undertaken for one full week of continuous traffic monitoring, from 19/09/22 (Mon, 11pm) to 26/09/22 (Mon, 11pm). This covered twelve individual routes designed specifically to address the scheme requirements.

Outcomes from the trial were that the junction achieves journey times from the M6 N to A556 N of less than 87 seconds, and that the scheme has negligible impacts on the M6 mainline, as evidenced by maximum queue lengths being shorter than the off-slips.

A few other insights were a high consistency of journey times throughout the week, i.e. excellent journey time reliability, and lack of significant traffic queues anywhere.

This clearly shows that the floating vehicle data approach has worked, thus enabling the traffic flows to be safely measured everywhere without the use of loops, or other hardware.

A drive through test during Easter holiday 2024 showed no congestion on any of the roads, despite heavy traffic and long delays elsewhere, thus validating the findings.

Summary and Way Forward

Floating vehicle data gives us speeds, and hence flow rates, from the comfort of our offices. We can tell if a road is running near to capacity, and when that capacity is likely to be exceeded. The mathematical techniques associated with stochastic modelling can be used to great effect here.

Perhaps the most exciting prospect is to use floating vehicle data to adjust traffic signal timings without human intervention. MOVA (Microprocessor Optimised Vehicle Actuation) adjusts the signal timings at an isolated junction according to the information from nearby detector loops. It knows nothing of what happens further away. Despite the sophistication, it still needs a person to configure and change the site parameters! Why not design the system to optimise itself by using floating vehicle data to look at a much wider area of traffic movements in a longer time period, and tweak itself as necessary? The concept of SCOOT (Split Cycle and Offset Optimisation Technique) is a similar idea, taking data from several sets of signals, but again only loop based.

But even more exciting is ‘Naked Roads’…..

Why are we doing this?

A 'naked road' is a term for a future road concept that does not have any physical roadside signage:

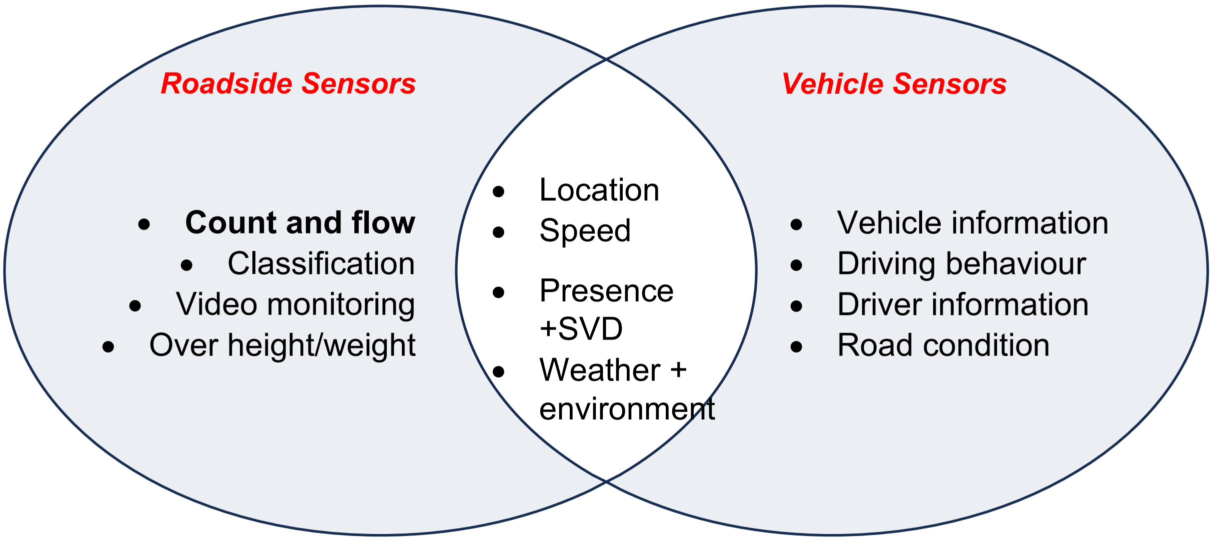
- no motorway gantries with variable message signs and signals
- no hard plate direction, information, or speed limit signs

Instead, the aim is for this information to be digitally transmitted directly to the connected vehicle. The naked road is the theoretical culmination of the development of digital signage on roadways and it forces people to think about and engage with a whole new way of sharing information with drivers and vehicles.

In addition to transmitting information into vehicles, vehicles themselves are becoming ever more advanced with arrays of sensors to generate data about their own performance and conditions in the ambient environment. Road operators with access to this connected vehicle data may get better insights into conditions:

- weather – vehicle lights on/off, wipers on/off
- road – vehicle traction control active/inactive, RADAR/LIDAR information
- driving – vehicle speed, harsh braking/acceleration events, cornering
- driver – attention, intoxication, biometrics
- traffic – corroborating data from crowd sourced connected vehicles

While similar data fields from vehicles are inherently different to data from roadside devices (e.g. speed) because their location is not fixed, it is possible to begin using vehicle data *in lieu* of roadside device data.

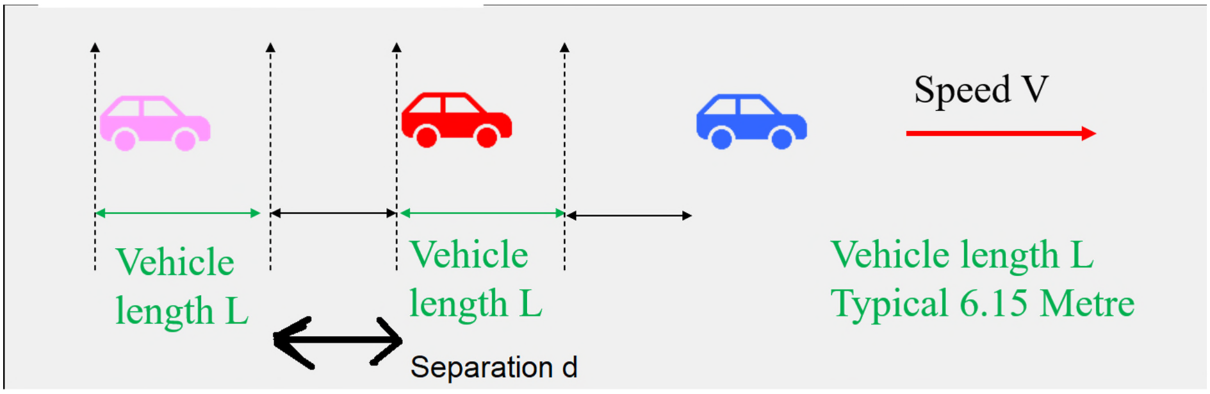


Traffic counting is fundamental to modelling. This work explores the art-of-the-possible for inferring **count and flow** information from vehicle data instead of traditional roadside devices or manual counts. The overlap of vehicle and roadside capability is likely to grow overtime, enabling a potential future where naked roads may also include the reduction and removal of many physical roadside sensors, replaced by methods like we've shown.

********************* The End! Thank you for reading this far! *********************

Appendix 1 Derivation of Speed – Flow Rate formula.

Assume saturated flow, ie one vehicles progress is limited by the one in front.
Consider a line of vehicles, length L, separation d, and velocity V (in metric units)



Time between vehicles to passing a fixed point is $(L + d) / V$ secs

Number of vehicles per hour is $= 3600 / \{ (L + d) / V \} = 3600 V / (L + d)$
Using metric units of metres and metres /sec

The separation d is also a function of speed. So in feet and MPH

$d = (V^2 / 20) + V$ (ie stopping distance taken from 'old' Highway Code)

which, when converted to metric gives:-

Stopping distance $d = 0.7626 V^2 + 0.681804 V$ (units of metres and metres /sec)

But drivers don't leave the full prescribed stopping distance, only a fraction of it.
Let that fraction be called alpha α

Therefore vehicles / hour $= 3600 V / \{ L + \alpha(0.7626 V^2 + 0.681804 V)\}$
(units of metres and metres /sec).

$$= 3600 V / \{ L + 0.7626 \alpha V^2 + 0.681804 \alpha V \}$$

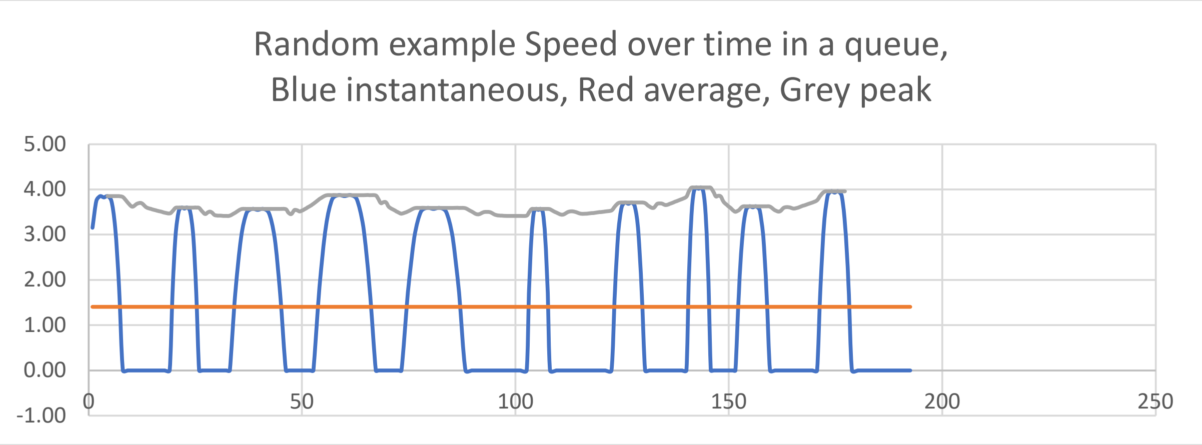
$$= 3600 / \{ L/V + 0.7626 \alpha V + 0.681804 \alpha \}$$

The value of alpha (fraction of stopping distance used on the day) will depend on many factors, such as weather, and even cultural attitude of the driver. Hence it is a similar problem to measuring the sizes of people. No matter how many measurements you make, you will still get a probability density function covering a range of sizes, and things like building design (or clothes) must take account of the range.

Vehicle length includes 'personal space', the distance into which one driver will never encroach, (eg to allow margin for error, or manoeuvring room to pass if the vehicle in front breaks down). Hence around 6.15 metres. . Remember 1km of stationary vehicles will contain approximately 150, which gives a vehicle length of 6.6 metres

Appendix 2 Low speed queues.

Consider the case of a traffic queue. Vehicles are stationary, move for a while, then stop again. A loop type detector does not detect the speed of a stationary vehicle. It will detect a speed when it moves, and record it. Hence the instantaneous speed detected in this way will be higher than average speed.



The study of this is outside the scope of this paper, but the key message is that floating vehicle data doesn't suffer from this measurement problem.
We can however compensate for this kind of pattern in loop derived data by making a transformation in the speed domain V -> V' such that V' = mV + C, where m and C are constants. (Where M ≈ 1.1, and C ≈ 9, determined by solution of best fit equations). The model is applicable in this case, providing the time spent standing still is known.

Appendix 3 High speed, low volumes.

This happens when the road is not busy, especially overnight. The traffic speed is not dictated by the vehicle in front. The road is operating well within capacity, and is thus of no interest. The model is not applicable in this case, (but others are).

However the opposite case to this is lower speed with low volume. (ie why is traffic going unusually slowly?) This suggests a problem, eg fog, or a broken down vehicle, and should be flagged up for immediate investigation. Why is traffic moving slowly when the road is fairly empty?

Conversion data

To convert MPH to metres / sec divide by 2.237 or multiply by 0.44704
To convert feet to metres divide by 3.281 or multiply by 0.3048
For example, 30MPH is 13.4 metres/sec

Appendix 4. Background :- Poisson Distribution

There exists a well documented formula referred to as ‘Poisson Distribution’ which gives the probability of the arrival of an event in a given time, knowing the average arrival time of events.

Suppose we determine an average arrival rate ϕ (units per time period). This may require observation over a long time period.

Now let us consider the time period of interest, T

The probability that r events will occur in time period T is given by the Poisson distribution:

$$P(r) = \frac{(\phi\ T)\ \hat{}\ r}{r!} \quad \exp(-\ \phi\ T\ )$$

$$= \frac{\exp(\ r\ \log e\ (\phi\ T)\ )\ \exp(-\ \phi\ T\ )}{r!}$$

It is easier to work out the probability P(some) = 1 – P (none),
since K^0 = 1 and 0! = 1

This formula can be used to model the arrival of vehicles in situations where they are spread out, ie flow rate is less than maximum.

Appendix 5. Queue Theory. M/M/1 queue.

This is applicable to a small supermarket with one checkout, or to a line of vehicles being controlled by traffic signals.

Customers are assumed to arrive according to the Poisson process (above).
There is a mean service time
The number of customers in the queue can be calculated.

Traffic intensity = Arrival rate / Service rate

Let P_n be the probability of n customers in the queue. Then

Arrival rate * P_{n-1} = P_n

Average queue length = Traffic intensity / (1 - Traffic intensity)

Average waiting time = Average queue length / Arrival rate

This discussion can be extended for more ‘servers’ (M/M/n queue), and with further calculations for throughput, but that is too complex to fit on this page.