

Steering with an eye to braking

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Locomotor control is fundamental for our survival: from the evolutionary importance of avoiding predators and catching prey, to the modern day requirement of driving at high-speeds along curving roadways, successful locomotion remains an essential component of our everyday existence. It is of great credit to the human visual system that we are able to control our locomotion at speeds far greater than those we would have encountered during our evolution. In this article we present an opinion on how one can routinely and rapidly determine whether the speed of approach toward an unknown bend is too fast, or whether a tight turn will be sufficient to stay within the safety limits of your vehicle.

The two predominant sources of information that can be used to control our course through the world are retinal flow and visual direction information¹⁻⁴. Imagine each visible texture element from the road surface ‘streaking’ across the photographic plate of the retina. Such retinal flow patterns can usefully inform you as to your own direction of motion. The visual direction of a road feature is specified by a visual target-heading angle (the *bearing angle*). In order to steer to the target you need to close down the angle between your direction of travel (which is usually coincident with the midline of your body) and the target. Two recent studies demonstrated that when retinal flow becomes degraded our dependence upon visual direction information increases during walking³ and high speed steering¹.

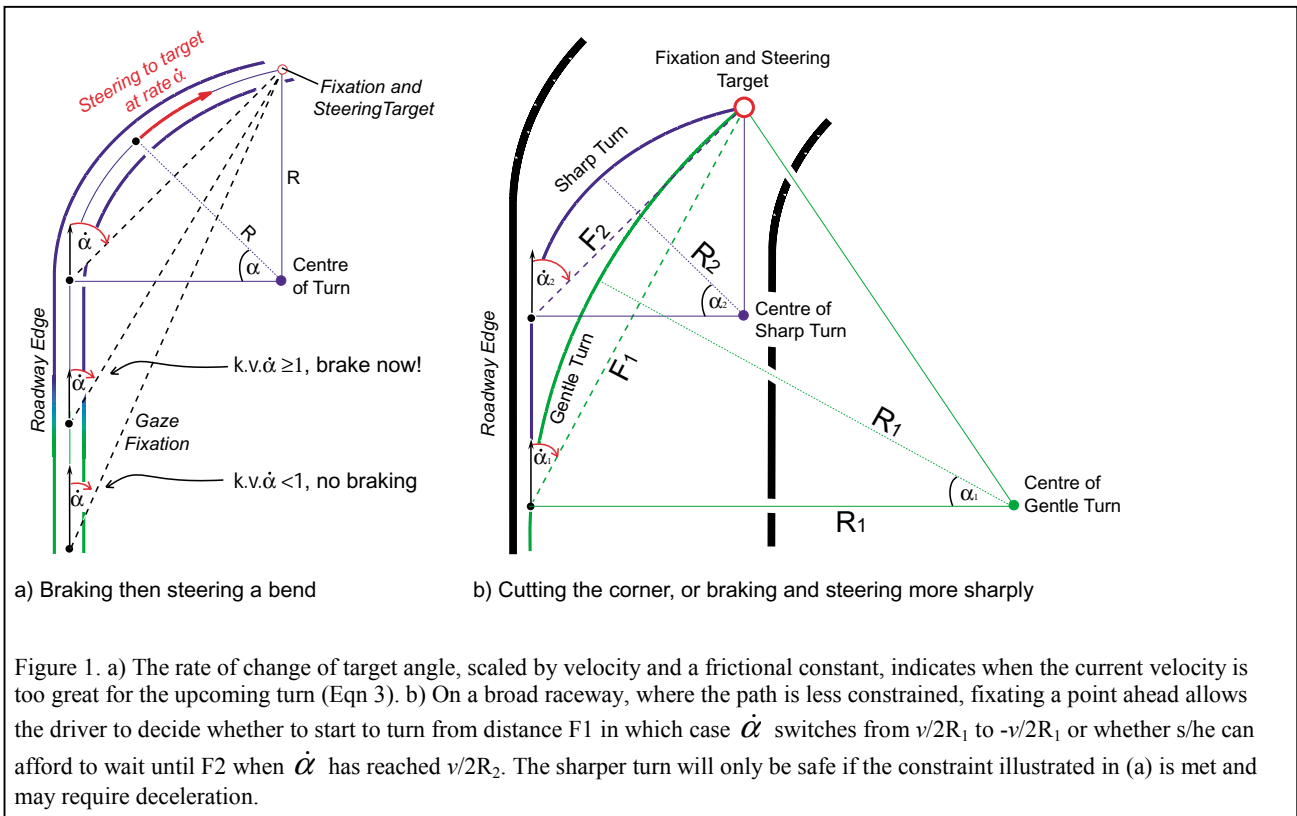
Models of Steering Control

In order to quantify the combination of this information, mathematical models have been used that generate locomotor trajectories on the basis of an angular point attractor system. Fajen & Warren⁵ proposed such a model that steers to the target attractor whilst negotiating a series of obstacles (which are treated as repellors). This model mimics human performance when navigating through a cluttered scene, however it requires the estimation of the bearing angles and distances of each target and obstacle. It works primarily by closing down the bearing angle of the target, but it may be that retinal flow is used for the calculation of your current direction of motion (heading). A

simpler system has been proposed by Wann & Wilkie⁶, which also allows for greater cognitive mediation, whereby you merely look to where you want to go. By fixating a steering target, gaze angle can be used in place of the bearing angle. Fixating the target also transforms the pattern of retinal flow so that it is more informative about progress towards the target⁷. Active gaze fixation therefore allows rotation estimates to be pooled from retinal flow and gaze angle without requiring properties such as distance or heading to be extracted from the world. The Wann/Wilkie model suggests that a driver will look to locations they wish to pass through as they travel down the road, and predicts that much of the skill in learning to take a racing line is in directing your gaze to the appropriate location on the upcoming bend. This is in line with advanced motorcycle training manuals that state ‘the machine will go where your eyes lead you’⁸.

Reading a bend from gaze rotation and flow

Fajen & Warren⁹ successfully extended their model to intercept both stationary and moving targets on foot, but a good fit of human data required use of the rate of change of bearing angle, equivalent to gaze angle rotation if the observer fixates the target to be intercepted. We propose that gaze angle is the essential perceptual variable because it is difficult to envisage how bearing angle (or its rate of change) could be estimated for a patch of tarmac around a bend without forward fixation of that point. If you are approaching a bend in the road, and fixate a point upon it, gaze angle can enable the driver to estimate the curvature of the road¹⁰ and the rate of gaze angle closure can confirm that the current steering rate will result in a constant curvature path through the point of fixation¹¹. The speed at which a corner can be taken without slipping sideways, however, is constrained by the frictional properties of the road surface and of the vehicle, which specify the maximum safe velocity (v_{max}) for taking a bend of a particular radius (See Box: Modelling Braking). How can we judge whether we know if we are travelling too fast for a turn, and whether to decelerate before steering into the corner? The rate of change of gaze angle may also provide a valuable solution to this critical problem since its properties cause it to vary as a function of both the current speed and the radius of curvature of bend. If the driver estimates his/her current velocity and scales this by gaze angle rotation ($v\dot{\alpha}$) to provide a safe-velocity margin (S_v , eqn 9), then for a safe turn this should remain below a constant



value dictated by the frictional properties of the road surface and tyres. Novice drivers would initially take bends at speeds that are well below v_{max} . Greater experience allows a speed increase at bends, to the point where some drivers may take a corner in a somewhat reckless manner and experience the consequences of approaching this limit. During cautious road usage drivers or cyclists ensure that S_v stays well below the limits imposed by friction and this may require deceleration prior to a turn. Most of us have also experienced travelling along a novel route, looking for a side road. You eventually spot the side road, but make a rapid judgment that you are travelling too fast to make the turn, so you continue past it and turn around further along the road. At the instant at which this judgment is made, we propose that the rate at which the target is sweeping sideways and velocity recovered from retinal flow are the perceptual variables that allow you to judge what is “safe”. A simulation of the braking model in operation for an autonomous vehicle can be viewed at: <http://www.rdg.ac.uk/ar/> (demos of displays).

Highly skilled drivers and the racing line

Highly skilled racing drivers develop a very good feel for the frictional limits of various tire compounds on different surfaces, but are not constrained to taking a bend within specified lane markings and often choose a quicker “racing

line”. The potential for this is illustrated in Figure 1b. At any point during the approach the driver can fixate a steering target, such as the apex of the bend, and the gaze angle will open up at a rate that is a function of the fixation distance and the instantaneous gaze angle. If the driver decides at that moment to head towards the fixation point then turning the wheel until the gaze angle starts to close down at that same rate will take him/her on a constant curvature path to the fixation point¹¹. Alternatively the driver may delay their response to a later time to take a sharper arc, but if at that time the value of S_v has exceeded their frictional estimate, they may have to switch their gaze to a less eccentric point than the apex of the bend in order to make the turn without braking. It is therefore the case that $\dot{\alpha}$ can provide the perceptual information to judge and execute a wide range of curved trajectories, including the selection of a racing line.

In summary, there is sufficient evidence that either gaze angle or bearing angle is a potent source of information in guiding locomotion¹⁻⁴. Here we outline how gaze angle rotation could also inform the driver about an upcoming turn and allow them to ensure speed and steering control that is appropriate for safely negotiating winding lanes and broad sweeping freeways.

Braking Box

When a vehicle of mass M travels around a bend of radius R, at velocity v, the force required at the road surface to steer the curved path is mass multiplied by centripetal acceleration ($f = M.v^2/R$), which is supplied through the frictional properties of the tires as $\mu.M.g$, where g is gravity and μ is the coefficient of friction. The velocity at which a vehicle will slide off the road (v_{max}) occurs when these two forces become equal:

$$\frac{M.v^2}{R} = \mu.M.g \tag{Eqn 1}$$

re-arranging Eqn 1 with respect to v^2 removes mass from the equation:

$$v_{max}^2 = \mu.g.R = kR \tag{Eqn 2}$$

Where k is a learned constant based on the frictional properties of the vehicle. For conventional car tyres on dry tarmac $\mu \approx 0.8$, $g \approx 10$, and therefore k would be 8. The more reckless driver may gain direct experience of k if they approach a bend at v_{max} . But we would suggest that the system may be calibrated by more cautious drivers on the basis of the vestibular/haptic cues that arise during a sharp turn and lead the driver to adopt a conservative strategy where k is significantly less than the true limit.

The problem for the use of Eqn 2 is that R is not known for an unfamiliar bend. Wann & Land¹¹, however, demonstrated that if the driver is fixating a future point on the circular path then the change in gaze angle ($\dot{\alpha}$) is a product of the locomotor velocity (v) and bend curvature:

$$\dot{\alpha} = \frac{v}{2R} \tag{Eqn 3}$$

Ideally what the driver wishes to know is the ratio of his/her current velocity to the maximum velocity that would be safe for the upcoming bend. Using Eqn 2 and rearranging Eqn 3 gives:

$$\frac{v^2}{v_{max}^2} = \frac{4.\dot{\alpha}^2.R^2}{k.R} = \frac{4}{k}\dot{\alpha}^2.R \tag{Eqn 4}$$

To substitute for the remaining term of R, we can either use an estimate of locomotor speed (v) estimated from ground flow or an estimate of the fixation distance D that gives rise to $\dot{\alpha}$.

$$R = v/2\dot{\alpha} \tag{Eqn 5}$$

$$R = D.\sin \alpha/2 \approx D.\alpha/2 \tag{Eqn 6}$$

$$D = I / \tan \gamma \approx I / \gamma \tag{Eqn 7}$$

Where I is the eye height γ is the vertical gaze angle. It is important to note that the approximations used in Eqn 6 and 7 are acceptable for the angles encountered when looking some 1-2s ahead on the road. Using Eqns 5-7 to substitute for R gives a range of options for judging a safe approach speed to a bend of unknown R.

$$\frac{v^2}{v_{max}^2} = \frac{2}{k}\dot{\alpha}.v = \frac{2}{k} \frac{\dot{\alpha}^2 D}{\alpha} = \frac{2}{k} \frac{\dot{\alpha}^2 I}{\alpha.\gamma} < 1 \text{ for a safe turn} \tag{Eqn 8}$$

In summary we propose that drivers learn a safe velocity margin S_v for their specific vehicle from driving a range of bends. In extreme cases this may be due to actual sideways slippage, in which case this margin is close to ($\mu.g/2 = 4$ for a conventional car). More usually this may be based on vestibular cues and/or the pitching of the vehicle which may result a safer margin (e.g. $S_v < 4.0$). What drivers learn is that for safe passage around a bend then:

$$\text{Either } 2.\dot{\alpha}.v \ll S_v \text{ or } \frac{\dot{\alpha}^2 D}{\alpha} \ll S_v \text{ or } \frac{\dot{\alpha}^2 I}{\alpha.\gamma} \ll S_v \tag{Eqn 9}$$

What is important to note that the heuristics in Eqn 9 do not include the turn radius R does not feature so the driver doesn't need to "know the bend" or have attempted the specific turn previously. Judging a safe velocity for a turn can be based on egocentric visual estimates without recourse to estimating the scene geometry.

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