A Naturalistic Cycling Study Including Preliminary Physical Considerations

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Abstract

A naturalistic cycle study was completed by ten cyclists where various risks were identified by the cyclist. The risk was then analysed in terms of the underlying physical parameters.

The format of documenting the cyclist's experience during their journey is based on a questionnaire/survey post journey and on a live recording from a helmet mounted camera. Various risks are identified and the related physical parameters are analysed (e.g. collision of cyclist plus bicycle with other path or road users).

The physical parameters of delta-*v* and centripetal force are examined. These physical characterisations are quantified for the hazardous situations identified by the cyclists. The magnitude values revealed in the physical analysis provide a positive match with the hazard identified by the cyclist and accident statistics for such hazards.

1 Introduction

PROS (*Priorities for Road Safety Research in Europe*) [1] calls for... "Naturalistic bicycle rider studies to enable assessment of countermeasures targeting cyclists; naturalistic studies to fill the gap in knowledge about pre crash conditions for cyclists." In the present investigation a naturalistic cycle study is completed by ten cyclists where risk is identified by the cyclist. The risks identified by the cyclists are described in section 2.

The format of documenting the cyclist's experience during their journey is based on a questionnaire/survey post journey and on a live recording from a helmet mounted camera. Various risks are identified and the related physical parameters are analysed (e.g. collision of cyclist plus bicycle with other path or road users).

The physical parameters of delta-*v* and centripetal force are examined in section 3. These physical characterisations are quantified for the hazardous situations identified by the cyclists. The magnitude values revealed in the physical analysis provide a positive match with the hazard identified by the cyclist and accident statistics for such hazards.

2 Naturalistic Cyclist Study

A cycling safety audit carried out by *Limerick Cycling* [2] concluded that the majority of the Limerick City Centre streets are classified as being "busy urban roads, without cycle facilities; also applies to complex signalised junctions and small roundabouts and are suitable for "experienced cyclists only". In suburbs of Limerick, such as Castletroy and Annacotty, there are some cycling provisions such as on-road cycle lanes and off-road cycle tracks. As is the case with many similar pieces of infrastructure, these facilities only provide safer cycling conditions compared with on-road cycling until they are discontinued at junctions. According to the National Cycling Manual [3], the majority of cycling accidents occur at or close to junctions in urban areas.

As part of this study to document the naturalistic experience of cyclists, a number of University of Limerick staff members, for whom cycling is their main commuting mode, were interviewed. In total detailed interviews took place with ten staff members. Each member was asked to comment on their experience during their commutes. Particular emphasis was placed on hazardous conditions as perceived by them. Interviewees were also invited to record their commutes using a helmet-mounted video camera to help describe various aspects of their commute.

All interviewed cyclists noted a number of infrastructural deficiencies or other hazards which led to either uncomfortable or dangerous cycling conditions. In all cases, uncomfortable conditions were described as the close proximity of moving vehicular, cycling or pedestrian traffic.

There are several well documented and advertised hazards for cyclists that exist on Irish roads and paths. Over the last number of years, the Road Safety Authority has published a series of cycle safety videos [e.g. 4,5], some of which have been shown on national television advertisements. The "Cycle Safety" presentation provides clear guidance to cyclists on negotiating left and right hand turns from minor roads to major roads and vice versa. It also offers advice on ideal cyclist behaviour on roundabouts which are often avoided by cyclists for safety reasons. Other examples of hazards documented in various publications include: cycling adjacent to parked cars, cycling adjacent to Heavy Goods Vehicles and cycling over cracked pavements, potholes, ironmongery or gravel.

The commentary that follows relates to instances of lesser documented cases. In each case the hazard is presented and a description of the hazard follows.

Right turning traffic across a continuous two-way cycle track: When right turning drivers are forced to yield to oncoming traffic, their focus is generally on gaps in traffic that would allow them to proceed. A driver may see a cyclist cycling in the opposite direction on a continuous off-road cycle track. However, due to the small proportion of cycle tracks crossing minor roads or development accesses, drivers tend not to look over their right shoulders to check for cyclists that are travelling on the cycle track in the same direction. A hazardous situation therefore is created with cyclists travelling in the same direction on a continuous cycle track and right turning vehicle.

The majority of off-road cycle tracks are designed such that cyclists must yield while crossing minor roads. However in some instances, there are no yield signs for cyclists and there may be contrasting coloured road painting suggesting that it is vehicular traffic that must yield to cyclists crossing minor roads.

One interviewed bicycle commuter stated that it is the lack of consistency that is dangerous and that where inconsistences occur, clear signage must be in place to ensure all road users know who has the right of way.

Seasonal Issues: Seasonal issues play a significant part to the safety for cyclists particularly on off-road facilities. Heavy rainfall and poorly-draining surfaces can lead the formation of puddles. One interviewee noted the vulnerability to puddling of an on-road cycle lane on his commute which dangerously encourages cyclists to use the trafficked lane. Another interviewee who uses an off-road shared surface highlighted the danger associated with these hazards as cyclists find themselves studying the path surface instead of monitoring oncoming path users.

"Narrow sections of the city centre to UL towpath are made even narrower when I have to avoid puddles and encroaching hedges."

A number of interviewees highlighted the hazard associated with summer overgrowth. One interviewed bicycle commuter noted the hazard associated with an overhanging tree on the bend on a well-used cycling trail while another referenced overhanging trees on a cycle track which forces cyclists to dip down to avoid eye injuries from protruding branches. The interviewee noted a feeling of vulnerability, to himself and others, as his eyes were not focussed on the track ahead for "approximately two seconds" while dipping to avoid low-lying branches.

Lack of Guidance on shared facilities: Shared off-road facilities or trails by definition are intended for a range of users including pedestrians, cyclists, dog-walkers, families and disabled people. They are not intended for motorised vehicles. From interviewing bicycle commuters that use such facilities, it is clear that for the majority of the time there are no risks of collision with other users. It is generally understood that pedestrians should have the right of way and this should be reinforced by signage however, on the shared facilities that the interviewees of this study use, no guidance on priority or otherwise is given. When passing other cyclists travelling in the opposite direction, one interviewee said that he stays to the left and expects the oncoming cyclist to stay on his/her left to pass safely. He noted that it has happened that opposing cyclists maintained a right position on the path and expected the interviewee to move to the right. When he did not move to the right, typically, both cyclists have had to brake to avoid a collision. Another interviewee stated that he ensures to make eye contact with the opposing cyclist and considers this to be appropriate given the low cyclist numbers on that path.

The character of many shared-use trails also attracts many dog-walkers. There is also no guidance given to dog-walkers about the use of dog leads. Among the bicycle commuters, it was noted that dogs on and off leads can be hazardous. Dogs off leads can be tame and walk alongside their owners however dogs can often meander erratically on the trail causing dangerous conditions for other users including faster moving bicycle commuters. Equally hazardous, it was noted, are the leads themselves which, when extended by more than a couple of metres, can lead to dangerous conditions when connected to meandering dogs. Dogs, often, by nature, are attracted to passing runners or cyclists, especially when wearing high-visibility clothing as noted by one interviewee, which has led to some dogs barking at or snapping at passers-by. The same interviewee stated that he would like to see signage instructing dog-walkers to keep their dogs in control.

Sharp corners: The National Cycle Manual gives guidance on maximum curve radii for different design speeds as shown in Table 1.

Design Speed (km/h)	Radius (m)
20	≤10
30	≤20
40 (e.g. downhill sections)	≤25

Table 1: Maximum curve radii for given design speeds

The acceleration due to this change in direction is given by v^2/r where v is the velocity and r is the radius of curvature. Therefore, as design speed doubles the radius of curvature should quadruple. This is not the case in the above guidelines.

One interviewee highlighted the danger associated with a tight double curve that he must negotiate on a downhill section while ramping from an on-road cycle lane to an adjacent cycle track. The gradient at this point is approximately 4% and therefore should have a design speed for cyclists of 40km/h. On inspection, the actual radius of curvature of the initial bend is approximately 3m. This assumes that the cyclist is initially in the centre of a 3m wide shared bus and cycle land and that the cyclist meets the kerbline at an angle 45deg. There is also a short sharp vertical transition to negotiate which forces cyclists to reduce speed further. The interviewee highlighted the dangerous scenario of cycling immediately in front of a bus and having to reduce speed significantly to safely join the cycle track. He added that a bus driver may not be expecting the cyclist to slow down given the usually free moving road traffic ahead.

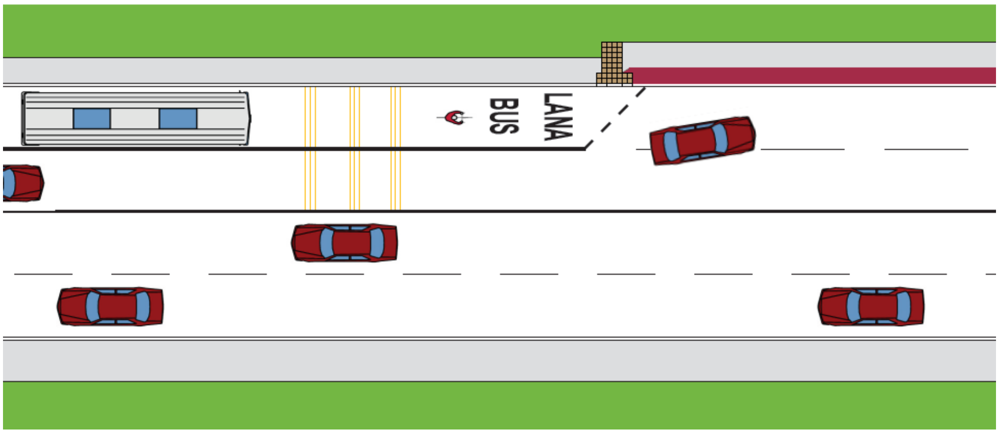

Figure 2 Diagram of hazardous infrastructure

Traffic at Signalled Junctions: All of the interviewed commuters agreed that the provision of feeder lanes and Advance Stop Lines (ASLs) at signalled junctions is welcome. Feeder lanes allow cyclists to pass stationary traffic and gain access to an ASL. The National Cycling Manual states that ASLs should not be installed without the provision of a feeder lane or two feeder lanes when a separate right turning lane is provided. However, many junctions do not include feeder lanes which lead to, as some interviewees have noted, frustration due to a difficultly in accessing the ASLs. It has been noted that cyclists generally feel safer due to the prominent position they hold within ASLs. This also allows cyclists to move ahead of traffic however a number of interviewed cyclists indicated that the feeling of safety is removed as traffic which generally can accelerate much faster than cyclists and that they would prefer to further ahead of traffic. This has led to some interviewees admitting that they often illegally, but carefully, move away from junctions if the pedestrian phase for all crossings is activated. A suggestion that cyclists should be allowed to proceed with caution during the pedestrian phase of traffic signals is raised.

Vertical Transitions: Cycle Lane to Cycle Track and vice versa: Design guidance indicates that ramps from cycle lanes to cycle tracks should be less than 5% in gradient and that the ends of ramps should be rounded with no abrupt edges. A number of interviewed cyclists highlighted that the dropped kerbs for some of the ramp ends have an abrupt height of several centimetres leading to uncomfortable and potentially dangerous cyclising conditions.

When cycling on the far left isn't the safest option: Cyclists are generally advised to maintain a left position in their lane to allow for traffic to pass in the RSA "Sharing the Road with Cyclists" video, drivers are reminded that "cyclists may need to avoid drains or other obstacles" and therefore to allow sufficient room when passing. One interviewee noted a number of instances where cycling on the far left isn't always the safety option:

1. When a cyclist is travelling in traffic, the view of an opposing driver may be blocked by traffic, particularly larger vehicles. If this driver is looking to take a right hand turn, he / she may expect the way to be clear when a gap in traffic appears leading to a dangerous situation for cyclists looking to continue straight.
2. When cycling around a roundabout, a cyclist should stay in the middle of the lane and discourage drivers behind from overtaking. Indeed this advice is described in the RSA video entitled "RSA Cyclist Safety - Cycle Safe" [5].
3. When approaching junctions, drivers looking to pull out from minor roads generally are expecting to see car-sized objects or larger. One interviewed bicycle commuter noted that cyclists hugging the left hand kerb of the major road are less visible than if they maintained a more central lane position and are therefore more vulnerable to collisions.

3 Preliminary Physical Analysis

A preliminary identification and analysis of the physical parameters relevant to the dangers cited by the cyclists follows. The cyclists reported feeling uncomfortable when in close proximity of moving vehicular, cycling or pedestrian traffic or when cycling adjacent to parked cars or adjacent to heavy goods vehicles. Additionally the specific hazards listed in Table 2 are reported. Hazards 1, 3 and 5 similarly relate to possible collision with other road/path users.

The relative risk presented to/by the cyclist with the other collision body is considered (Fig.2). The cyclist plus bicycle and the other colliding body are treated as an isolated system. The collision forces are consider much greater than any external forces acting on the system during the time of the collision. Following this assumption the conservation of momentum gives

$$m_{bc}v_{bc,i} + m_b v_{b,i} = m_{bc}v_{bc,f} + m_b v_{b,f} \,, \qquad (1)$$

where,

m_{bc}= mass of cyclist plus bicycle,

m_b = mass of other colliding body,

$v_{bc,i}$ = velocity of cyclist plus bicycle before collision,

$v_{b,i}$ = velocity of other colliding body before collision,

$v_{bc,f}$ = velocity of cyclist plus bicycle after collision, and

$v_{b,f}$ = velocity of other colliding body after collision.

Table 2 Identified hazards and corresponding physical characteristics

Identified Hazard	Physical Characteristics
1. Right turning traffic across a two way cycle track	Collision risk, visibility
2. Seasonal issues	Increase in kinetic energy (KE) Reduced visibility
3. Shared facilities	Collision risk
4. Sharp corners	Increased centripetal force, stability and control issues, field of view
5. Traffic junctions	Collision risk, stability, acceleration
6. Vertical transitions	Energy loss, stability
7. Cycling on the far left	Visibility and field of view

The momentum law is valid whether the collision is elastic (no loss in mechanical energy by the system) or inelastic (mechanical energy is lost by the system).

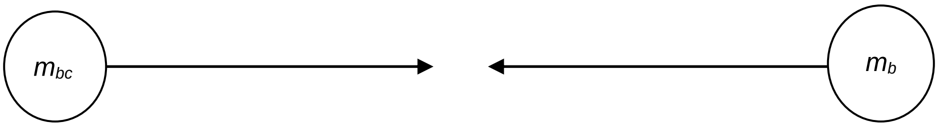

Fig.2 Collision between cyclist + bicycle moving at an initial velocity $v_{bc,i}$ and another body (pedestrian, another cyclist + bicycle, passenger car or HGV) travelling at an initial velocity $v_{b,i}$, which may be zero.

Re-arranging eqtn.(1) in terms of the mass of each colliding body gives

$$m_{bc}(v_{bc,f} - v_{bc,i}) = -m_b(v_{b,f} - v_{b,i}) \quad (2)$$

The term in parenthesis on the lhs represents the change in velocity of the cyclist plus bicycle due to the collision, and the term in the rhs parenthesis represents the change in velocity of the other colliding body during the collision. The change in velocity (delta-*v*) of a body during collision is used extensively as an indicator of collision severity e.g. [6,7]. However, the velocities of the colliding bodies just prior to and just after collision may not be known (the more widespread use of speed data loggers is making this direct velocity data more readily available, e.g. [7]).

Re-arranging eqtn.(2) provides a mass ratio between the bodies that is equal to the magnitude of the delta-*v*s for the bodies.

$$\frac{m_b}{m_{bc}} = -\left(\frac{v_{bc,f} - v_{bc,i}}{v_{b,f} - v_{b,i}}\right) = -\left(\frac{\Delta v_{bc}}{\Delta v_b}\right) \quad (3)$$

As the masses of the colliding bodies are known eqtn.(3) can be used to infer relative risk severity for the colliding bodies. If the bodies have equal masses their delta-*v*s are equal and their relative risk severities are equal.

Eqtn.(3) is applied to determine the mass ratios and hence delta-*v* ratios for cyclist plus bicycle and pedestrian, cyclist plus bicycle, passenger car , and HGV collisions.

$$\frac{m_p}{m_{bc}} = \left| -\frac{\Delta v_{bc}}{\Delta v_p} \right| = \frac{75}{89} = 0.84 \qquad (4)$$

$$\frac{m_{car}}{m_{bc}} = \left| -\frac{\Delta v_{bc}}{\Delta v_{car}} \right| = \frac{1200}{89} = 13.48 \qquad (5)$$

$$\frac{m_{HGV}}{m_{bc}} = \left| -\frac{\Delta v_{bc}}{\Delta v_{HGV}} \right| = \frac{8000}{89} = 89.89 \qquad (6)$$

where,

m_p =the mass of a pedestrian = 75 kg,

m_c =the mass of a passenger car = 1200 kg, and

m_{HGV} =the mass of a heavy goods vehicle (HGV) = 8000 kg, and
mass of bicycle = 14 kg (steel frame bicycle), giving
m_{bc}= mass of cyclist plus bicycle = 89 kg.

For a 10 kg carbon frame bicycle, m_{bc}= mass of cyclist plus bicycle = 85 kg and the delta-*v* ratios are

$$\frac{\Delta v_{bc}}{\Delta v_p} = 0.88, \qquad (7)$$

$$\frac{\Delta v_{bc}}{\Delta v_{car}} = 14.12 \text{, and} \qquad (8)$$

$$\frac{\Delta v_{HGV}}{\Delta v_{bc}} = 94.12\,. \qquad (9)$$

In words, eqtn.(4), (5) and (6) state that the change in velocity resulting from a cyclist plus bicycle and pedestrian, car, and HGV collision respectively are 16% less than, 13.5 times more and 90 times more than a cyclist plus bicycle and cyclist plus bicycle collision. And as delta-*v* has been shown to be a robust indicator of accident severity these indices may serve as first estimates of relative injury risk. These indices [(7), (8) and (9)] are slightly higher for the carbon frame bicycle due to the lower mass. The indices apply regardless of the initial velocity of the second body colliding with the cyclist plus bicycle. For example, if a cyclist impacts with a stationary HGV, the delta-*v* of the cyclist plus bicycle is still over ninety times that of an equivalent (same initial velocities) cyclist plus bicycle/cyclist plus bicycle collision. Sixteen out of the twenty one cyclist fatalities in the Dublin City Council area in the last seven years involved HGVs [8].The figures provide an initial objective quantification of the relative risks indentified/perceived by the cyclist regarding moving and stationary vehicles in the naturalistic study and coincide with statistical data of fatal accidents involving cyclists.

A seasonal issue identified was vegetation growth which encroached on the cycle path which may force the cyclists to dip down to avoid eye injury. Physically when the cyclist dips they

reduce the centre of mass of the cyclist plus bicycle system. The potential energy of the system is reduced due to the lowered centre of mass and if a conservative system is considered (mechanical energy is conserved) the kinetic energy of the system increases.

Hence the cyclist momentarily speeds up compounding the difficulty of the avertible action manoeuvre.

Another seasonal issue is swerving to avoid puddles. A somewhat similar swerving type motion may also be required to navigate a sharp turn due to potentially hazardous infrastructure (Fig.2). To safely initiate a turn on a bicycle requires subtlety as the cyclist must momentarily turn the handlebars to the right in order to facilitate a lean to the left. The lean to the left is required for stability when taking the left turn. When moving in a straight line the reaction vector to the gravitational force on the cyclist plus bicycle points upwards, normal to the ground surface. However when travelling along a curved path the ground's reaction vector points at an angle to the surface as the reaction comprises the frictional force providing the centripetal force, pointing toward the instantaneous centre of the curved path, as well as the gravitational force. In the particular case of the bus lane the centripetal force acting on the cyclist plus bicycle system during a turn of radius *r* is

$$F_c = \frac{m_{bc} {v_{bc}}^2}{r} . \qquad (10)$$

If this is attempted over a short radius e.g. r = 3m when travelling at 40 km/hr, the centripetal force is

$$F_c = \frac{89 \times (11.11)^2}{3} = 3661.8 \quad \text{N} .$$

This compares with the recommended radius of turn of 25 m when travelling at a speed of 40 km/hr (11.11 m/s).

$$F_c = \frac{89 \times (11.11)^2}{25} = 439.4 \quad \text{N}$$

The centripetal force is over eight times greater in the first case.

Stability is also a consideration when moving from a stationary position (a risk identified by the cyclists at the traffic junctions which is partially addressed through the use of Advance Stop Lines - ASLs). When the cyclist is stationary the cyclist plus bicycle system is unstable i.e. with a slight movement of the cyclist left or right the cyclist plus bicycle system will begin to topple over. A certain speed is required for the system to become stable, where slight left or right torques do not topple the cyclist plus bicycle system. The attention required by the cyclist during these manoeuvres may detract from normal observational awareness. The cyclists appear to feel safer when they and the accompanying traffic are travelling at constant speed.

4 Discussion, Conclusion and Future Work

A naturalistic cycle study was completed by ten cyclists. The cyclists reported hazards such as cycling in close proximity to moving vehicular, cycling or pedestrian traffic and cycling adjacent to parked cars or heavy goods vehicles. Further issues reported included right turning traffic across a two way cycle track, seasonal issues, shared facilities, sharp corners, traffic junctions, vertical transitions and cycling on the far left.

A preliminary physical characterisation and relative quantification of the reported hazards was then undertaken. A delta-*v* analysis highlighted the relative risk of collision with different vehicle types with a cyclist plus bicycle and HGV collision resulting in a ninety fold increase in change in velocity than a cyclist plus bicycle/cyclist plus bicycle collision.

A comparison of the centrifugal forces for different radii of turn for a given speed provided quantitative support relating to the hazard of sharp turns. The issue of stability was also highlighted in the content of moving from a stationary position and when turning.

Combining the naturalistic study with the physical analysis helps to focus attention on specific hazardous situations. The combined studies enable the beginning of disassembling and quantifying the contributing components to risk and severity of potential accidents. Awareness of risk and, demonstration and training based on physical parameters, may form the basis for safe behavioural change strategies. Future studies will examine naturalistic studies that follow physically informed studies i.e. where naturalistic studies are repeated following physical characterisation and feedback to previous naturalistic studies. Implementing more refined physical models and analysis, and recording a more detailed set of measurements (including physiological and video data) during naturalistic studies, form the basis of future work.

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