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The Potential Safety Benefit of Propulsion in Obstacle Avoidance Manoeuvres with Oncoming Traffic

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The obstacle avoidance manoeuvre with oncoming traffic scenario is analysed. The possibility of using propulsion, specifically from electric motors, to reduce the risk of collision with oncoming traffic is investigated. Analysis is done using a point mass and a two track vehicle model in an optimal control framework. It is found that propulsion can be of help in reducing the collision risk in such scenarios for a certain set of manoeuvre parameters.

Topics/Autonomous driving and collision avoidance, Active safety and driver assistance systems

1. INTRODUCTION

NHTSA estimates that over 15000 overtaking related crashes with oncoming vehicles are reported in the US and has an economic cost of close to 1 billion USD [1]. Studies of similar scenarios have been done previously in [2,3,4,5] wherein overtaking and double lane change manoeuvres in the context of obstacle avoidance are investigated, but in the absence of oncoming vehicles. In [6,7], oncoming vehicles are considered, but insofar as to abort the manoeuvre when a potential collision is detected and they do so by controlling the lateral or longitudinal dynamics of the vehicle individually. The possibility of accelerating to complete the manoeuvre faster and thereby reducing the collision risk is not considered, which is addressed in this work.

In this context, the safety benefit of using electrified drivetrains over traditional internal combustion (IC) engines for propulsion is investigated. Traditional IC engines, especially modern downsized turbocharged ones [8], have the disadvantage of poor transient response [9] which is not shared by electrified drivetrains. The availability of an electric traction motor in combination with the brakes allows independent control of wheel torques which can enhance the vehicle transient response [10] and the potential benefit due to this is also investigated.

Fig. 1 shows an illustration of the obstacle avoidance manoeuvre with oncoming traffic scenario that is considered in this work.

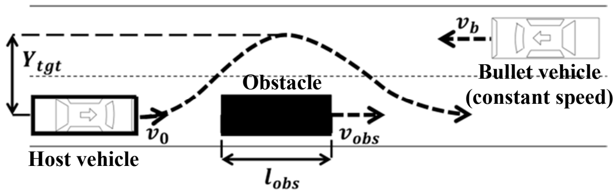


Fig. 1: Obstacle avoidance with oncoming vehicle

The objective in this scenario is to perform a double lane change manoeuvre, in order to avoid or overtake an obstacle, while minimizing the risk of collision with the oncoming vehicle.

2. APPROACH

The benefit of propulsion in this scenario is investigated using two different vehicle models in an optimal control framework. First, the manoeuvre is investigated for a wide range of manoeuvre parameters using a 2-DOF point mass model. This enables a detailed study of the dynamics of the manoeuvre and also the effect of propulsion on the collision risk. Here, the longitudinal force and the course angle of the point mass are optimised. The point mass has no yaw moment of inertia and hence has no yaw dynamics. The point mass dynamics are given as follows:

$$F_x = m\,\dot{v}_x \tag{1}$$

$$F_y = m\,v_x\,\dot{\psi} \tag{2}$$

$$F_x^2 + F_y^2 \leq (\mu\,m\,g)^2 \tag{3}$$

where, F_x and F_y are the longitudinal and lateral forces on the point mass respectively, v_x the velocity and ψ the course angle.

Manoeuvres that show a significant reduction in collision risk using propulsion are identified and analysed in detail using a 3-DOF two track model with load transfer. The longitudinal and lateral tyre forces of all four wheels along with the steering wheel angle are optimised in this problem. The steering wheel angle amplitude is limited to 500 deg and rate to 900 deg/s which are typical values for expert drivers in emergency situations as identified in [11].

A schematic of the two track model with the forces and the states under consideration are shown in Fig. 2.

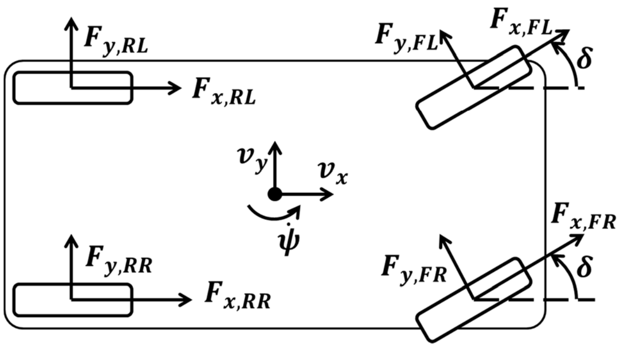


Fig. 2: Two track vehicle model with states, forces and actuator inputs.

The constraints on the longitudinal wheel forces are as follows:

$$-\mu F_{z,ij} \le F_{x,ij} \le \mu F_{z,ij}, \quad \text{with propulsion}$$
$$-\mu F_{z,ij} \le F_{x,ij} \le 0, \quad \text{no propulsion} \tag{4}$$

The slip equations for the two track model are given by:

$$v_{yw,ij} = -\left(v_x + \dot{\psi}\, l_{y,j}\right) \sin\delta_{ij} + \left(v_y + \dot{\psi}\, l_{x,i}\right) \cos\delta_{ij} \tag{5}$$

$$v_{xw,ij} = \left(v_x + \dot{\psi}\, l_{y,j}\right) \cos\delta_{ij} + \left(v_y + \dot{\psi}\, l_{x,i}\right) \sin\delta_{ij} \tag{6}$$

$$\alpha_{ij} = -\operatorname{atan}\frac{v_{yw,ij}}{v_{xw,ij}} \tag{7}$$

where, $l_{y,j}$ and $l_{x,i}$ represent the distance along the Y and the X axis respectively to the wheel ij from the vehicle centre of gravity.

$$F_{x,ij}^2 + F_{y,ij,max}^2 = \left(\mu\, F_{z,ij}\right)^2 \tag{8}$$

$$F_{y,ij} = F_{y,ij,max} \tanh\frac{c_i\, \alpha_{ij}}{\mu} \tag{9}$$

$$\Delta F_{z,ij} = (-1)^i\, \sigma_x\, a_x + (-1)^j \sigma_{y,i}\, a_y \tag{10}$$

$$\Sigma\, F_{x,ij} = m\left(\dot{v_x} - v_y\, \dot{\psi}\right) \tag{11}$$

$$\Sigma\, F_{y,ij} = m\left(\dot{v_y} + v_x\, \dot{\psi}\right) \tag{12}$$

$$\Sigma\,(F_{x,ij}\, l_{y,j} + F_{y,ij}\, l_{x,i}) = I\, \ddot{\psi} \tag{13}$$

A possible way to estimate the risk of collision with the bullet vehicle is to consider the distance between the host and the bullet vehicle at the end of the manoeuvre (post encroachment distance [12]) – henceforth termed the safety potential. A variation of this performance metric is considered for minimization in the optimal control problem and can be expressed as:

$$J = \int_0^{t_f} \left((v_x \cos\psi - v_y \sin\psi) + v_b\right) dt \tag{14}$$

where, t_f is the time instant when the manoeuvre is complete and is given by the conditions:

$$Y = 0 \tag{15}$$

$$\delta = 0 \tag{16}$$

$$|\psi| \le 2\ deg \tag{17}$$

$$\left|v_y/v_x\right| \le 2\ deg \tag{18}$$

This objective function measures the sum of the distance travelled by the host and bullet vehicle and is independent of their initial positions thereby allowing fair comparison of different scenarios irrespective of their initial conditions. Improvement in the safety potential due to the addition of propulsion is henceforth termed the safety benefit in this text.

The vehicle parameters used for the optimisation is listed in Table 1. Note that the parameters have been normalised with the mass of the vehicle in order to aid in the optimisation performance.

Table 1: Vehicle parameters used for the two track model in the optimisation

Parameter	Value
m	1 kg
I	1.74 $\mathrm{kg.m^2}$
$l_{x,i}$	[1, -1.5] m
$l_{y,j}$	[-0.75, 0.75] m
h	0.5 m
c_i	[19.12, 22.98] 1/rad
σ_x	0.1 $\mathrm{N/(m/s^2)}$
$\sigma_{y,i}$	[0.17, 0.16] $\mathrm{N/(m/s^2)}$

3. BENEFIT OF PROPULSION CONSIDERING LONGITUDINAL AND LATERAL DYNAMICS ALONE

A large number of optimisations were done for different manoeuvre parameters using the point mass model. The parameters and the variations considered are tabulated in Table 2.

Table 2: Parameters variations for point mass analysis

Parameter	Variation
Obstacle velocity (vObs)	0 - 60 km/h
Host initial velocity (v0)	(vObs+20) - 120 km/h
Bullet vehicle velocity (vb)	0 - 140 km/h
Obstacle length (lObs)	[0, 3, 15, 25] m
Road surface friction (mu)	[0.5, 1]
Lateral displacement (Ytgt)	[1.5, 3] m

The obstacle lengths chosen for investigation correspond to realistic scenarios as follows: zero length to a pedestrian or wildlife, 3 m to an average car, 15 m to an average tractor semitrailer combination and 25 m to a Scandinavian tractor semitrailer trailer combination. The lateral displacements chosen correspond, roughly, to a half and full average lane widths in Europe. When the obstacle length is non zero, the host vehicle is allowed a +/- 0.5 m lateral position margin within which it is allowed to travel while passing the obstacle.

In total, 4544 optimisations were done using the point mass model. Based on a preliminary analysis of the manoeuvre, certain metrics that characterize the manoeuvre were chosen which were expected to have an impact on the safety benefit. A simple linear regression analysis was done to determine most significant metrics among these and the results from this analysis is summarized in Fig. 3.

The metrics vb/(v0-vObs) (velocity ratio) and lObs (obstacle length) are chosen for further investigation. The metric v0-vObs is not considered for further investigation, since it is contained in the first metric which has a higher correlation.

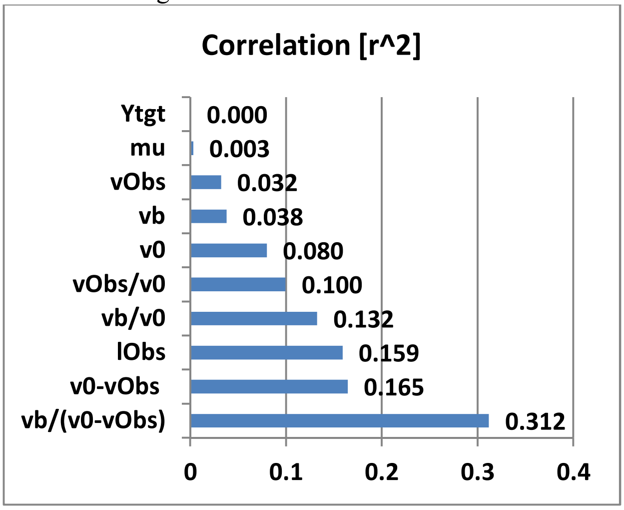


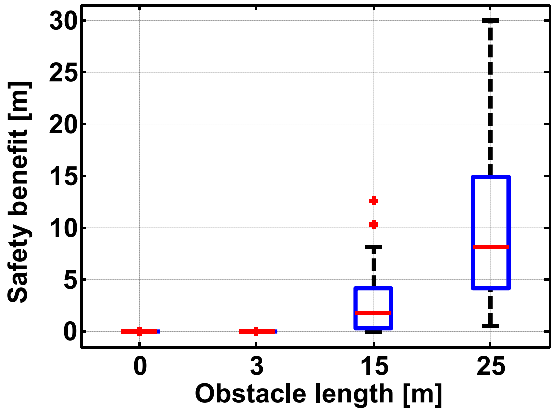
Fig 3: Manoeuvre characterizing metrics sorted in ascending order of impact

The influence of the obstacle length on the safety benefit is easily explained: the longer the obstacle, the larger the time spent in the wrong lane and hence the capability to accelerate helps reduce the same. The impact of velocity ratio is less obvious. The denominator, like the obstacle length, influences the time spent by the host vehicle in the wrong lane. The numerator on the other hand is a quantification of the decreasing time available for the manoeuvre, i.e., as the bullet vehicle travels faster, reducing the manoeuvre duration takes precedence over reducing the distance covered by the host vehicle.

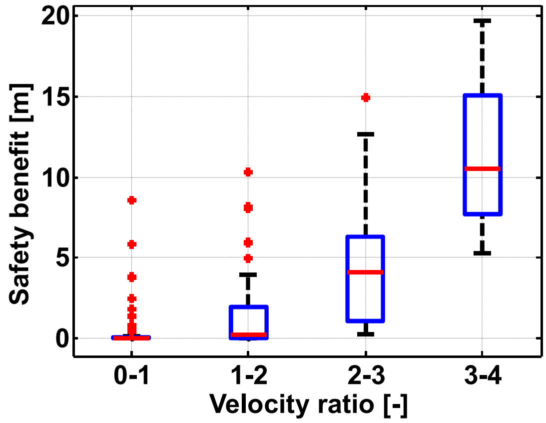
Fig. 4 shows box plots of the safety benefit for two sets of cases. In these figures, the red lines within the boxes represent the median, the limits of the blue boxes the 25th and 75th percentile marks, the black whiskers the 99.3 percentile marks and the red '+' markers the outliers.

Fig. 4a shows the relationship between the obstacle length and the safety benefit. Only results from cases with a velocity ratio of between 1.5 and 2 are shown in this figure to prevent confounding. It can be seen that the obstacle length has a significant and a non-linear influence on the safety benefit. Low safety benefit is seen with small obstacle lengths mainly due to the small time scales involved in overtaking a short obstacle, which are too small for propulsion to make a significant impact. Note also that the velocity ratio in this case is fairly low and a significant safety benefit is seen even for short obstacles with higher velocity ratios.

Fig. 4b shows the relationship between the velocity ratio and the safety benefit. Once again, to prevent confounding, only cases with an obstacle length of 15 m are shown in this figure. It can be seen that the velocity ratio has a clear and significant influence on the safety benefit. The increased number of outliers at lower velocity ratios is due to the fact that a larger numbers of manoeuvres with larger velocity ranges are possible with low velocity ratios than with high velocity ratios.



(a)



(b)

Fig. 4: Box plots of the safety benefit versus (a) obstacle length for a velocity ratio between 1.5 and 2 and (b) versus velocity ratio for an obstacle length of 15 m.

Fig. 5 shows the velocity profiles of two cases: one where propulsion increases the safety potential and another, where it doesn't. In the case with 60 km/h host vehicle initial speed, due to the high velocity ratio, the reduction of manoeuvre duration is prioritized over manoeuvre distance. As a result, propulsion is used to speed up the vehicle. In the case with 120 km/h host vehicle initial speed however, the velocity ratio is relatively low and hence there is no need to accelerate and consequently no use for propulsion.

Summary results of the optimisation show that a safety benefit potential of up to 150 m can be obtained. However, the cases with such high safety benefit correspond to those that involve high speeds of host, obstacle and bullet vehicle but a small relative speed between the host and the obstacle. While these cases show dramatically higher safety benefit, an alternative method to improve safety becomes feasible: brake, slow down and get back behind the obstacle. The higher the speed of the obstacle and lower the relative speed between the host and obstacle, the more feasible this becomes. Hence, this dramatically increased safety benefit does not reflect the "true" safety benefit. Regardless, the above information can be a useful input to the decision making algorithm of the controller which determines what kind of intervention is to be made. Since, from the regression analysis, the influence of the obstacle velocity alone is not seen as significant, and since, having a non-zero obstacle velocity makes it more difficult to make concrete statements about the true safety benefit, for further analysis, only stationary obstacles are considered.

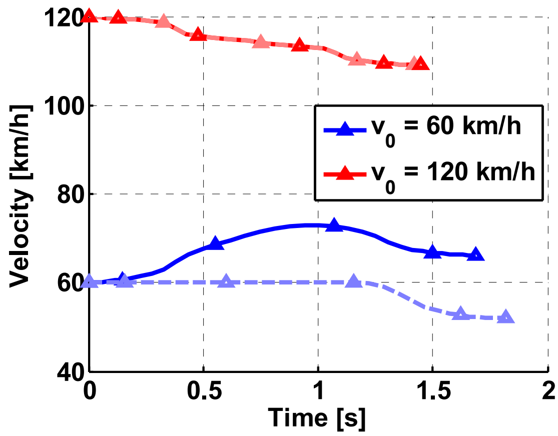


Fig. 5: Point mass optimisation results for a 15 m long stationary obstacle, bullet vehicle speed of 140 km/h and initial host vehicle speed of 60 km/h and 120 km/h. Friction level of 1 and a lateral displacement of 1.5 m. Safety benefit of 2.9 m and 0 m seen for host vehicle initial speeds of 60 and 120 km/h respectively. Lighter plots represent case without propulsion.

Even with only stationary obstacles, it is possible to achieve a safety benefit of nearly 105 m. This benefit, however, corresponds to a host vehicle velocity of 20 km/h, in which case, it is entirely possible to brake to a halt behind the obstacle. This specific scenario, therefore, is only of significance when the driver – possibly unaware of the oncoming vehicle – has already initiated the overtaking manoeuvre. In such a case, the entire safety benefit cannot be achieved since the manoeuvre is already underway before an intervention is started. Furthermore, due to the long duration involved in overtaking an obstacle with a 20 km/h relative speed, the assumption that an IC engine is not quick enough to respond to be used in such scenarios is no longer realistic.

A realistic case from which concrete safety benefit predictions can be made then are those that involve stationary obstacles and host vehicle speeds of at least 40 km/h. With host vehicle initial speeds higher than 40 km/h, the distance required for a successful avoidance by braking alone becomes larger than that required by steering [13]. In such cases, a safety benefit of up to 30 m can be achieved.

4. BENEFIT OF PROPULSION CONSIDERING COMBINED LONGITUDINAL, LATERAL AND YAW DYNAMICS

From the point mass analysis, since the friction, lateral displacement and obstacle length were not seen to be significantly influential, constant friction and lateral displacement of 1 and 1.5 m respectively and only stationary obstacles are considered for the two track analysis. A smaller range of parameter variations, expected to show large safety benefit, were considered. The same is tabulated in Table 3.

Table 3: Parameter variations for two track analysis

Parameter	Variation
Host initial velocity (v0)	[40, 60, 100] km/h
Bullet vehicle velocity (vb)	[60, 100, 140] km/h
Obstacle length (lObs)	[0, 3, 15, 25] m

Two additional variations were also investigated: with and without torque vectoring. Torque vectoring in this context is simply the ability to supply unequal torques to the wheels on an axle. This is easily achieved using a brake system equipped with ESC functionality. The availability of a propulsion system that can respond quickly enhances the effectiveness of the same since it allows for larger torque vectoring magnitudes. The purpose of investigating a case without torque vectoring is twofold. Firstly, it allows fair comparison of the two track model performance to that of the point mass since the point has no yaw dynamics. Secondly, on comparison with the case with torque vectoring, it gives an estimate of the relative benefit of torque vectoring in addition to propulsion.

Fig. 6 shows the vehicle states for a vehicle lacking torque vectoring capability for cases with and without propulsion. Due to the relatively high bullet to host vehicle velocity ratio (140/60), as expected, the vehicles try to maintain a relatively high speed throughout the manoeuvre. When propulsion is available, the vehicle accelerates to maintain a higher speed. It can be seen from the plots that the vehicle with propulsion completes the manoeuvre in a shorter duration at the cost of a larger travelled distance. Despite this, the vehicle with propulsion achieves a safety benefit of 2.8 m in this case.

Fig. 6b shows the axle longitudinal force commanded by the optimisation. It can be seen easily comparing the two cases that propulsion is used far more than braking, which coincides with the observation regarding the importance of speed control when the bullet vehicle is travelling fast.

Fig. 6c shows the optimal steering wheel angle for the two cases. It can be seen that the steering wheel angle hits the rate limit for most of the manoeuvre duration whereas the steering amplitude limit is never hit. The fact that the steering rate limit is hit indicates that there is some room for enhancing the lateral and yaw dynamics even more.

Fig. 7 shows the vehicle states for a vehicle with torque vectoring capability for cases with and without propulsion. Compared to the case without torque vectoring, the velocity profiles are more exaggerated. In the case of no propulsion, the use of brake based torque vectoring to enhance manoeuvrability comes at the cost of an even further reduction in vehicle speed. For the case with propulsion on the other hand, torque vectoring improves the manoeuvrability of the vehicle allowing for even higher vehicle speeds. The reduction in manoeuvre duration using propulsion in this case is even larger allowing for a higher safety benefit of approximately 7.3 m.

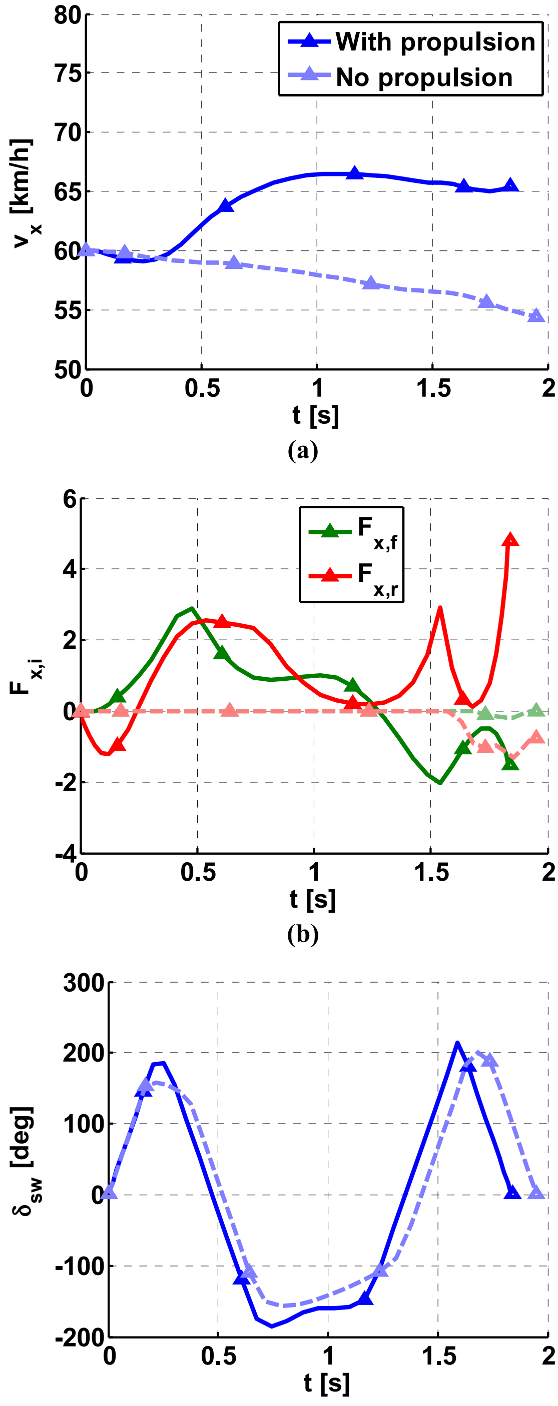


Fig. 6: Two track optimisation results without torque vectoring for with and without propulsion showing host vehicle: (a) velocity, (b) longitudinal axle forces and (c) steering wheel angle. Obstacle has a length of 15 m and is stationary. Bullet vehicle speed of 140 km/h. Safety benefit of 2.8 m seen with propulsion. Lighter plots represent case without propulsion.

Fig. 7b shows the longitudinal tyre forces commanded by the optimisation. Comparing to the case without torque vectoring, it can be seen immediately that a lot more of the tyre longitudinal capacity is utilized. When propulsion isn't available, predominantly, light braking is done, and only on the inner wheels in order to achieve a compromise between improving manoeuvrability and speed control. A sharp increase in the utilization of the tyre longitudinal capacity is seen when propulsion is made available. This is because, there is now virtually no compromise between speed control and manoeuvrability enhancement. Braking is done on the inner wheels and even more propulsion is done on the outer wheels resulting in significant improvement in manoeuvrability while at the same time maintaining a desirable velocity profile. The effectiveness of such an electric propulsion and brake based torque vectoring system may be lower in reality due to motor peak torque and power limitations.

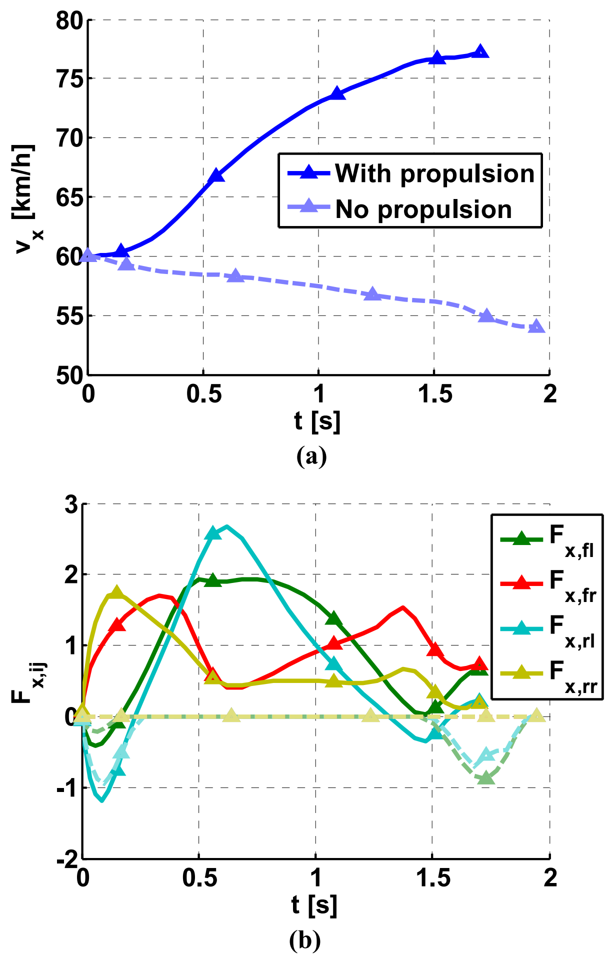


Fig. 7: Two track optimisation results with torque vectoring for with and without propulsion showing host vehicle: (a) velocity and (b) longitudinal tyre forces. Obstacle has a length of 15 m and is stationary. Bullet vehicle speed of 140 km/h. Safety benefit of 7.3 m seen with propulsion. Lighter plots represent case without propulsion.

Summary results of the optimisation using the two track model show similar trends as in the case of the point mass model. Ratio of the bullet vehicle to host vehicle speeds and the obstacle lengths are once again seen to be the most important metrics that determine the potential safety benefit of propulsion in a manoeuvre.

As predicted, significantly higher safety benefit is seen in the case of the two track model. While a maximum safety benefit of 30 m was seen using the point mass model, using the two track model maximum safety benefits of 45 and 42 m were seen with and without torque vectoring capability respectively.

This difference is mainly attributed to the fact that the two track model also has yaw dynamics which is coupled to the longitudinal dynamics. Additionally, the two track model has significantly worse manoeuvrability than the point mass model. Consequently, the availability of propulsion helps not only with the speed but also in improving manoeuvrability. Torque vectoring capability specifically targets the manoeuvrability deficiency and hence improves the safety potential even further by anywhere between 0.5 to 12 m. This is a relatively small improvement when compared to that achieved by propulsion alone. This indicates that, in the presence of optimal steering, control of longitudinal dynamics (or speed control) is more critical than the yaw dynamics.

The results of optimisation show that the presence of propulsion helps reduce the encroachment distance in some cases not only by allowing acceleration but also by allowing larger torque vectoring magnitudes and by mitigating the deceleration side-effect of using only the brakes.

5. CONCLUSION

In this paper, an in-depth analysis of the dynamics of the obstacle avoidance with oncoming vehicle manoeuvre is presented. The possibility and potential of using propulsion to reduce the encroachment distance in this scenario is investigated and presented. For short obstacles of length 3 m and less, relatively large velocity ratios of over 1.5 are required to achieve safety benefit of over 2 m and up to a maximum of 8 m. With obstacles of length 15 m or higher, safety benefit of over 1 m can be achieved even with velocity ratios of less than 1. Safety benefit of between 5 to 15 m can be achieved when the velocity ratios are between 1.5 and 2 and up to 45 m when the velocity ratios are even higher. It was found that even with optimal steering control, on average, a safety benefit of approximately 3 m was achieved using torque vectoring capability. This safety benefit is expected to be even more pronounced when a sub-optimal steering profile is used.

6. FUTURE WORK

In future investigations, the impact of various actuator limitations such as motor torque and power, steering amplitude, rate, etc., on the safety benefit will be investigated. Specifically, the benefit offered by torque vectoring in the presence of suboptimal steering will be investigated.

Validation of the optimisation results will be done in real world experiments and the interaction between the driver and such a system that intervenes in an emergency will be investigated.

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