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'CIRCLING THE SQUARE', OR THE GENERALISATION OF A RAPID PREDICTOR FOR BLAST WAVE SHIELDING

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ABSTRACT

An accurate, fast-running engineering model (FREM) has been developed to estimate the extent and magnitude of a lone obstacle's mitigation of peak specific impulse, serving as a surrogate for CFD. Its full-field predictions offer a 26,000-fold reduction in computation time relative to the CFD software used in its development, with a conservative point-to-point predictive error of 1.25%. However, its accuracy has only been verified for annular sector obstacles – a geometric simplification eliminating second-order flow-field interferences – significantly limiting its practical applicability. This work extends the FREM to more realistic urban geometries, namely rectilinear obstacles, via a 'curvilinear transform' that draws approximate equivalency to the simplified geometry necessary for applying the predictor. A preliminary transform, derived from engineering judgement, was evaluated against *Viper::Blast* CFD simulations of 273 unique rectilinear obstacles. It achieved a mean point-to-point error of 1.4% on average. Evolutionary optimisation of the analogues' dimensions produced no meaningful improvement. Therefore, the proposed approach is found to be an effective, accurate and conservative extension of the FREM to more practical urban blast scenarios. The surrogate's accuracy implies its idealisation of a uniform arrival to be representative of the physics of the true blast-obstacle interaction, demonstrating the assumption of a planar shock to be approximately valid for the range of geometries considered. The analytical framework can therefore be used to ascertain the scaled obstacle dimensions and stand-off distances bounding the validity of the planar shock assumption to inform design guidance.

INTRODUCTION

Explosive incidents are harmful to people and structures, and their severity may be heightened in densely populated urban centres. It is therefore imperative that blast effects be accurately and rapidly modelled to facilitate both proactive protective design and reactive life-saving response. Numerical modelling has been shown to be highly effective in meeting this need [1, 2], particularly with GPU-accelerated computational fluid dynamics (CFD) programmes like *Viper::Blast* [3]. Nevertheless, the runtime of hydrocode simulations remains too protracted for many applications [4, 5], including probabilistic methods for design and risk assessment [6], as well as iterative inverse analysis [7]. Thus, fast-running engineering models (FREMs) – reduced-order, rapid predictive methods – for the prediction of urban blast loading have grown in prevalence, e.g., the Direction-encoded Neural Network [8].

One such FREM is the polynomial assembly predictor developed by the authors in [9]. It is designed to predict the full-field mitigation of peak specific impulse occurring in the wake of a lone obstacle that is caused by the blast-obstacle interaction phenomenon 'shielding'. The FREM operates approximately 26,000-times faster than the CFD software it was informed by (*Viper::Blast*), and it incurs a median predictive error of

1.25%. However, its applicability is presently restricted to cases in which the obstacle's plan geometry exactly matches the curvature of the hemispherically-expanding blast wave that it interacts with. This constraint is a direct consequence of the predictor's reduced-order nature and imposes significant limitations in the practical applicability of the FREM. To address this, the FREM must be adapted for use with more typical structural forms: obstacles with rectilinear plan geometry.

Herein, a 'curvilinear transform' is developed to approximate a rectilinear geometry as a nominally equivalent annular sector, such that analysis of the latter by the polynomial assembly FREM serves as an effective surrogate for the peak specific impulse mitigation computed by a *Viper::Blast* simulation of the true rectilinear obstacle. Initially, a preliminary transform is proposed from engineering judgement and intuition. Its performance is evaluated using 273 individual rectilinear obstacles as a proof-of-concept to demonstrate the efficacy of using a curvilinear analogue. To maximise the accuracy of this representation, evolutionary optimisation is used to identify the annular sector analogues whose full-field shielding differs minimally from that of the true rectilinear geometries. Predictive error is shown to be low, demonstrating the FREM's generalisation. Furthermore, the efficacy of this idealised representation indicates the physics of the blast-obstacle interaction not to be significantly divorced from the that of the true obstacle, which has implications for future work to bound the conditions under which the planar shock assumption is approximately valid.

THE EXISTING FREM

The FREM for predicting the mitigation of peak specific impulse in the wake of a lone obstacle was conceptualised in [9], derived from data-driven insights obtained through a parametric numerical study of obstacle plan dimensions. The investigation used idealised annular sector geometry to isolate the principal blast-obstacle interaction behaviour governing mitigation – shielding – from second-order interferences induced by oblique blast wave impingement, e.g., local diffraction, non-uniform incidence and reflection. This is achieved by the idealisation effectively generalising the planar shock assumption (ordinarily practically restricted to nuclear-scale investigations [10]) to hemispherical or spherical blast events of any stand-off distance and scale.

Figure 1 presents a schematic of this infinitely tall, idealised geometry, with the parametrically varied plan dimension variables annotated: R, rear-face stand-off distance; d, plan depth; θ, projected angle (a measure of lateral extent).

This model for shielding was extended into a predictive FREM by fitting curves to the various behavioural features it describes, such as the spatial position of the unshielded-shielded transition boundary. The coefficients of these feature curves are expressed as continuous functions of an annular sector obstacle's plan dimensions and the radial distance from the charge centre to the points of interest. These feature curves are combined to produce a prediction of the full-field mitigation of peak specific impulse (to distances up to 16.4 $m/kg^{1/3}$ from a hemispherical ground burst charge) that results from a user-defined annular sector obstacle. The FREM was validated using 100 unseen annular sector geometries simulated in *Viper::Blast*. In comparison to *Viper::Blast*, the median value of the FREM's predictive error was 1.25%, with a runtime of less than 0.05 seconds, versus approximately 22 minutes for the CFD.

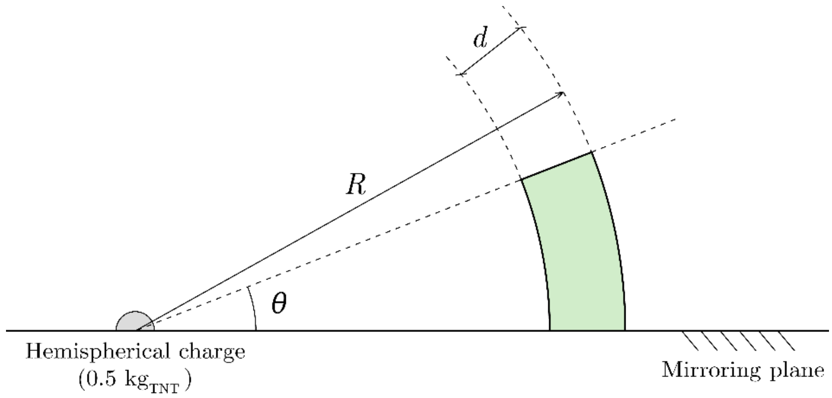

Figure 1: Plan elevation of an infinitely tall annular sector obstacle geometry. The parametric variables are indicated.

The practical applicability of the predictor, however, is currently very limited. At present, it has been designed for and evaluated against annular sector obstacles exclusively. It is therefore necessary to assess the FREM's performance in predicting the mitigative effects of more realistic urban obstacles – particularly those with rectilinear geometries – to determine whether and how it can be adapted for such use cases, thereby extending the FREM's applicability to more practical environments.

THE FEASIBILITY OF A CURVILINEAR ANALOGUE

To evaluate the efficacy of modelling a rectilinear obstacle as an annular sector, the similarity in the magnitude and spatial distribution of the respective geometries' mitigation of peak specific impulse must be assessed. To enable this feasibility study, a baseline curvilinear transform – the 'midpoint transform' – is preliminarily adopted.

The midpoint transform, illustrated in Figure 2, was intuited using engineering judgement as a suitably representative initial approach, preserving the plan dimensions of the rectilinear geometry by using its face midpoints to define the resulting annular sector. The dimensions of the equivalent annular sector produced by the midpoint transform for some rectilinear obstacle are defined according to Equations 1–3.

$$R_{c,m} = \sqrt{{R_r}^2 + \left(\frac{R_r \cdot \tan\theta_r}{2}\right)^2} \tag{1}$$

$$d_{c,m} = R_{c,m} - \sqrt{(R_r - d_r)^2 + \left(\frac{R_r \cdot \tan\theta_r}{2}\right)^2} \tag{2}$$

$$\tan\theta_{c,m} = \frac{R_r \cdot \tan\theta_r}{R_r - d_r} \tag{3}$$

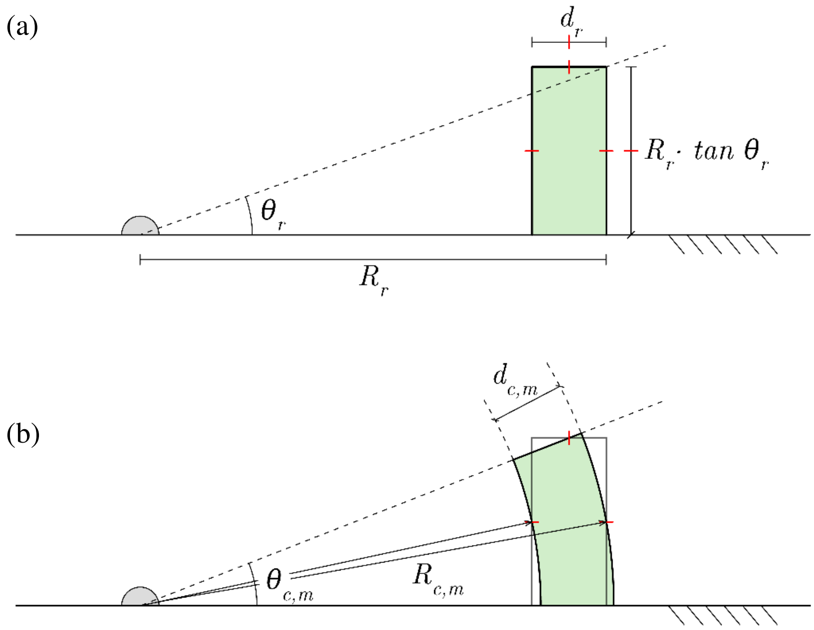

Figure 2: Illustration of applying the midpoint transform.
(a) True rectilinear obstacle. (b) Equivalent annular sector.

The rectilinear geometries used to evaluate the transform were selected to match the original FREM development study [9]. The variable values were therefore: R_r [m] = {4, 5, ... 9, 10}; θ_r [°] = {10, 15, ... 35, 40}; d_r = {0.04, 0.2, 0.5, 1, 2, 3}, with every combination trialled provided the front face stand-off distance was no less than 3 m/kg$^{1/3}$ (to avoid potential near-field complexities [11]), i.e., $R_r - d_r \geq 3$ m/kg$^{1/3}$. Application of the transform produced 273 indicatively equivalent rectilinear-curvilinear wall pairs, each of infinite height. For each obstacle, $i_{p,r}$ – the full-field peak specific impulse mitigation relative to the unobstructed case – was computed using *Viper::Blast* for the rectilinear obstacles and using the FREM for the transformed annular sectors.

Beyond the small error intrinsic to the FREM (a 1.25% average deviation from *Viper::Blast* when predicting the shielding of annular sector obstacles), the difference in peak specific impulse mitigation between rectilinear and curvilinear obstacles represents the error when approximating the true geometry as an annular sector. This error, which is inversely proportional to the efficacy of the transform, is calculated as the absolute difference in peak specific impulse at each point in the shielded regions of either obstacle. Points in the shielded region of one obstacle geometry but not the other had the value of relative peak specific impulse for the latter assumed to be 100% of its free-field value, promoting an effective comparison whilst reflecting the inability of the FREM to estimate the loading at locations it deems to be unshielded.

Figure 3 presents the mean full-field predictive error for each of the 273 obstacle cases as a result of the midpoint transform. Note, the robust metrics of median and median absolute difference (MAD) are adopted to summarise the performance of the transform overall, given the skew in the results [12].

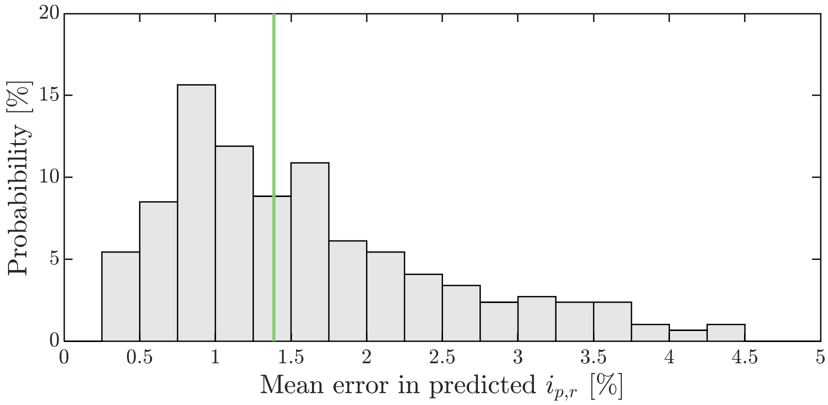

Figure 3: The mean full-field error in estimated shielding resulting from the midpoint transform, for each of the 273 cases analysed. The median value is annotated.

The midpoint transform enabled the FREM to estimate the full-field shielding of the rectilinear obstacles with a median error of 1.4% (MAD: 0.73%). Of the 273 trials, 75% incurred a mean error no greater than 2.1%, and the predicted shielding was conservative in all cases. These findings suggest that approximating a rectilinear geometry as an equivalent annular sector via some curvilinear transform is a viable approach for extending the FREM to more practical scenarios.

To understand the extent to which the curvilinear transform may be improved beyond this preliminary approach, the annular sector analogues are herein optimised to maximise their equivalency to the rectilinear obstacles they represent. The performance of these optimised geometries indicates an upper bound to the accuracy of the FREM in the analysis of rectilinear obstacles.

AN OPTIMISED TRANSFORM

The midpoint transform, being derived solely from engineering judgement, may produce annular sector analogues with sub-optimal plan dimensions. In other words, alternative annular sectors may exist that more accurately represent the rectilinear obstacles for the purpose of their shielding estimation by the FREM. Such improved analogues may reduce predictive error. Therefore, an optimisation routine is employed to identify the dimensions of the annular sectors whose resulting full-field impulse mitigation is minimally different from those of the rectilinear obstacles they represent.

A genetic algorithm (GA) is adopted for the optimisation given its efficacy in other simulation-based studies [13, 14], and its robustness to the non-convex solution spaces [15] that may manifest from the variability inherent to urban blast events [16, 17].

A GA is an evolutionary metaheuristic optimisation method [18] that explores a solution space in search of its global optimum. The algorithm begins with a randomised population of candidate solutions that are each evaluated using a fitness function. The population evolves over successive generations through mechanisms inspired by Darwin's natural selection [18], driving the search towards regions of the solution space containing higher-performing candidates by biasing subsequent trials to have variable values similar to the most successful prior solutions. In this way, the GA iteratively improves upon past evaluations, approximating the optimum through trial and error.

For this application, each candidate solution corresponds to an annular sector whose plan dimensions are the variables to be optimised. The fitness function minimises the predictive error previously defined: the absolute point-to-point difference in relative peak specific impulse at all locations within the shielded regions (retaining the assumption that all unshielded points experience free-field loading for the purposes of this evaluation). The GA is configured following [14], where it was successfully applied to the inverse characterisation of free-field explosive events. The specific features of the continuous GA adopted are fully detailed therein and are not repeated here for brevity. This work's GA is adjusted from the original implementation to use a population of 100 trials per epoch, and to terminate the iteration after population stagnation (specifically, when 15 consecutive epochs occur without more than a 0.01% reduction in the error of the highest-performing individual).

Figure 4 shows the mean point-to-point error in peak specific impulse resulting from the GA-optimised annular sector analogues for each of the 273 rectilinear obstacle cases. For comparison, the results from the midpoint transform are also included.

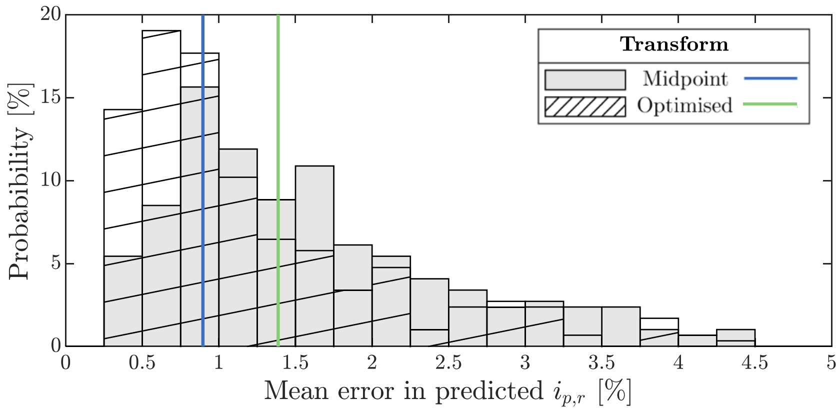

Figure 4: A comparison of the mean full-field error in estimated shielding resulting from both the midpoint transform and the GA-optimised annular sector equivalents for each of the 273 cases analysed. The median values are annotated.

The GA-optimised annular sectors enabled an increase in predictive accuracy compared to the midpoint transform, reducing the median error from 1.4% to 0.9% and the MAD from 0.73% to 0.67%. While this suggests that a curvilinear transform superior to the midpoint approach may be identifiable, any potential gains are likely to be minimal within the range of dimensions considered. Furthermore, the upper bound to accuracy that this represents is likely inflated, given that the optimisation produced a median error lower than the error intrinsic to the FREM (1.25%) which indicates the GA to have compensated for the model's inherent predictive limitations, alongside maximising analogue equivalency. These findings imply that the existing midpoint transform is likely to be near-optimal, a conclusion reinforced by the similarity of the dimensions of the optimised analogues to those of this intuition-based approach (e.g., a mean difference of 1% in R_c).

The accuracy displayed by the surrogate model suggests that the simplifications made to the physics of the blast-obstacle interaction by the FREM's geometric idealisation do not differ significantly from the conditions of the blast's impingement on the true rectilinear obstacle, within the range assessed. This finding offers a basis for exploring the validity of the planar shock assumption and its relationship to scaled obstacle size.

THE VALIDITY OF ASSUMING A PLANAR SHOCK

In the original investigation [9], obstacle geometry was idealised with a plan curvature exactly matching that of the (hemi)spherically expanding blast wave. This idealisation imposes perfectly uniform impingement of the blast wave across the reflecting face, and perfectly normal incidence along the obstacle's sides. Consequently, the obliquity effects inherent to non-ideal geometry are eliminated from the flow-field because the associated blast-obstacle interaction mechanisms cannot physically occur.

The present study adopted this geometric idealisation as part of a surrogate model for estimating the shielding of rectilinear obstacles. Although the surrogate neglects the obliquity effects that necessarily arise from the blast wave's interaction with rectilinear geometry, it achieves high predictive accuracy over the range of problems examined. This indicates that the neglected behaviours contribute negligibly to the shielding of these obstacles; if their influence were significant, substantial discrepancies from the blast-obstacle interaction of the true geometry would be observed.

With the effects of obliquity in the rectilinear blast-obstacle interaction found to be negligible downstream, it follows by induction that the blast wave impingement may be regarded as approximately uniform for the purposes of estimating shielding. For impingement to be uniform, the curvature of the blast and the obstacle must be equal. Since the rectilinear obstacle has no curvature, the local curvature of the blast wave must be effectively zero – that is, the shock can be considered planar.

The assumption of a planar shock is a practical simplification commonly used in blast analysis and protective design, e.g., it is a prerequisite in the prediction of hemispherical ground burst loading via UFC 3-340-02 [19]. However, the literature provides no guidance on the conditions under which this assumption is valid, despite a strictly planar shock being non-physical except in limit cases involving infinitesimal obstacles or infinite stand-off distances. By demonstrating planar shocks to have arisen within the breadth of scenarios tested in this work, we propose that this analytical framework be extended to characterise the bounds of the assumption's validity by varying an obstacle's scaled dimensions and stand-off distance. Where the downstream loading of a rectilinear obstacle and its equivalent annular sector are similar, the idealisation of a uniform impingement – and thus the planar shock assumption – may be regarded as physically reasonable; where the deviation becomes significant, the validity of the assumption necessarily deteriorates.

SUMMARY & OUTLOOK

Recent data-driven insights into the shielding of lone obstacles [9] have produced a fast-running engineering model (FREM) capable of accurately, reliably and conservatively predicting the peak specific impulse mitigation in their wake. The FREM was previously limited to obstacles of annular sector geometry, hence this work sought to extend its functionality to include more practical cases involving rectilinear obstacles. A 'curvilinear transform' was proposed to represent a rectilinear obstacle as a nominally equivalent annular sector, thereby enabling the FREM to rapidly estimate the shielding effects of the original geometry via its analogue.

A simple curvilinear transform was initially developed using intuition and engineering judgement. Its efficacy in enabling the FREM to estimate the shielding of rectilinear obstacles was benchmarked against *Viper::Blast* CFD simulations. Across 273 rectilinear geometries, the surrogate model achieved a conservative median error of 1.4% (MAD: 0.73%) in the prediction of peak specific impulse mitigation, demonstrating the curvilinear representation of rectilinear obstacles to be highly effective. By applying a genetic algorithm to maximise analogue equivalency, the midpoint transform was shown to be approximately optimal which confirms its appropriateness for direct incorporation into the FREM as a means of increasing its utility. Consequently, the FREM can now be employed for the reliable and accurate analysis of the shielding of rectilinear obstacles, allowing its 26,000-fold reduction in computational cost relative to *Viper::Blast* across a broader and more practical range of urban blast scenarios.

Finally, the accuracy of the surrogate model indicates that its enforcement of uniform blast wave impingement (via a geometric idealisation), and the resulting elimination of obliquity effects, cannot be considerably different from the physics of the true interaction. With respect to the shielding downstream, the conditions of a planar shock must approximately occur for the range of rectilinear geometries considered, otherwise the effect of obliquity would be significant, and the predictive error would be high. This finding promotes the extension of the analytical framework to systematically to explore the scaled dimensions and stand-off distances over which the planar shock assumption is physically valid, addressing a notable absence of such guidance within blast protection design literature despite the common use of this assumption.

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