



STAR RADCLIFFE ACADEMY
BALL STRIKE RISK ASSESSMENT



LABOSPORT

BALL STRIKE ASSESSMENT – STAR RADCLIFFE ACADEMY

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INTRODUCTION	Several new proposed sports pitches at Star Radcliffe Academy are in close proximity to school buildings within the development and an adjacent train line. There is a risk that balls may be hit towards buildings in the development and the train line causing potential for accidents. Reasonable worst-case scenarios were identified for the site and a sophisticated trajectory model was used to predict the flight path of balls, based on representative scenarios. Analysis of the trajectories reveals the predicted height of the balls as they pass the proposed site boundaries. This information is used to provide recommendations for the height of any required ball stop mitigation in specific locations.
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Section 1 – Site Overview

Site Overview

Several new proposed sports pitches at Star Radcliffe Academy are in close proximity to school buildings within the development and an adjacent train line, and this report will consider the ball trajectories towards the areas of concern in all directions from the pitches. The illustration below provides an overview of the proposed site.

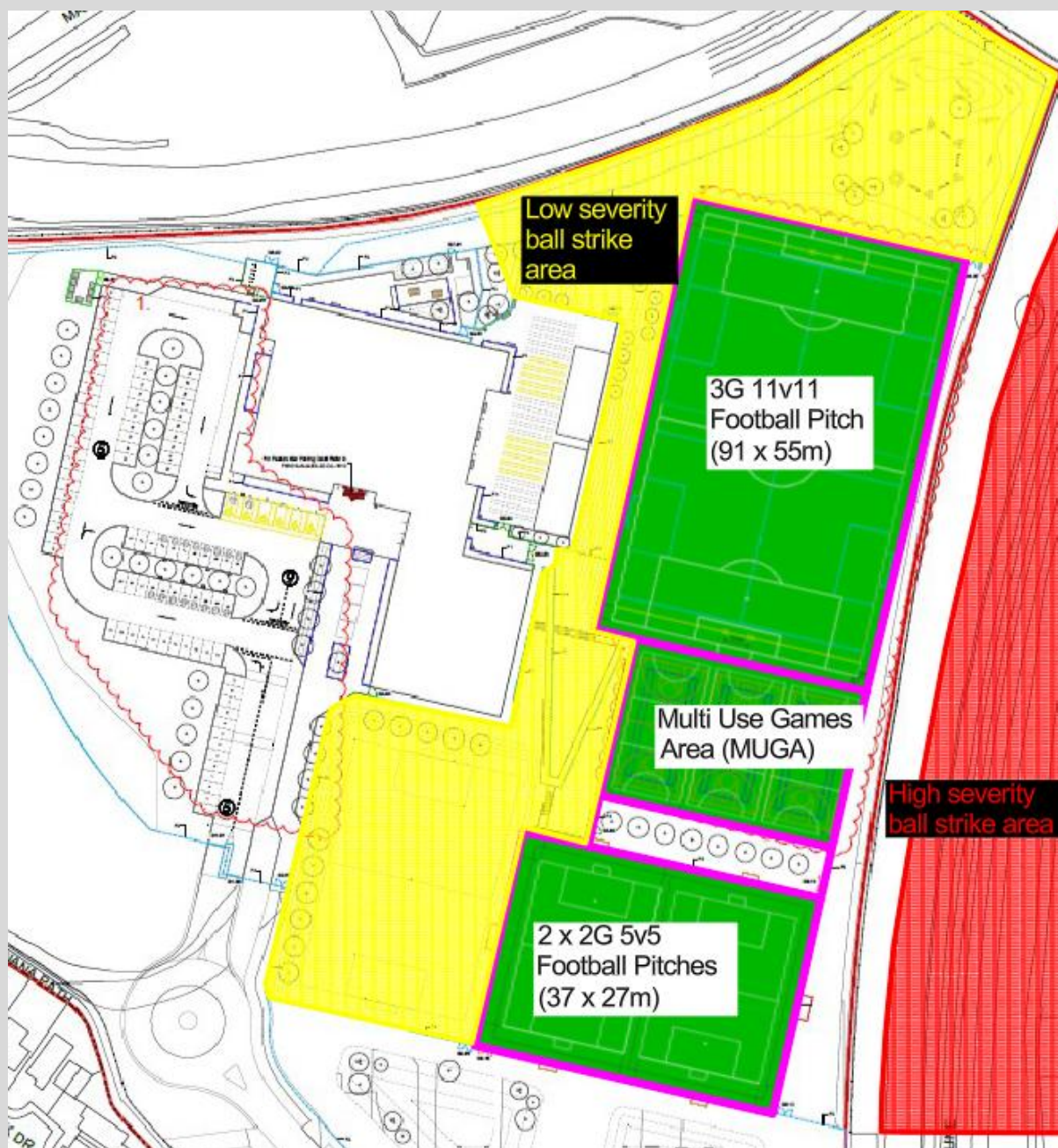


Figure 1. Overview of the site at Star Radcliffe Academy, Bury and areas of different risk severity.

It is acknowledged that the adjacent areas which could be impacted by potential ball strikes have different severity of risk associated with ball strikes. For example, the train line to the east of the proposed pitches carry a high severity of risk associated with ball strikes, since the potential consequences of a stray ball was hit onto the train line could be fatal. Whereas the areas to the north and west of the proposed pitches carry less severity of risk associated with ball strikes, since the potential consequences of a ball going into these areas are likely to only result in nuisance or minor injury. These areas of risk severity have been marked on Figure 1.

Section 2 – Football Trajectory Model

Football Trajectory Model Overview

A sophisticated three-dimensional trajectory model was developed to analyse the trajectory of the football ball. The model was built in the numerical programming software 'Matlab' and incorporated aerodynamic drag and lift forces, and the complexities arising from the ball's spin rate.

The model used published aerodynamic coefficients taken from wind tunnel studies on football balls at different kick velocities (Asai, T., Seo, K., Kobayashi, O. *et al.* Fundamental aerodynamics of the soccer ball. Sports Eng 10, 101–109).

The aerodynamic forces of drag (F_D) and lift (F_L) are proportional to the ball's velocity relative to the air flow, frontal area, air density and the drag coefficient respectively lift coefficient. The forces are defined as:

$$F_D = \frac{1}{2} C_D \rho V^2 A$$

$$F_L = \frac{1}{2} C_L \rho V^2 A$$

with C_D and C_L are the non-dimensional drag and lift coefficients, ρ the air density in kg/m^3 , V the air stream velocity in m/s and A the frontal area of the ball in m^2 .

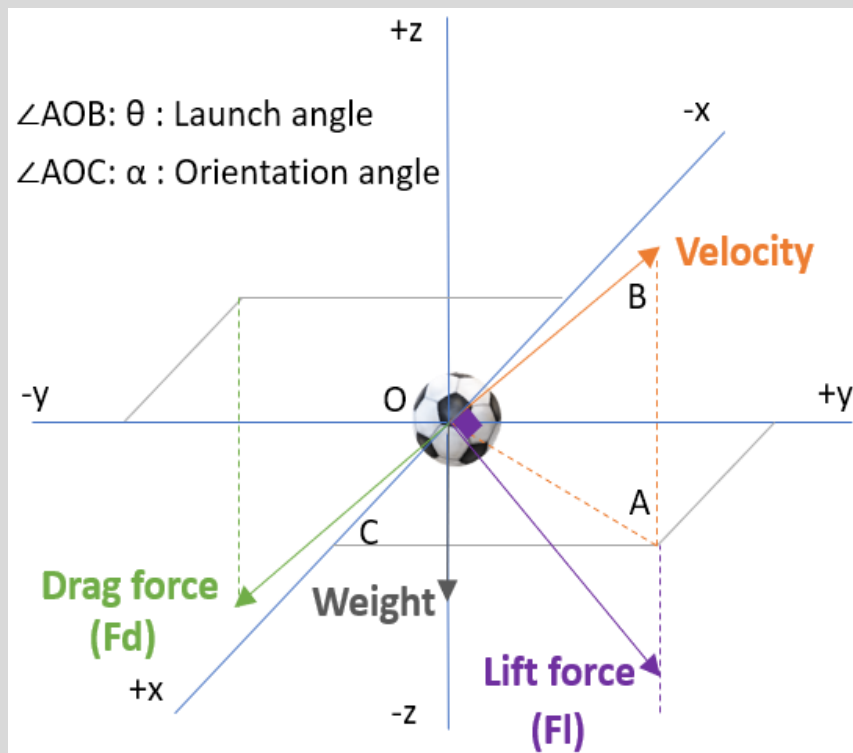


Figure 2. A free body diagram for the football ball trajectory model showing the aerodynamic drag and lift forces.

Due to the complexity of the flight dynamics, the trajectory can only be resolved by using a numerical time step approach whereby the ball conditions are calculated at small timesteps throughout the trajectory. The conditions at time step 1 are used to calculate the conditions at time step 2; the conditions at timestep 2 are used to calculate the conditions at time step 3 and henceforth. A timestep of 0.001 seconds was used to generate high-resolution trajectory data.

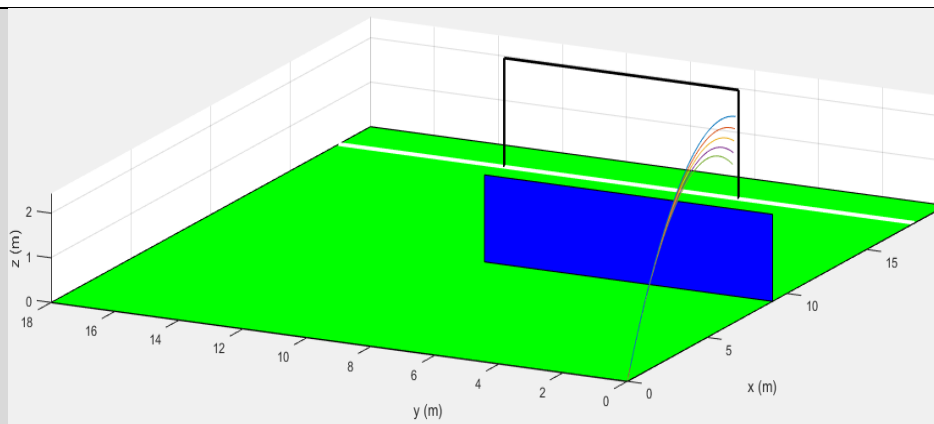


Figure 3. An example of a trajectory simulation from the Matlab model.

Trajectory models are known to exhibit high accuracy; however, it is not possible to model the full complexity of the real world and the model developed for this project is best regarded as an indicative predictive tool.

Football Kick Scenarios

In the game of football, the ball can be kicked in any direction with a wide range of velocities. Nonetheless, some trajectories are far more common than others. This risk assessment uses a proportionate approach by focusing on the common trajectories to determine the most likely scenarios where a ball may surpass the site boundary.

Labosport has significant experience and expertise in football and provides technical support to the world's national governing bodies (e.g. the FA, FFF, KNVB etc) as well as to FIFA. Labosport have drawn on their expertise to define four different in game scenarios where the ball may be kicked on a trajectory that surpasses the site boundary.

For each kick scenario, a reasonable initial speed is determined, and the trajectory is simulated for a range of different launch angles (25 degrees to 35 degrees).

Football Kick Velocities

In the game of football, the ball can be kicked with a wide range of velocities (speeds and angles). Nonetheless, previous researchers have made accurate measurements of ball speeds and spin rates using high speed video and similar technologies. The table below summarises maximal kick velocities from three different studies (taken from; Sterzing, Thorsten, and Ewald M. Hennig. "The influence of soccer shoes on kicking velocity in full-instep kicks." Exercise and Sport Sciences Reviews 36.2 (2008): 91-97).

TABLE 1. Maximum resultant ball velocity achieved with selected kicking techniques.

Study/Authors	Kicking Technique	Maximum Ball Velocity (ms ⁻¹)	SD (ms ⁻¹)	Subject Characterization
Levanon and Dapena (1998) (15)	Full-instep	28.6	2.2	Intercollegiate players, n = 6
	Side-foot	22.5	1.8	
Nunome et al. (2002) (18)	Full-instep	28.0	2.1	High school players, n = 5
	Side-foot	23.4	1.7	
Neilson and Jones (2005) (17)	Full-instep	27.1	2.2	Professional club players, n = 25
	Inner-instep	23.5	2.3	
	Outer-instep	20.9	3.1	

Figure 4. Maximum resultant ball velocity achieved with selected kicking techniques overview

We also have to consider the level of play and age when considering velocities. The table below defines the findings collated from the study into 'Kicking Performance in Young U9 to U20 Soccer Players: Assessment of Velocity and Accuracy Simultaneously'. (Luiz H. P. Vieira et al. (2018) Kicking Performance in Young U9 to U20 Soccer Players: Assessment of Velocity and Accuracy Simultaneously, Research Quarterly for Exercise and Sport, 89:2, 210-220).

Table 1. Mean $\pm$ standard deviation (95% confidence limits) for kicking performance variables according to age ($n = 366$).

	U9	U11	U13	U15	U17	U20
V_{ball} (km/hr ⁻¹)	48.54 $\pm$ 8.31 ^{a, b, c, d} [42.96, 54.12]	57.87 $\pm$ 10.93 ^{e, f, g, h} [55.32, 60.42]	66.70 $\pm$ 13 ^{i, j, k} [63.81, 69.60]	76.92 $\pm$ 15.58 ^l [73.90, 79.93]	81.35 $\pm$ 16.04 ^m [77.74, 84.97]	98.74 $\pm$ 16.35 [90.55, 106.62]
V_{foot} (km/hr ⁻¹)	49.08 $\pm$ 5.16 ^{a, b, c, d} [45.62, 52.55]	53.79 $\pm$ 7.25 ^{e, f, g, h} [52.10, 55.48]	60.54 $\pm$ 8.77 ^{i, j, k} [58.58, 62.49]	65.17 $\pm$ 10.43 ^l [63.15, 67.19]	68.44 $\pm$ 11.83 ^m [65.77, 71.10]	78.24 $\pm$ 9.49 [73.66, 82.81]
V_{ball}/V_{foot} ratio (a.u.)	0.99 $\pm$ 0.13 ^{a, b, c, d} [0.90, 1.07]	1.07 $\pm$ 0.11 ^{e, f, g, h} [1.05, 1.10]	1.1 $\pm$ 0.11 ^{i, j, k} [1.07, 1.12]	1.18 $\pm$ 0.1 ^l [1.16, 1.20]	1.19 $\pm$ 0.1 [1.16, 1.21]	1.26 $\pm$ 0.11 [1.21, 1.31]
LSL (m)	1.09 $\pm$ 0.14 ^{a, b, c, d} [1.00, 1.18]	1.25 $\pm$ 0.14 ^{e, f, g, h} [1.21, 1.28]	1.36 $\pm$ 0.19 ^k [1.32, 1.40]	1.43 $\pm$ 0.23 ^l [1.38, 1.47]	1.44 $\pm$ 0.2 ^m [1.39, 1.48]	1.6 $\pm$ 0.14 [1.54, 1.67]
$D_{support-ball}$ (m)	0.33 $\pm$ 0.07 [0.28, 0.37]	0.3 $\pm$ 0.07 ^{e, f, g} [0.29, 0.32]	0.34 $\pm$ 0.06 [0.33, 0.35]	0.34 $\pm$ 0.09 [0.33, 0.36]	0.34 $\pm$ 0.06 [0.33, 0.36]	0.35 $\pm$ 0.04 [0.32, 0.37]
MRE (m)	1.4 $\pm$ 0.49 [1.07, 1.73]	1.65 $\pm$ 0.6 ^{f, g, h} [1.52, 1.79]	1.59 $\pm$ 0.59 ^{i, j, k} [1.46, 1.72]	1.34 $\pm$ 0.48 [1.24, 1.43]	1.29 $\pm$ 0.5 [1.18, 1.40]	1.14 $\pm$ 0.35 [0.98, 1.31]
BVE (m)	1.26 $\pm$ 0.58 [0.87, 1.65]	1.47 $\pm$ 0.73 ^{f, g, h} [1.31, 1.64]	1.30 $\pm$ 0.57 [1.17, 1.43]	1.18 $\pm$ 0.51 [1.08, 1.27]	1.17 $\pm$ 0.5 [1.06, 1.28]	1.05 $\pm$ 0.32 [0.90, 1.21]
ACUR (m)	1.93 $\pm$ 0.64 [1.50, 2.36]	2.25 $\pm$ 0.84 ^{f, g, h} [2.06, 2.45]	2.09 $\pm$ 0.72 [1.93, 2.25]	1.81 $\pm$ 0.62 [1.69, 1.93]	1.77 $\pm$ 0.5 [1.63, 1.92]	1.57 $\pm$ 0.4 [1.38, 1.76]

Note. a = U9 $\times$ U13; b = U9 $\times$ U15; c = U9 $\times$ U17; d = U9 $\times$ U20; e = U11 $\times$ U13; f = U11 $\times$ U15; g = U11 $\times$ U17; h = U11 $\times$ U20; i = U13 $\times$ U15; j = U13 $\times$ U17; k = U13 $\times$ U20; l = U15 $\times$ U20; m = U17 $\times$ U20. Confidence limits = (lower, upper bound). V_{ball} = ball velocity; V_{foot} = foot velocity; V_{ball}/V_{foot} = ball velocity-to-foot velocity ratio; LSL = last stride length; $D_{support-ball}$ = distance between support foot and ball; MRE = mean radial error; BVE = bivariate variable error; ACUR = accuracy. Significance level of post-hoc comparisons: V_{ball} = ^{a, e} $p < .01$. ^{b, c, d, f, g, h, i, j, k, l, m} $p < .001$. V_{foot} = ⁱ $p < .05$. ^{a, m} $p < .01$. ^{b, c, d, e, f, g, h, j, k, l} $p < .001$. V_{ball}/V_{foot} ratio = ^{a, l} $p < .05$. ^{b, c, d, f, g, h, i, j, k} $p < .001$. LSL = ^{e, l, m} $p < .01$. ^{a, b, b, d, f, g, h, k} $p < .001$. $D_{support-ball}$ = ^{e, f, g} $p < .01$. MRE = ^{i, k} $p < .05$. ^{f, h, j} $p < .01$. ^g $p < .001$. BVE = ^{g, h} $p < .05$. ^f $p < .01$. ACUR = ^{j, k} $p < .05$. ^h $p < .01$. ^{f, g} $p < .001$.

Figure 5. Mean standard deviation for kicking performance variables according to age

The usage of the football pitches at Star Radcliffe Academy will be as follows:

- 3G 11v11 Football Pitch – will be used by school children, as well as community use by adults, therefore, a maximal kick velocity of 28.0 m/s with a spin rate of 40 rad/s has been selected for this ball strike assessment.
- 2 x 2G 5v5 Football Pitches – will be predominantly used by school children, therefore, a maximal kick velocity of 21.36 m/s with a spin rate of 40 rad/s has been selected for this ball strike assessment.

Section 3 – Trajectory Model Simulations

Trajectory simulation

The diagram below shows a global view of the nine different football trajectory scenarios that will be considered for the 3G football pitch.



Figure 6. A global overview of the site with the nine different trajectory scenarios identified for the football pitch.

Trajectory 1 – A football clearance – 7.92 metres to the pitch boundary. (28 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	2.29	3.05	3.88	4.79

Trajectory 2 – A football clearance – 13.43 metres to the pitch boundary. (28 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	3.09	4.30	5.58	6.95

Trajectory 3 – a penalty missing the goal wide– 19.84 metres to the pitch boundary. (28 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	3.09	4.66	6.25	7.82

Trajectory 4 – a penalty missing the goal high– 14.1 metres to the pitch boundary. (28 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	3.14	4.40	5.72	7.13

Trajectory 5 – A football clearance – 14.95 metres to the pitch boundary. (28 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	3.18	4.50	5.88	7.33

Trajectory 6 – A football clearance – 19.52 metres to the pitch boundary. (28 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	3.12	4.68	6.25	7.83

Trajectory 7 – A football clearance – 8.95 metres to the pitch boundary. (28 m/s ball speed)

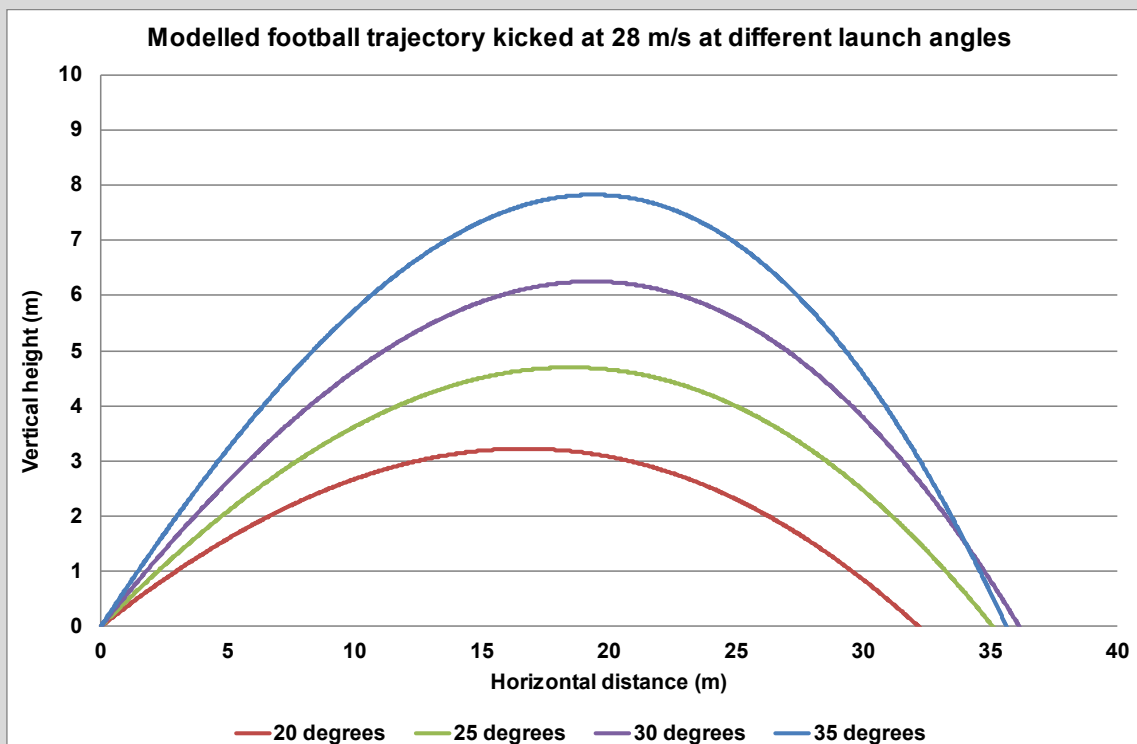
Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	2.49	3.35	4.27	5.27

Trajectory 8 – a penalty missing the goal wide– 23.47 metres to the pitch boundary. (28 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	2.62	4.29	5.90	7.37

Trajectory 9 – a penalty missing the goal high– 14.43 metres to the pitch boundary. (28 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	3.16	4.44	5.79	7.21



The diagram below shows a global view of the twelve different football trajectory scenarios that will be considered for the 2G football pitches.



Figure 6. A global overview of the site with the nine different trajectory scenarios identified for the football pitch.

Trajectory 1 – A football clearance – 10.79 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	1.37	2.23	3.10	3.98

Trajectory 2 – A football clearance – 7.24 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	1.52	2.17	2.85	3.58

Trajectory 3 – a penalty missing the goal wide– 14.85 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	0.40	1.37	2.29	3.09

Trajectory 4 – a penalty missing the goal high– 11.47 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	1.27	2.16	3.05	3.93

Trajectory 5 – a penalty missing the goal high– 11.47 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	1.27	2.16	3.05	3.93

Trajectory 6 – a penalty missing the goal wide– 16.74 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	0	0.62	1.48	2.14

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Trajectory 7 – A football clearance – 8.25 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	1.54	2.26	3.01	3.79

Trajectory 8 – A football clearance – 12.79 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	1.00	1.94	2.86	3.73

Trajectory 9 – a penalty missing the goal wide– 12.79 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	1.00	1.94	2.86	3.73

Trajectory 10 – a penalty missing the goal high– 11.66 metres to the pitch boundary. (21.36 m/s ball speed)

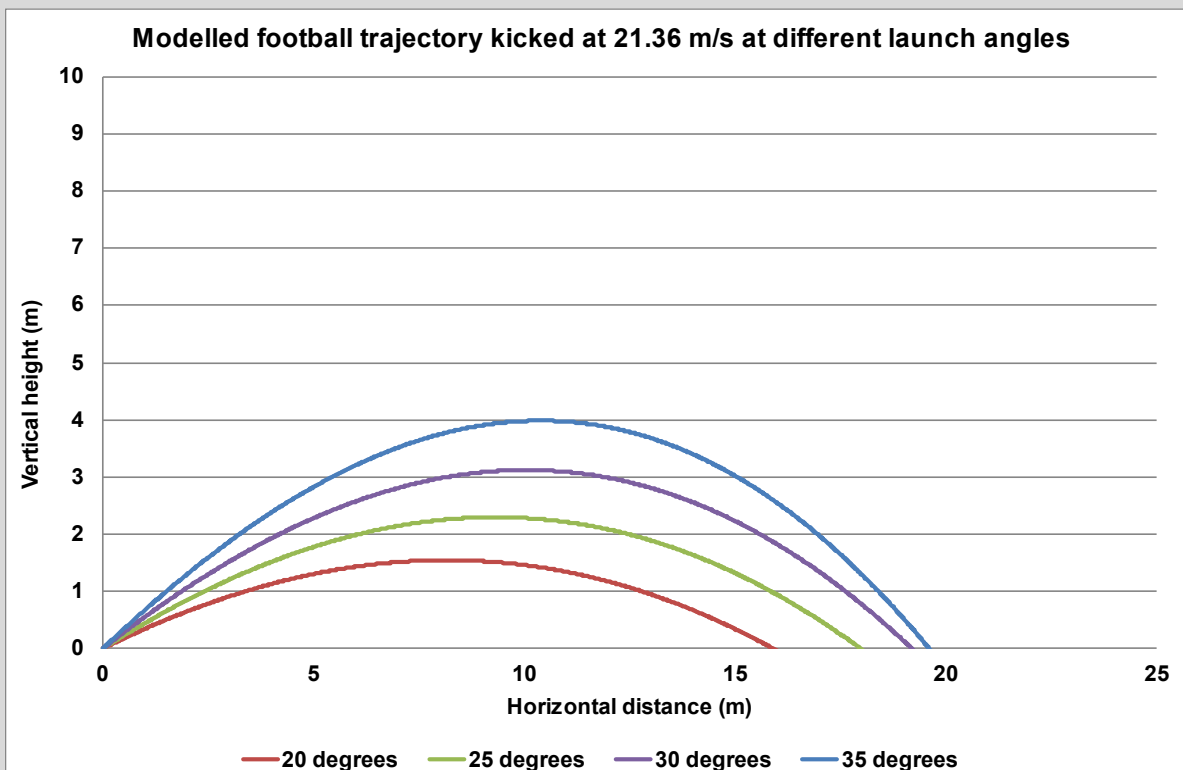
Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	1.24	2.14	3.03	3.91

Trajectory 11 – a penalty missing the goal wide– 14.78 metres to the pitch boundary. (21.36 m/s ball speed)

Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	0.42	1.40	2.31	3.12

Trajectory 12 – a penalty missing the goal high– 11.66 metres to the pitch boundary. (21.36 m/s ball speed)

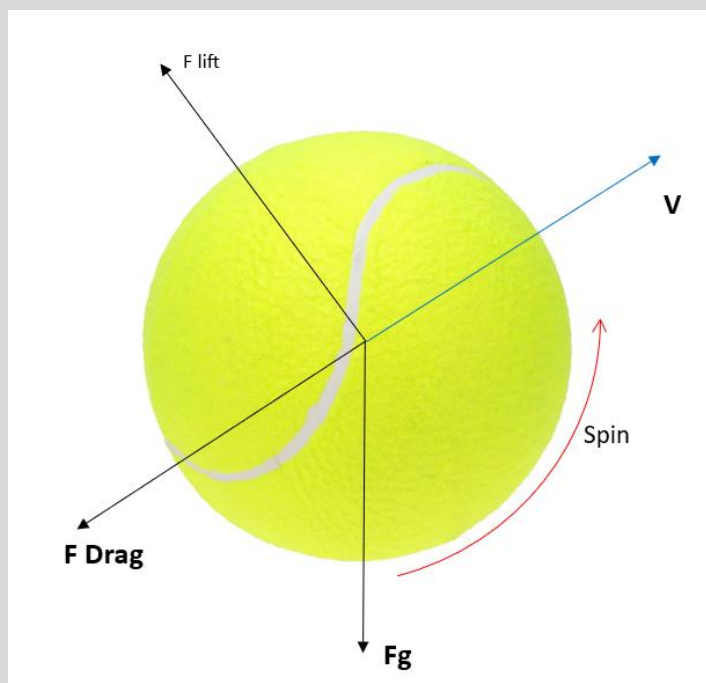
Kick launch angle (degrees)	20	25	30	35
Predicted trajectory height as ball intersects boundary (m)	1.24	2.14	3.03	3.91



Section 4 – Tennis Trajectory Model

Tennis Trajectory Model Overview

The trajectory model uses aerodynamic principles and Newtonian physics to predict the ball flight path whilst accounting for the effect of air resistance. The model uses aerodynamic coefficients taken from published wind tunnel studies on baseballs at different velocities given the limited peer reviewed literature to determine tennis ball drag coefficients.



The aerodynamic forces of drag (F_D) and lift (F_L) are proportional to the ball's velocity relative to the air flow, frontal area, air density and the drag coefficient respectively lift coefficient. The forces are defined as:

$$F_D = \frac{1}{2} C_D \rho V^2 A$$

$$F_L = \frac{1}{2} C_L \rho V^2 A$$

where C_D and C_L are the non-dimensional drag and lift coefficients, ρ is the air density in kg/m^3 , V is the air stream velocity in m/s and A is the frontal area of the ball in m^2 . Due to the complexity of the flight dynamics, the trajectory can only be resolved by using a numerical time step approach whereby the ball conditions are calculated at small timesteps throughout the trajectory. The conditions at time step 1 are used to calculate the conditions at time step 2; the conditions at timestep 2 are used to calculate the conditions at time step 3 and henceforth. A timestep of 0.001 seconds was used to generate high-resolution trajectory data.

Trajectory models are known to exhibit high accuracy. However, it is not possible to simulate the full complexity of the real world and this model does not account for variations in bat/ball restitution or wind (speed and direction). Due to these limitations, the model is regarded as an indicative prediction tool.

Tennis ball shot Scenarios

In the game of tennis, the ball can be hit in any direction with a wide range of velocities (speeds and angles). Nonetheless, some trajectories are far more common than others. This risk assessment uses a proportionate approach by focusing on the common trajectories to determine the most likely scenarios where a ball may surpass the site boundary.

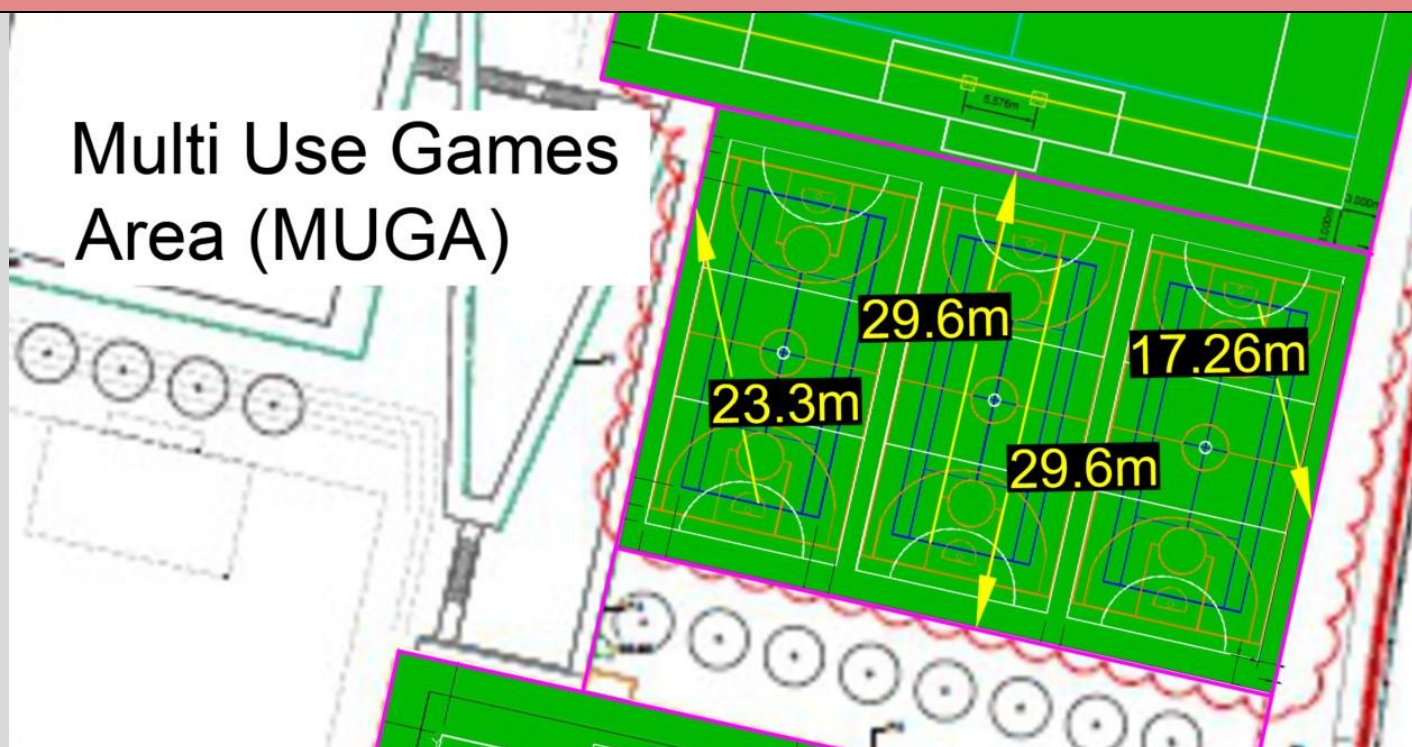
Tennis ball Velocities

In the game of Tennis, the ball can be hit in any direction with a wide range of velocities. In a sample of 21 male tennis players forehand ball velocities were recorded between 15 and 40 m/s (Rota Et al. 2012) with spin rates of up to 2500 rpm (Cross et al. 2013). Since these tennis courts will be primarily used by school children, a maximum ball velocity of 30 m/s will be used for this assessment.

Numerous studies have been done to determine the drag coefficient of tennis balls with values ranging between 0.5 and 0.57 depending on the age of the ball. (Chadwick et al. 2000).

Section 5 – Site Measurements

Site Measurements



The above diagram illustrates the minimum distances from the tennis courts to the site boundaries. Note as this is a risk assessment the worst-case scenarios are considered; consequently, the shortest measured (and calculated) distance is used for the study. The following distances have been used to calculate the projected height of the ball for different shot conditions as specified below:

Measured Distance	Shortest Boundary (m)
North – Closest reasonable shot location to proposed mitigation location	Circa 29.60 m
South – Closest reasonable shot location to proposed mitigation location	Circa 29.60 m
East – Closest reasonable shot location to proposed mitigation location	Circa 17.26 m
West – Closest reasonable shot location to proposed mitigation location	Circa 23.3 m

Section 6 – Estimated Ball Height

Tennis Estimated Ball Height

North boundary – Service hit long – 29.6 metres to the pitch boundary. (30 m/s ball speed)

Kick launch angle (degrees)	12	16	20	24
Predicted trajectory height as ball intersects boundary (m)	0	0	0	0

South boundary – Service hit long – 29.6 metres to the pitch boundary. (30 m/s ball speed)

Kick launch angle (degrees)	12	16	20	24
Predicted trajectory height as ball intersects boundary (m)	0	0	0	0.18

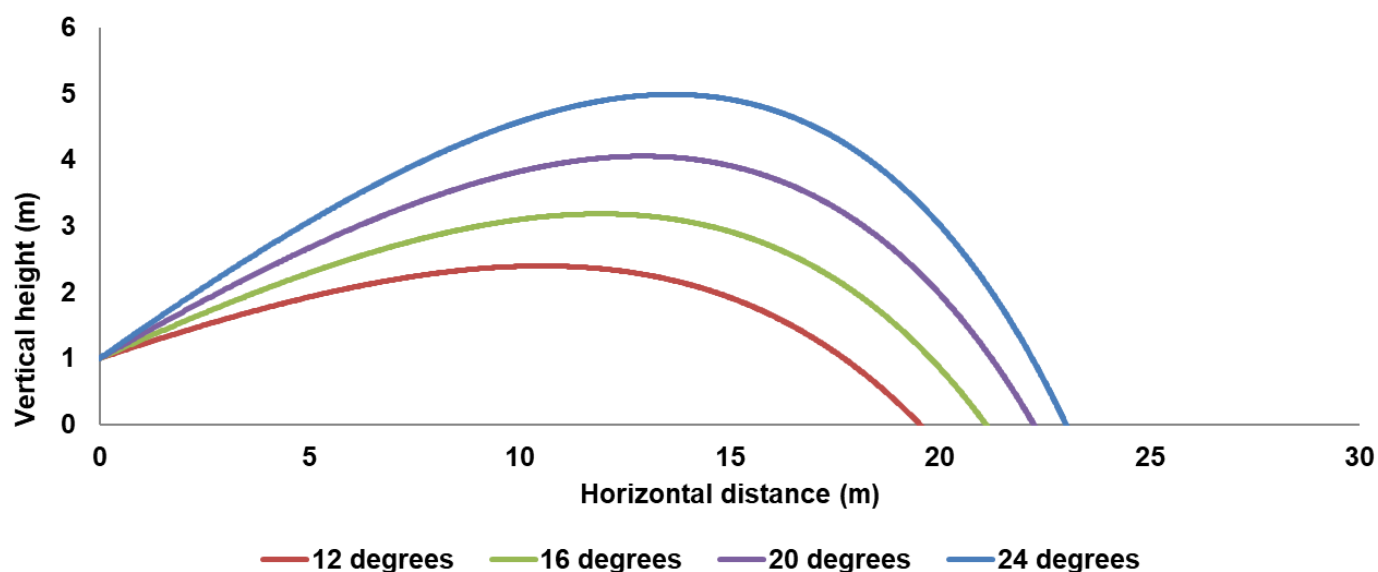
East boundary – Service hit wide – 17.26 metres to the pitch boundary. (30 m/s ball speed)

Kick launch angle (degrees)	12	16	20	24
Predicted trajectory height as ball intersects boundary (m)	1.3	2.4	3.5	4.5

West boundary – Service hit wide – 23.2 metres to the pitch boundary. (30 m/s ball speed)

Kick launch angle (degrees)	12	16	20	24
Predicted trajectory height as ball intersects boundary (m)	0	0	0	0.1

Modelled tennis ball trajectories hit at 30 m/s at different launch angles



Section 7 – Discussions and Conclusions

Discussions and Conclusions

This report has been prepared to assess the potential risk of balls surpassing the boundaries of proposed new sports pitches at Star Radcliffe Academy and to advise on the mitigation recommended to provide a suitable level of protection.

The exact frequency of events resulting in a ball being hit into the adjacent area is unknown and impossible to predict with certainty (player skills, type of game and many other factors can influence this) hence a proportionate approach needs to be taken to provide safety to these users. In reality, there may be a “freak” trajectory that will result in a further than expected trajectory, but a balanced risk mitigation strategy needs to be implemented that is proportionate. Indeed, there are risks associated with many everyday activities, but plans need to be developed to reduce risk following good practical health and safety principles including a combination of likelihood and severity.

In consideration of the risks posed by the simulated ball trajectories in relation to the context of the location, this report recommends the mitigation solutions shown below, in addition to the weldmesh fencing already proposed on the site layout plans for this development.

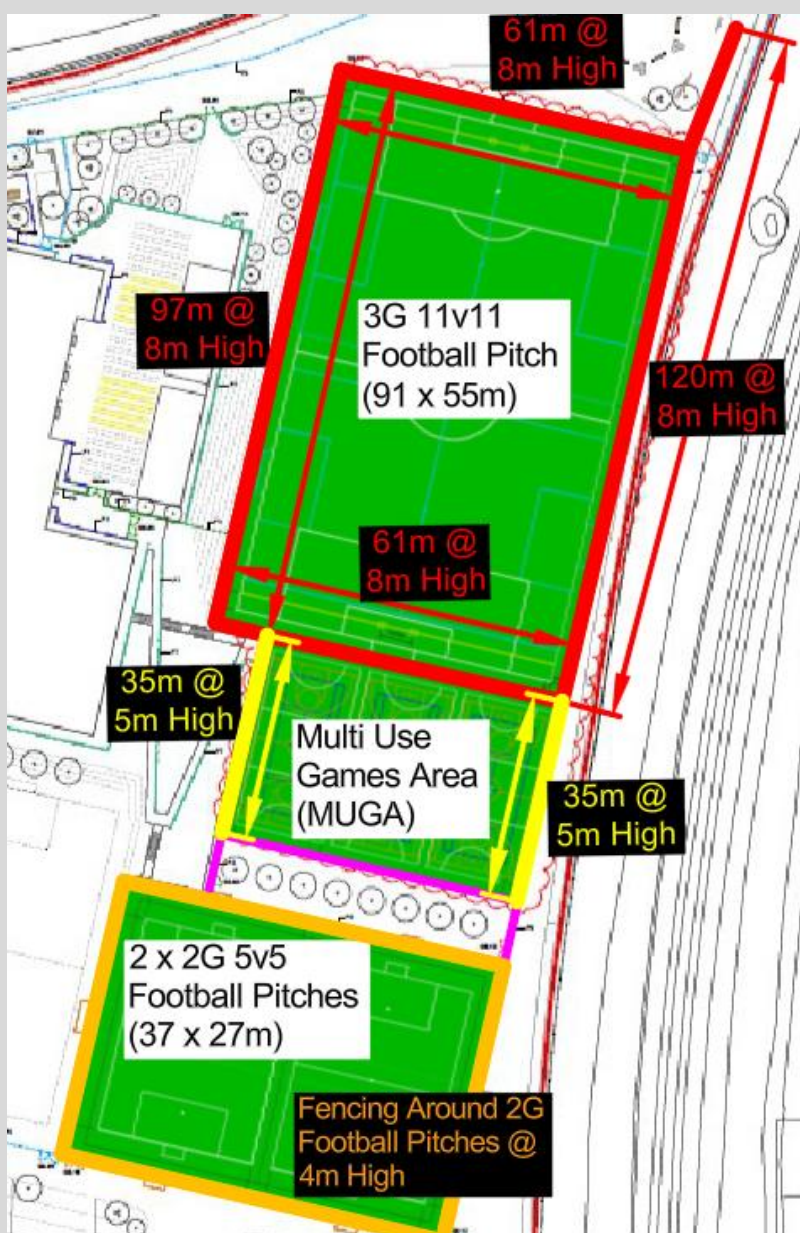


Figure 7. Ball containment recommendations based on simulated trajectories.

Alternative mitigation solution

If the recommended mitigation solution shown in Figure 7 cannot feasibly be installed at the site, an alternative mitigation solution according to the identified areas of ball strike risk severity is shown below. Due to the area east of the proposed pitches being identified as high severity of risk due to the presence of the train line, the height of ball stop mitigation must remain at their previously stated heights to prevent the majority of balls from surpassing the boundaries of the pitch and impacting on the train line. However, due to the areas to the north and west of the proposed pitches being identified as lower severity of risk, ball stop mitigation along these boundaries could be reduced to provide protection against low trajectory ball flights in these directions. Though there would be a risk that higher launch angle trajectories in these directions would surpass the pitch boundaries and impact on the adjacent areas.

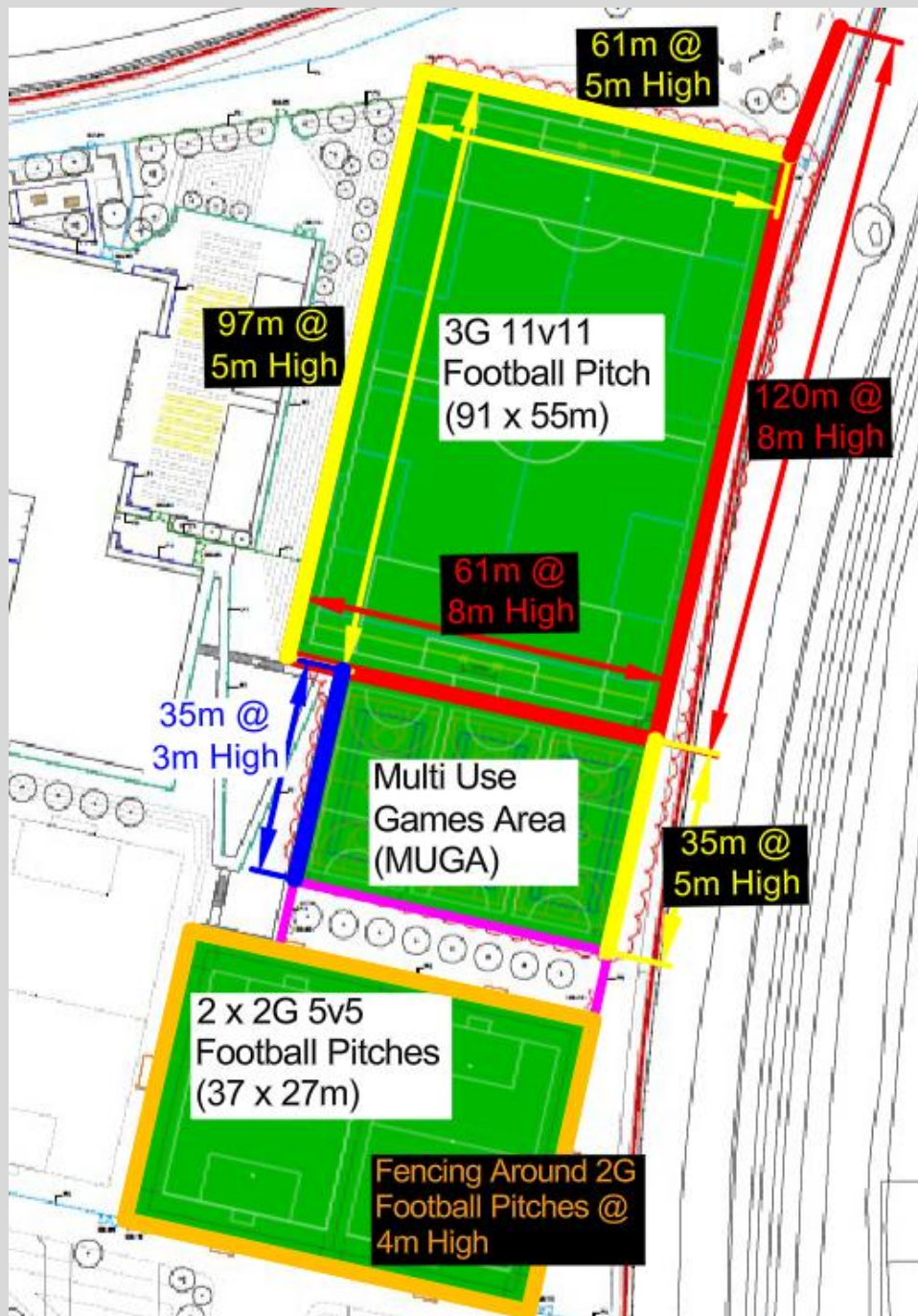


Figure 7. Alternative ball containment recommendations based on simulated trajectories and severity of risk.

It is important to note that these recommendations may not stop all balls from landing beyond the proposed mitigation location, but it is predicted from the assessment of ball trajectory it will significantly reduce their frequency.

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