

The CCK
CLERESTORY



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**“Playing football is very simple, but playing
simple football is the hardest thing there is.”**

Johan Cruyff



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Editor's Note

Dear Reader,

Following the publication of the first issue of *The CCK CLERESTORY*, we are pleased to present the second issue of the journal, this time with football as its central theme. In the inaugural issue, the tooth and dentistry were selected to show how school-based concepts can be revisited through practical, tangible, and interdisciplinary contexts. This issue continues the same approach, placing football, one of the world's most widespread cultural, social, and sporting phenomena, at the centre of educational exploration.

The selection of football as the central theme of this issue, in the lead-up to the World Cup, has offered an opportunity to reframe concepts from mathematics, physics, chemistry, biology, geography, history, technology, and social studies through problems and educational materials connected to football. However, the purpose of this issue is not to report on or analyse the World Cup as a sporting event. Rather, it uses the familiar and motivating context of football to raise educational questions and show how curricular concepts appear in real situations.

Football is far more than a game. The motion of the ball through the air, the design of stadiums, the climatic conditions of host cities, the materials used in balls and playing surfaces, the energy demands placed on players, match statistics, refereeing decisions, and the collective role of spectators can all serve as windows into knowledge. Through such examples, students can see that classroom concepts are also present on the field, in sports technology, in urban planning, in scientific design, and in public culture.

The CCK CLERESTORY seeks, in each issue, to build connections among different fields of knowledge through a shared central theme. The present issue is therefore an attempt to view football not only as global entertainment, but also as an educational context through which the relationships among knowledge, society, and everyday experience become more visible.

We hope that this issue will be useful to teachers, students, and all those interested in interdisciplinary education, and that it will open new paths for designing classroom problems, encouraging educational dialogue, and connecting learning with the world beyond the classroom.

Sincerely,
Dr. Kamal Shahtalebi
Editor-in-Chief



Trionda: The Referee's Mobile Sensor

Abstract

Trionda is the official match ball of the Fédération Internationale de Football Association (FIFA) World Cup 26. Its design is not only visual: it brings together symbolic graphics, a four-panel geometry, surface features intended to influence flight, and connected-ball technology that can provide motion data to support match officials. This article-problem uses Trionda as a teaching context to connect geometry, pressure, sampling rate, drag, and fairness in sport.

1) Introduction

At first sight, a football is simply a sphere. At World Cup level, however, the match ball must be designed to behave reliably under demanding conditions: it must satisfy the laws of the game, retain suitable pressure, resist water uptake, grip the foot, and fly in a way players can learn to control.

FIFA describes Trionda as the Official Match Ball of FIFA World Cup 26. Its name refers to 'three waves' and its red, green, and blue visual language represents the three host countries: Canada, Mexico, and the United States. FIFA also reports that the ball uses a new four-panel construction with deep seams, embossed surface details, and connected-ball technology with a 500 hertz (Hz) motion sensor chip that sends data to the video assistant referee (VAR) system in real time [1]. A public adidas release further explains that the chip is side-mounted within one of the four panels, while counterweights across the other panels help preserve flight stability and balance [2].

The geometry is also educationally rich. A Scientific American analysis explains that Trionda's four-panel design can be understood through a tetrahedron-based idea: four curved panels are shaped so that flat or nearly flat pieces can form a near-spherical object. The article also compares Trionda with earlier World Cup balls such as Telstar, Brazuca, and Jabulani, and discusses how panel shape, seam depth, surface texture, drag, symmetry, and low-spin 'knuckleball' behaviour can influence flight stability [3].

This matters because a ball is not only kicked; it is interpreted. A goalkeeper reads its early path. A referee team interprets events around it. A video system searches for precise moments of contact. A connected match ball therefore becomes more than a passive object: it becomes a mobile sensor at the centre of play.



Figure 1) Top: Telstar. Bottom: Trionda

The Telstar-type ball uses the classic pattern of pentagons and hexagons, giving it high rotational symmetry and a familiar distribution of seams. Trionda, the 2026 World Cup ball, uses a modern four-panel design with deeper seams, surface texture, and connected-ball technology. Together, they show how soccer-ball design has moved from mainly geometric panel construction toward a combination of geometry, aerodynamics, materials, and embedded technology.

2) Scientific and educational background

The International Football Association Board (IFAB) Laws of the Game specify that the ball must be spherical and set standard ranges for circumference, mass, and pressure. For a size-5 match ball, the circumference must be 68-70 cm, the mass must be 410-450 g at the start of the match, and the pressure must be 0.6-1.1 atmosphere at sea level [4]. Aerodynamically, a ball is difficult because its surface is neither perfectly smooth nor randomly rough. The seams, panel edges, embossing, and texture can change how the boundary layer separates from the ball and therefore how much drag the ball experiences. The National Aeronautics and Space Administration (NASA) general drag equation collects these complex effects into the drag coefficient, C_d , while experimental football studies show that panel number, panel shape, and orientation can influence soccer-ball drag and flight characteristics [5,6].

For students, the goal is not to reproduce a wind-tunnel experiment. The goal is to see how a real sports object can connect geometry, pressure, motion, data sampling, aerodynamics, materials, and fairness in decision-making.



Figure 2) Green's error

A softly struck shot, aimed almost directly at England goalkeeper Robert Green, somehow became a goal during England's match against the United States at the 2010 FIFA World Cup in South Africa. Many later linked Green's error to the controversial structure and unpredictable flight of the tournament's official ball, the Jabulani.

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3) Problem statement

Use the information in Table 1 and Table 2. Some values in Table 1 are official or standard-based; others are simplified educational values chosen to make the calculations accessible. The sensor-radius value and drag coefficients are not official Trionda specifications; they are modelling assumptions for this problem.

Table 1) Data for solving the problem

Parameter	Value used in the problem	Note
Ball circumference	69 cm	Within Law 2 match-ball range
Ball mass	430 g	Within the Law 2 range
Gauge pressure inside the ball	0.8 atmosphere (atm)	Relative to outside air
Shot speed	28 m/s	Educational model* value
Effective radius of sensor contact area	7 mm	Educational model value
Ball sensor data rate	500 samples/s = 500 hertz (Hz)	Reported sensor rate
Example video rate	60 frames/s	Frame rate for comparison
Air density	1.2 kg/m ³	Approximate near sea level (ρ)
Drag coefficient, regular case (C_d)	0.25	Simplified model value
Drag coefficient, unstable case (C_d)	0.35	Simplified model value
Trionda panel idea	4 curved panels	Tetrahedron-based design idea
Reference symmetry comparison	Trionda: 12; Telstar-type: 60	Used for the geometry question

*Model values are educational estimates, not exact proprietary specifications.

Table 2) Useful relations for students

Relation	Formula
Radius from circumference	$r = C/(2\pi)$
Cross-sectional area of the ball	$A = \pi r^2$
Volume of a sphere	$V = (4/3)\pi r^3$
Pressure force on a small area	$F = PA$, with 1 atm = 101325 Pa
Time between samples	$\Delta t = 1 / f$, where f is sampling frequency
Distance travelled between samples	$d = v\Delta t$
Simplified aerodynamic drag	$F_d = 1/2\rho C_d A v^2$



Figure 3) Tiento and T-Model

Illustrated reconstructions of the two balls used in the 1930 World Cup final: Tiento (left), chosen by Argentina, and T-Model (right), chosen by Uruguay. Both teams seemed to understand that the ball could quietly influence the fate of the match: Argentina led 2-1 at halftime, but Uruguay came back to win 4-2.

Questions

- a) Use the circumference relation $r = C/(2\pi)$ to calculate the approximate radius of the ball. Then use $A = \pi r^2$ for cross-sectional area and $V = (4/3)\pi r^3$ for volume. Check whether the circumference and mass are consistent with the standard match-ball range.
- b) Estimate the pressure force acting on a circular sensor contact area of radius 7 mm. Use $A_{\text{sensor}} = \pi r^2$ for the sensor contact area, convert 0.8 atmosphere to pascals using $1 \text{ atm} = 101325 \text{ Pa}$, and then use $F = PA_{\text{sensor}}$. What does this suggest about protecting electronics inside a pressurised and repeatedly kicked ball?
- c) For a 500 hertz (Hz) sensor, calculate the time between two data samples using $\Delta t = 1/f$, where f is the sampling frequency. If the ball moves at 28 m/s, calculate how far it travels between samples using $d = v\Delta t$.
- d) Repeat the same sampling calculation using $\Delta t = 1/f$ and $d = v\Delta t$ for a 60 frames/s video system. Then compare 500 Hz with 60, 120, and 240 frames/s. What does a sensor add, and what does video still do better?
- e) Use the simplified aerodynamic drag equation $F_d = 1/2 \rho C_d A v^2$ to calculate the drag force for $C_d = 0.25$ and $C_d = 0.35$. Here ρ is air density, C_d is the drag coefficient, A is cross-sectional area, and v is ball speed. Why can a change in surface pattern, seam depth, or flow stability matter so much?
- f) Geometry extension: Trionda uses a four-panel design that can be related to a tetrahedron-based idea. Compare the 12 rotational symmetries associated with this tetrahedral design idea with the 60 rotational symmetries often associated with a classic Telstar-type geometry. Use the ratio $60 / 12$ to state how many times larger the Telstar-type symmetry count is, and explain why this matters for distributing seams and surface roughness around a ball.
- g) Concept question: Explain why panel design, seam depth, surface texture, internal sensor placement, and counterbalancing are not merely cosmetic issues.

4) Worked solution

a) Geometry and basic standard check

$$r = C/(2\pi) = 0.69/(2 \times 3.14) \approx 0.110 \text{ m}$$

$$A = \pi r^2 = 3.14 \times (0.110)^2 \approx 0.038 \text{ m}^2$$

$$V = (4/3)\pi r^3 = (4/3) \times 3.14 \times (0.110)^3 \approx 0.0056 \text{ m}^3$$

A circumference of 69 cm and a mass of 430 g are within the Law 2 match-ball ranges. This standardization matters because it makes matches fairer and results more comparable across teams, stadiums, and climates [4].

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b) Pressure force on the sensor contact area

First convert the gauge pressure to pascals:

$$P = 0.8 \times 101325 \approx 81060 \text{ Pa}$$

For a circular effective contact area with radius 7 mm:

$$A_{\text{sensor}} = \pi r^2 = 3.14 \times (0.007)^2 \approx 1.54 \times 10^{-4} \text{ m}^2$$

$$F = PA_{\text{sensor}} = 81060 \times 1.54 \times 10^{-4} \approx 12.5 \text{ N}$$

This simplified estimate shows why a sensor module cannot simply be placed loosely inside a ball. It needs mechanical protection against pressure, impacts, vibration, and repeated deformation during kicking.

c) Sensor sampling at 500 Hz

$$\Delta t_{\text{sensor}} = 1/f = 1/500 = 0.002 \text{ s}$$

$$d_{\text{sensor}} = v\Delta t = 28 \times 0.002 = 0.056 \text{ m} = 5.6 \text{ cm}$$

At 28 m/s, the ball moves about 5.6 cm between two samples from a 500 Hz sensor. That time resolution is useful for identifying very short events such as ball contact, deflection, or the exact moment a pass is played [1,2].

d) Comparison with video frame rates

$$\Delta t_{60} = 1/f = 1/60 \approx 0.0167 \text{ s}$$

$$d_{60} = 28 \times 0.0167 \approx 0.467 \text{ m} = 46.7 \text{ cm}$$

Improvement relative to 60 frames/s = $0.0167 / 0.002 \approx 8.3$

$$d_{120} = 28 \times (1/120) \approx 0.233 \text{ m} = 23.3 \text{ cm}$$

$$d_{240} = 28 \times (1/240) \approx 0.117 \text{ m} = 11.7 \text{ cm}$$

This comparison does not mean that the ball sensor replaces video. Video provides spatial evidence: player positions, body parts, lines, and visual context. The ball sensor can provide finer timing information about the ball itself. The educational point is that modern officiating is increasingly a data-fusion problem: timing data, images, rules, and human judgement must fit together.

e) Aerodynamic drag

Using the simplified drag model with the cross-sectional area calculated above:

$$F_d(\text{regular}) = 1/2 \times 1.2 \times 0.25 \times 0.038 \times 28^2 \approx 4.47 \text{ N}$$

$$F_d(\text{unstable}) = 1/2 \times 1.2 \times 0.35 \times 0.038 \times 28^2 \approx 6.26 \text{ N}$$

Increasing C_d from 0.25 to 0.35 increases the calculated drag force by about 40%. In real footballs, C_d is not a universal constant; it depends on speed, surface roughness, seam geometry, panel orientation, spin, and flow regime. That is why wind-tunnel testing and flight testing are important, and why ball design can become controversial when players perceive unusual movement [5,6].

f) Geometry extension: panels, tetrahedral thinking, and symmetry

A tetrahedron has four triangular faces. Trionda is not a sharp tetrahedron; it is a playable sphere-like ball. Still, the four-panel design can be viewed as a tetrahedron-inspired idea in which curved panel boundaries help transform a low-face-count geometry into a round match ball [3].

A classic Telstar-type geometry can be associated with many more rotationally equivalent views than a tetrahedral design idea. Using the values in the problem, 60 is five times larger than 12. The point is not that symmetry alone determines ball flight. Rather, symmetry helps distribute seams and roughness more evenly as the ball rotates. When a ball flies with little spin, the air can interact differently with rougher and smoother regions. That is one route to the knuckleball-like unpredictability discussed in the literature and in popular scientific explanations of modern balls [3,6].

This is why Trionda is interesting for teachers: it lets students move from a geometric question, “How can panels form a sphere?”, to a physical question, “How does the surface change the air flow?”, and then to a technological question, “How can the ball itself support fairer decisions?”

g) Conceptual conclusion

The match ball is not just sports equipment. If its circumference, mass, or pressure were outside the standard range, the game would become less fair. If its seams and surface texture made its flight unstable, players and goalkeepers would experience the ball differently. If its sensor were not protected or balanced, its data could become unreliable. Trionda therefore offers a compact interdisciplinary case study: geometry shapes the panels; physics explains pressure, motion, and drag; materials science protects the ball; and sensing technology supports refereeing.

Figure 4) The 1986 FIFA World Cup Match Ball

The Azteca was the official ball of the 1986 FIFA World Cup. The Azteca ball used in Argentina’s famous match against England became legendary: it reportedly stayed in play for the full 90 minutes, witnessed both Maradona’s “Hand of God” and the “Goal of the Century,” and later attracted multimillion-dollar attention at auction.



Table 3) Curriculum alignment

Grade / level	Subject	Curriculum topic	Connection to the problem
Grades 8-9	Mathematics	Circles, spheres, area, volume, unit conversion	Calculate radius, cross-sectional area, and volume from circumference.
Grades 9-10	Science / introductory physics	Force, pressure, speed, motion, measurement units	Estimate pressure force on a sensor and distance travelled between samples.
Grades 10-11	Mathematics	Ratios, rates, powers, modelling	Compare 500 Hz sampling with 60, 120, and 240 frames/s video.
Grade 11	Physics	Forces, drag, simplified aerodynamic models	Use the drag equation to connect velocity, area, air density, and Cd.
Grades 10-12	Geometry / mathematical thinking	Polyhedra, symmetry, geometric modelling	Relate four-panel construction to tetrahedral thinking and compare symmetry counts.
Grades 11-12	Chemistry / materials science	Polymers, layered structures, durability	Discuss surface texture, seams, water resistance, and sensor protection.
Grades 11-12	Technology / engineering	Sensors, data sampling, measurement error, sport technology	Explore connected-ball data and its role in referee support.
Grades 10-12	Interdisciplinary studies / critical thinking	Standards, fairness, evidence, decision-making	Connect equipment standards and data-supported officiating to fairness in sport.

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World Cup Turf Engineering

Abstract

A football pitch is not just a green rectangle. It is a living and engineered system where mathematics, physics, biology, chemistry, environmental science, and technology meet. Mathematics appears in area, volume, moisture percentage, drainage rate, and energy cost. Physics appears in light, power, energy, and water flow. Biology appears in photosynthesis, root growth, and turfgrass selection. Chemistry and environmental science appear in the design of the rootzone, water management, energy use, and sustainability. This article presents a student-friendly problem inspired by the preparation of high-quality natural or hybrid turfgrass surfaces for major football competitions, including FIFA World Cup 26. The goal is not to train students as groundskeepers, but to help them see how a familiar sport can become a rich scientific system.

1) Introduction

A football pitch is a living, engineered surface. It needs healthy roots, a smooth playing surface, rapid drainage, controlled moisture, enough air in the rootzone, and enough usable light for photosynthesis. If the turf is too dry, roots and leaves are stressed. If it is too wet, the surface can become slippery, soft, and unsafe. If there is not enough light, the grass becomes thinner and recovers more slowly after training and matches.

The Fédération Internationale de Football Association (FIFA) describes the pitch as the main stage of the stadium. FIFA stadium guidance explains that pitch quality affects player performance, match appearance, and the reputation of a competition. The same guidance describes the interaction between stadium design and the pitch: roofs, high stands, shade, and reduced air movement can all affect natural grass. For elite grass and hybrid pitches, FIFA guidance also discusses a combined upper and lower rootzone depth of about 300 mm, drainage, irrigation, vacuum ventilation, and grow lights as parts of pitch design and maintenance [1].

For FIFA World Cup 26, the University of Tennessee, Knoxville (UT), in collaboration with Michigan State University (MSU) and FIFA, has been working on installation, testing, and maintenance of natural turfgrass at 16 stadiums and many training facilities in Canada, Mexico, and the United States. The purpose is to make the playing fields safe and consistent across very different climates and stadium types [2]. FIFA has also described the Pitch Research Project as a major attempt to create uniform, high-quality pitches across three countries, 16 stadiums, 84 training sites, and 178 practice fields [3].

Modern stadium turf is especially challenging. Some stadiums are open, some are partly covered, and some are domed or retractable. Some are designed for natural grass; others normally use artificial turf and must be converted temporarily for the tournament.

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UT explains that two important systems are involved: a conventional rootzone system used beneath high-end natural turf fields, and a shallow-profile system for temporary natural grass installations. In the shallow-profile system, geotextile and modular drainage-cell materials help regulate moisture and allow water to pass through, while the pitch can be removed more quickly than a conventional gravel-based system [2].

Light is another part of the engineering story. Stadium lights help people see the match, but grow lights serve the plant. Turfgrass responds to photons used in photosynthesis. For this reason, plant scientists often use terms such as photosynthetically active radiation (PAR), photosynthetic photon flux density (PPFD), and daily light integral (DLI). High-pressure sodium (HPS) and light-emitting diode (LED) grow-light systems are used in some stadium environments to help compensate for shade and limited natural sunlight. For example, the LU440 grow-light system from SGL System covers 440 m², provides a listed light level of 316 $\mu\text{mol m}^{-2} \text{s}^{-1}$, and consumes 2×31.35 kilowatts (kW), or 62.7 kW in total [4]. DLI calculations combine light intensity and time, so both the strength of the light and the number of hours matter [5].



Figure 1) Educational schematics of two natural-turf stadium pitch profiles

- A.** Professional natural or hybrid pitch profile, showing from top to bottom: turfgrass canopy, root mat/thatch, sand-based rootzone with hybrid fibre reinforcement, gravel raft, and subsurface drainage/air infrastructure.
- B.** Temporary shallow-profile pitch profile, showing from top to bottom: turfgrass canopy, root mat/thatch, sand rootzone, geotextile layer, modular drainage-cell layer, and existing base/sub-base. Layer thicknesses are approximate.

2) Problem scenario

A host stadium must prepare a high-quality natural or hybrid pitch for a major match. Part of the pitch is shaded for long periods because of the stadium structure, so the grounds team must manage not only irrigation and drainage but also supplemental grow lighting. A student team is asked to check whether the water and light management plan is reasonable. The data used in this educational model are given in Table 1.

Table 1) Input data for the stadium pitch water and grow-light management scenario

Parameter	Value in the educational model	Reason / source connection
Pitch dimensions	105 m × 68 m	Common professional match-pitch size
Effective rootzone depth	0.30 m	Based on the elite-pitch rootzone depth discussed in FIFA stadium guidance [1]
Current volumetric water content	15%	A relatively dry rootzone condition
Target volumetric water content	20%	A more suitable rootzone moisture condition
Rainfall before the match	25 mm	A moderate to fairly heavy rainfall event
Acceptable extra surface water	5 mm	A safety-oriented limit in this simplified model
Effective water removal rate	15 mm/h	A model value for a professional pitch with strong drainage and ventilation
Shaded area needing grow lights	1,320 m ²	Equivalent to three 440 m ² lighting units
Natural DLI in the shaded zone	10 mol m ⁻² day ⁻¹	A low-light condition for the shaded area
Target DLI	18 mol m ⁻² day ⁻¹	A model target for maintaining turf under match pressure
Supplemental PPFD	316 μmol m ⁻² s ⁻¹	Listed light level for an LU440 grow-light unit [4]
Coverage of one grow-light unit	440 m ²	Listed lighting footprint for an LU440 unit [4]
Power of one grow-light unit	62.7 kW	2 × 31.35 kW consumption listed for an LU440 unit [4]
Electricity price	0.15 United States dollars per kilowatt-hour (USD/kWh)	Educational cost assumption

Questions

- Calculate the pitch area. Then calculate the volume of the effective rootzone using the formula: rootzone volume = pitch area × rootzone depth. Next, calculate how much water is needed to raise volumetric water content from 15% to 20%. Use: water volume = rootzone volume × change in volumetric water content. Give the answer in cubic metres and litres.

- b)** After 25 mm of rainfall, only 5 mm of extra water is considered acceptable in this model. Calculate the water depth that must be removed. Then use: $\text{drainage time} = \text{water depth to be removed} \div \text{effective water removal rate}$. How long is needed for the pitch to approach a suitable condition?
- c)** Calculate the DLI deficit in the shaded area. Use: $\text{DLI deficit} = \text{target DLI} - \text{natural DLI}$. Then calculate how many hours the grow lights must run. Use the less familiar DLI formula: $\text{added DLI} = \text{PPFD} \times \text{lighting time} \times 3,600 \div 1,000,000$, where PPFD is in $\mu\text{mol m}^{-2} \text{s}^{-1}$ and time is in hours. Rearrange it as:
 $\text{lighting time} = \text{DLI deficit} \times 1,000,000 \div (\text{PPFD} \times 3,600)$.
- d)** Calculate how many LU440 grow-light units are needed. Use: $\text{number of units} = \text{shaded area} \div \text{coverage of one unit}$. Then calculate daily energy use with: $\text{energy} = \text{number of units} \times \text{power per unit} \times \text{operating time}$. Finally, calculate the daily electricity cost with: $\text{cost} = \text{energy} \times \text{electricity price}$.
- e)** Geometry and pitch design question: Compare the engineered rootzone volume for a full 105 m × 68 m pitch at 0.30 m depth with the volume that would be needed if a temporary sand rootzone were 0.20 m deep over the same area. What is the difference in volume? Why does this geometric difference matter for material transport, installation time, drainage, and pitch consistency?
- f)** Based on climate, what types of turfgrass are more suitable for warmer and cooler host locations? Explain how hybrid reinforcement, rootzone design, and standardised pitch testing can support player safety and consistent ball behaviour.



Figure 2) Turf Grow Lights

Supplemental grow lights mounted on overhead trusses above the pitch, used to support turfgrass growth in shaded stadium areas.

3) Worked Solution

a) Rootzone volume and water requirement

First, calculate the pitch area:

$$\text{Area} = 105 \times 68 = 7,140 \text{ m}^2$$

With an effective rootzone depth of 0.30 m:

$$\text{Rootzone volume} = 7,140 \times 0.30 = 2,142 \text{ m}^3$$

The change in volumetric water content is:

$$\Delta\theta = 20\% - 15\% = 5\% = 0.05$$

Therefore, the water volume needed is:

$$\text{Water volume} = 2,142 \times 0.05 = 107.1 \text{ m}^3$$

$$107.1 \text{ m}^3 = 107,100 \text{ L}$$

About 107,000 litres of water are needed to raise the effective rootzone from 15% to 20% volumetric water content. This is why professional pitch irrigation is an engineered operation, not simply “watering the grass.”

b) Drainage time after rainfall

The rainfall depth is 25 mm, but only 5 mm of extra water is acceptable in this simplified safety model. The depth that must be removed is:

$$\text{Water to remove} = 25 - 5 = 20 \text{ mm}$$

With an effective removal rate of 15 mm/h:

$$\text{Drainage time} = 20 \div 15 = 1.33 \text{ h} \approx 1 \text{ h } 20 \text{ min}$$

So the pitch needs about 1 hour and 20 minutes to approach the suitable water condition in this model. In real stadiums, the exact time depends on slope, rootzone material, air temperature, wind, drainage condition, and vacuum ventilation. FIFA guidance emphasises that drainage design must be based on local climate and extreme rainfall risk [1].

c) Daily light deficit and grow-light operating time

The natural DLI in the shaded zone is $10 \text{ mol m}^{-2} \text{ day}^{-1}$, and the target is $18 \text{ mol m}^{-2} \text{ day}^{-1}$.

The deficit is therefore:

$$\text{DLI deficit} = 18 - 10 = 8 \text{ mol m}^{-2} \text{ day}^{-1}$$

Using the DLI formula introduced in the question:

$$\text{Lighting time} = 8 \times 1,000,000 \div (316 \times 3,600)$$

$$\text{Lighting time} \approx 7.03 \text{ h}$$

The grow lights must run for about 7 hours per day to make up this light deficit. This result also explains why lux alone is not enough for turfgrass management: plants respond to the accumulated photosynthetic photon supply, not only to how bright the light appears to the human eye [5].

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d) Number of grow-light units, energy use, and cost

Each LU440 unit covers 440 m^2 . The shaded area is $1,320 \text{ m}^2$:

$$\text{Number of units} = 1,320 \div 440 = 3$$

Three units are needed. Each unit consumes 62.7 kW, and the operating time is 7.03 h:

$$\text{Energy} = 3 \times 62.7 \times 7.03 \approx 1,322 \text{ kWh/day}$$

At 0.15 United States dollars per kilowatt-hour (USD/kWh):

$$\text{Cost} = 1,322 \times 0.15 \approx 198 \text{ USD/day}$$

The direct electricity cost is therefore about 198 USD per day for this shaded area. This does not include labour, moving the lighting units, ventilation, maintenance, equipment rental, or control systems. The calculation is still useful because it makes the invisible energy cost of pitch quality visible to students.

e) Geometry of rootzone volume

For the 0.30 m professional rootzone used in the main model:

$$\text{Volume at 0.30 m} = 7,140 \times 0.30 = 2,142 \text{ m}^3$$

For a 0.20 m temporary sand rootzone over the same pitch area:

$$\text{Volume at 0.20 m} = 7,140 \times 0.20 = 1,428 \text{ m}^3$$

The difference is:

$$\text{Difference} = 2,142 - 1,428 = 714 \text{ m}^3$$

This is not a small difference. A change of only 0.10 m in depth across a full-sized pitch changes the required engineered material by 714 m^3 . That affects truckloads, installation time, cost, water storage, drainage behaviour, and how consistently the surface behaves from one stadium to another. This is a geometry problem hidden inside a sports-management problem.

f) Turf selection, reinforcement, and testing

Turfgrass selection must match the climate and the stadium environment. FIFA guidance notes that cool-season grasses, such as perennial ryegrass and Kentucky bluegrass, suit cooler regions, while warm-season grasses, such as bermudagrass and zoysiagrass, suit warmer or tropical climates [1]. UT explains the same basic idea for FIFA World Cup 26: bermudagrass is used for warmer climates, while Kentucky bluegrass and perennial ryegrass mixtures are used for cooler climates [2].

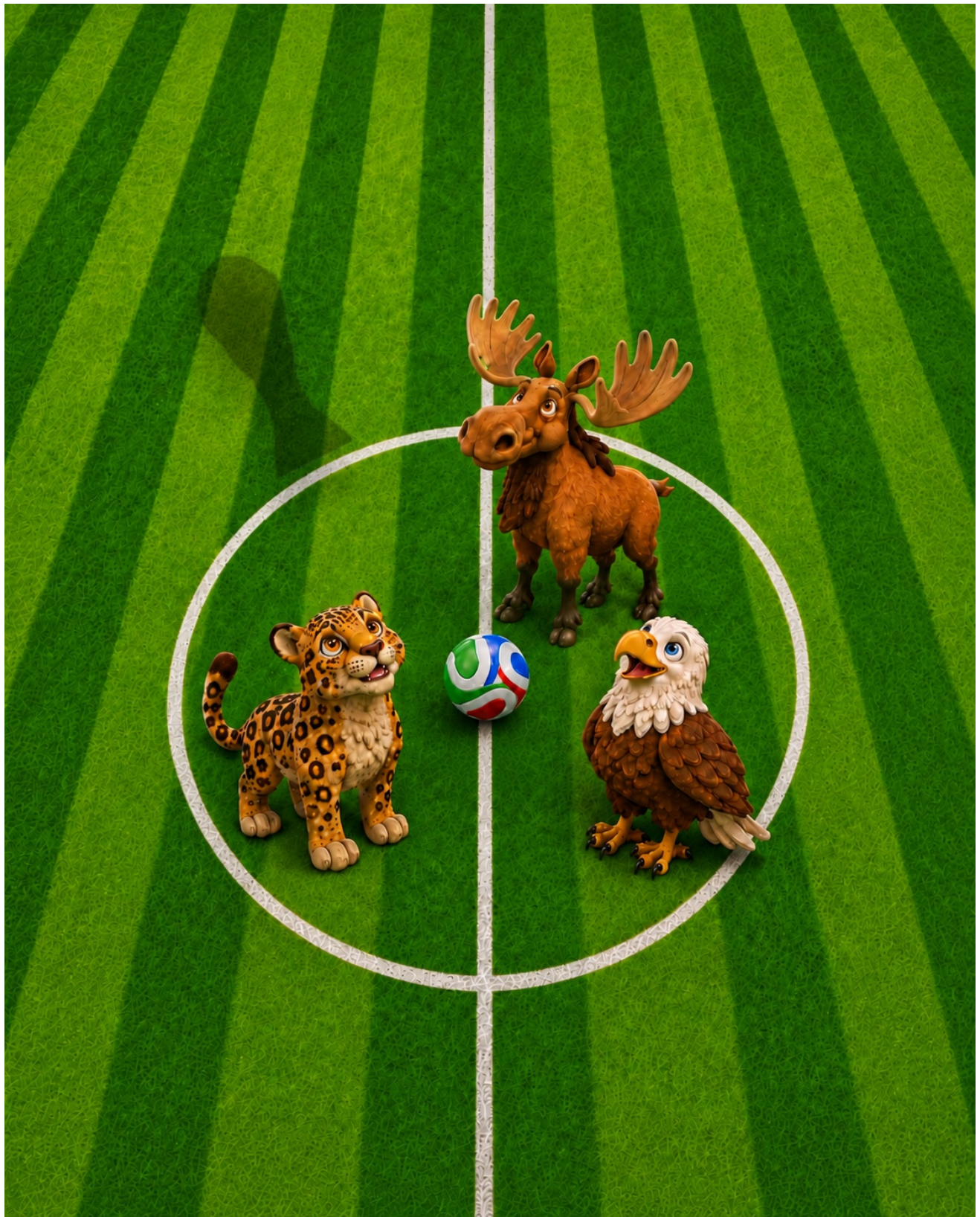
Hybrid reinforcement is not only a cosmetic feature. Synthetic fibres or carpet-based reinforcement can help the natural grass resist tearing, deformation, and heavy wear. This matters for player safety, boot traction, ball roll, ball bounce, and pitch consistency during a dense match schedule. The FIFA Quality Programme for Natural Playing Surfaces aims to reduce subjectivity by using technical and agronomic tests to compare natural playing surfaces in a more standardised way [6].

Table 2) Curriculum connections

Grade / Level	Subject	Topic	Connection to the problem
Grades 8–9	Science	Plants, photosynthesis, water, and growing conditions	Students see turfgrass as a living system that needs water, light, roots, and suitable environmental conditions.
Grades 9–10	Mathematics	Area, volume, percentages, unit conversion	Students calculate pitch area, rootzone volume, and water needed for a change in volumetric water content.
Grade 10	Earth and Environmental Science	Soil, water movement, drainage, and sustainability	Students connect rainfall, excess water, drainage, and safe playing conditions.
Grade 11	Physics	Power, energy, rate, and quantitative modelling	Students calculate drainage time, grow-light operating time, energy use, and daily electricity cost.
Grades 11–12	Biology	Photosynthesis, light, and plant adaptation	Students understand PPFD, DLI, and grass selection for warmer or cooler climates.
Grades 11–12	Chemistry / Environmental Science	Materials, rootzone media, energy use, and environmental impact	Students discuss engineered materials, energy demand, and sustainable stadium management.
Grades 11–12	Technology and Engineering	Systems design, testing, optimisation, and maintenance	Students compare pitch profiles and consider how irrigation, drainage, lighting, and testing work together.

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Split-Flap Displays: A Brief Overview

How They Work

A split-flap display uses sets of lightweight rotating flaps printed with letters, numbers, symbols, or parts of an image. A small electronically controlled motor rotates the mechanism until the required flap reaches the viewing position. Electronic controllers and position sensors help coordinate the movement and determine when the motor should stop.

Traditional Uses

Split-flap displays became widely associated with airport departure boards, railway stations, bus terminals, and other public-information systems. As the flaps move rapidly from one position to another, they produce the distinctive clicking sound that became characteristic of these displays.

Modern Uses

Although digital screens have replaced many traditional installations, split-flap technology has found new applications in advertising, retail spaces, restaurants, hotels, museums, stadiums, and interactive art. Modern systems can be digitally programmed, while image-based versions such as Picture Flap use coordinated panels to form and change complete images.

Split-flap sequence images: Asanagi, own work, CC0 1.0, via Wikimedia Commons.

<https://commons.wikimedia.org/w/index.php?curid=46442905>

Note: The fictional story that follows takes the split-flap display in a different direction. Set around football, it imagines a social use of this familiar technology, not simply to display information, but to create connection and a shared experience.

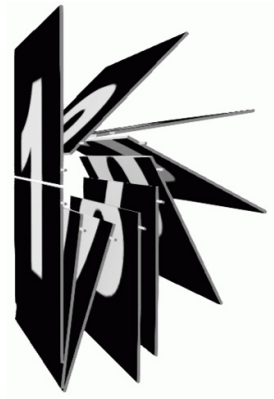
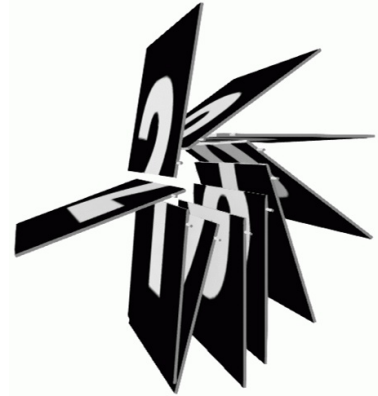
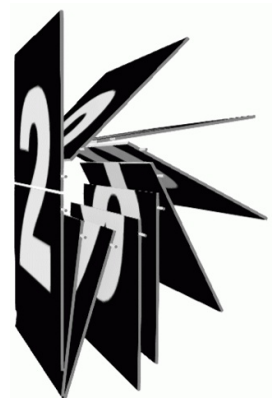
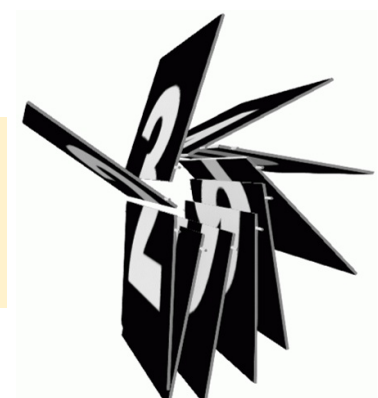




Figure 1) Today, split-flap displays are used in public and commercial spaces, especially for advertising, where their distinctive motion and sound create a striking sensory effect.

Seat 6

Almost everyone who came to Ravenford Stadium* to watch Northbridge FC knew that Seat 6 was not just a seat. On the stadium map, it was Block 106, Row C, Seat 6. But to everyone at Northbridge, it belonged to Mr. Edward Zane.

For more than fifty years, Mr. Zane had sat in the same place, in the same row, wearing the same deep-blue scarf, watching the same club through bright afternoons, rainy evenings, painful defeats, and impossible victories. He had seen young players become legends, managers come and go, and generations of supporters grow old around him. He was not the loudest fan in the stadium. He did not bang drums or lead chants. But everyone knew that when Northbridge needed a goal, Mr. Zane would lean forward, place one hand over his heart, and stare at the pitch as if he could send courage directly to the players.

The players knew him too.

After a difficult loss, when the team walked slowly toward the tunnel, they would often look toward Seat 6. If Mr. Zane was there, still standing, still applauding, still refusing to let disappointment turn into anger, the defeat felt different. It was not only the scoreboard they wanted to repair. It was his silence. His tired smile. The way he kept believing in them even when belief seemed unreasonable.

For the players, winning the next match was not just about points.

It was about bringing the smile back to Seat 6.

Mr. Zane was also known outside the stadium. He was the founder of ZaneTech Systems, a small but respected technology company that designed communication devices, mechanical displays, and low-cost interactive systems for public spaces. His engineers often joked that their company had two laboratories: one in the building where they worked, and one in Seat 6, where Mr. Zane tested every idea against the oldest question in sport: “Does it make people feel more connected?”

Then, a few weeks before the final matchday of the season, Mr. Zane fell at home and fractured his hip. The doctors were clear.

No stadium.

No stairs.

No crowd.

Absolute rest.

For the first time in decades, Seat 6 would be empty.

** This story and its accompanying images are fictional. Any resemblance to real persons, clubs, organizations, or events is coincidental.*



Figure 1) The passage of time

Top: Edward Zane at Ravenford Stadium, Saturday, May 9, 1970

Bottom: Edward Zane at Ravenford Stadium, Sunday, June 16, 2024

The timing could not have been worse. Northbridge was fighting for the league title, and the final match was against Westport United, the strongest team in the league. Northbridge had to win. A draw or a loss would hand the title to Westport.

The players needed the crowd.

The crowd needed belief.

And everyone knew that, on a night like that, the team would instinctively look toward Seat 6.

On the last Sunday of May, Ravenford Stadium filled long before kickoff.

People noticed it almost immediately.

Seat 6 was not empty.

Mounted carefully on the back of the seat was a small mechanical split-flap portrait frame. It was not a digital screen. It did not glow like a tablet. Inside it were rows of small turning panels, each one carrying parts of a face: eyes, eyebrows, mouth, cheeks, and the familiar lines of Mr. Zane's expression.

Below the frame, folded neatly across the chair, was his old blue scarf.

At first, the portrait showed Mr. Zane with a calm, hopeful smile.

The supporters around the seat stood still for a moment. Some smiled. Some took photographs. One elderly woman touched the scarf gently as she passed.

High above the stadium, in a quiet room at home, Mr. Zane was watching the match on a large screen. Beside him was a small control panel designed by his own engineers. It had only a few buttons, each large enough for his tired hand to press comfortably:

Believe

Nervous

Hope

Cheer

Goal

The system was simple. Almost old-fashioned. But that was the beauty of it.

It did not pretend to replace Mr. Zane.

It only helped his seat respond.

A few moments before kickoff, Mr. Zane pressed one of the buttons.

In the stadium, the small panels began to turn.

Click. Click. Click.

The calm smile on the portrait became warmer. The eyes seemed brighter. Those sitting nearby heard his familiar voice from a small speaker near the seat:

"Come on, Northbridge."

The people around Seat 6 clapped first. Then a few rows joined them. Soon, that entire section of the stadium was chanting his name.

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The match began.

And from the first minute, it was tense.

Westport United did not need to chase the match. A draw would make them champions, and they played with the patience and authority of a team that knew it could hurt Northbridge at any moment.

Northbridge attacked, but nothing opened.

In the twentieth minute, Mason Reed sent a low pass across the box, but no one reached it.

In the thirty-first minute, Leo Hart rose for a header, but it sailed over the bar.

In the forty-fourth minute, Elias Vale struck from distance, and the ball curled just wide.

At halftime, it was still 0–0.

As the players walked off, some of them looked toward Seat 6. The portrait had changed. Mr. Zane's face now looked serious but steady: eyes focused, mouth firm, the soft smile gone but not the belief behind it.

The second half was worse.

Westport began to attack.

Twice, they almost ended it.

Once, their striker broke through the defensive line and struck the ball low toward the corner. Northbridge's goalkeeper, Daniel Cross, reached it with the tips of his fingers. The ball brushed the post and spun away.

The stadium gasped.

At Seat 6, the panels turned.

Click. Click. Click.

The portrait changed into a worried face. The eyes narrowed. The mouth tightened. The old lines of his face seemed deeper now, as if every second on the pitch was passing through him too.

Those sitting nearby looked at it, then at the pitch, and somehow felt that the old man was suffering through every moment with them.

The second chance was even worse.

A Westport corner came in fast. Their centre-back met it six yards from goal. The header beat everyone. For one breathless second, the ball seemed certain to cross the line.

Then captain Leo Hart threw himself backward and cleared it with his chest.

The stadium went silent after that.

Not quiet.

Silent.

The clock moved toward ninety minutes.

The score was still 0–0.

On the touchline, Westport's substitutes were already standing. Their staff kept looking at the referee. One whistle, and the title would be theirs.

Northbridge's players looked exhausted. Their shirts were heavy with sweat. Their runs shortened. Their passes grew riskier. Their hope thinner. Stoppage time was almost gone. Westport had the ball near the corner flag. Their left-back slowed down, shielding it with his body. He thought the ball was rolling out. He thought the final whistle was only a second away.

On the touchline, Westport's bench was standing. The title was only one whistle away.

At home, Mr. Zane leaned forward in his chair.

Slowly, painfully, he placed one hand over his heart.

His other hand rested near the control panel.

Trembling. Ready.

But Mason Reed did not stop.

He chased the ball all the way to the line.

Just before it crossed, he stretched out his foot and stole it back.

For a split second, Westport froze.

Mason did not look at the referee.

He did not look at the clock.

He did not try to be clever.

He whipped the ball into the penalty area.

Fast. Low. Desperate.

Elias Vale had already started his run.

He arrived between two defenders, met the ball first time, and drove it toward goal.

The shot struck the inside of the far post and went in.

For half a second, nobody moved.

Then Ravenford Stadium exploded.

Players fell to their knees. The bench rushed onto the touchline. Daniel Cross sprinted with both arms raised, hardly knowing where he was going.

Westport's players stood frozen, staring at the net. The ball rested quietly among the threads; a silent betrayal in the final breath of the season.

Northbridge had scored.

In the last breath of the season.

At Seat 6, the split-flap frame came alive.

Clickclickclickclickclick.

The anxious face vanished. The panels turned faster than they had all night. The eyes widened. The tired lines softened. A bright, impossible smile appeared. And then, for the first time that evening, the voice did not come from the small speaker near the seat.



Figure 2) Zane's split-flap portrait

At Ravenford Stadium, Edward Zane's open seat holds his mechanical portrait frame and old blue scarf, turning an empty place in the stands into a living symbol of loyalty, memory, and connection.

It rolled through the stadium speakers.

Warm. Cracked. Unmistakable.

“I told you, my boys... champions never give up.”

For one second, Ravenford Stadium did not sound like fifty thousand people.

It sounded like one heart.

Moments later, the referee blew the final whistle.

Northbridge were champions.

The players scattered across the pitch. Some fell to the grass. Some lifted the coach into the air. Some waved the blue flag toward the stands. The goalkeeper kept running with both arms raised, laughing and crying at the same time.

But after the first storm of celebration, they began to gather near Seat 6.

Leo Hart removed his captain’s armband and placed it gently over the back of the chair. Mason Reed touched the old blue scarf. Elias Vale, still breathless from the goal, stood in front of the split-flap portrait and lowered his head for a moment, as if trying to find the right words.

The portrait showed Mr. Zane smiling.

At home, Mr. Zane could no longer see the screen clearly. Tears had blurred everything. His hand still rested near the control panel, but he did not press anything else.

He did not need to.

The stadium was speaking for him now.

The next morning, newspapers called it “the most human piece of technology in football.”

But inside ZaneTech Systems, the engineers knew it was only the beginning.

Mr. Zane had already asked them to develop a larger version: a low-cost split-flap reaction system that could be installed on selected seats for supporters who could not attend matches because of illness, age, distance, or disability. Each seat would not need a robot or a bright screen. It could simply have a small mechanical portrait, a few personal expressions, and a voice that could reach the people who still remembered it.

A child in hospital could smile from a seat in the old family section.

An elderly supporter could press a button from home and send courage into the stand.

A family living overseas could let their club know they had never really left.

The club began to call the idea Living Seats.

But for the supporters of Northbridge, it had a simpler name.

It was still Seat 6.

And as long as the panels kept turning, everyone knew that Mr. Edward Zane was still part of the match.

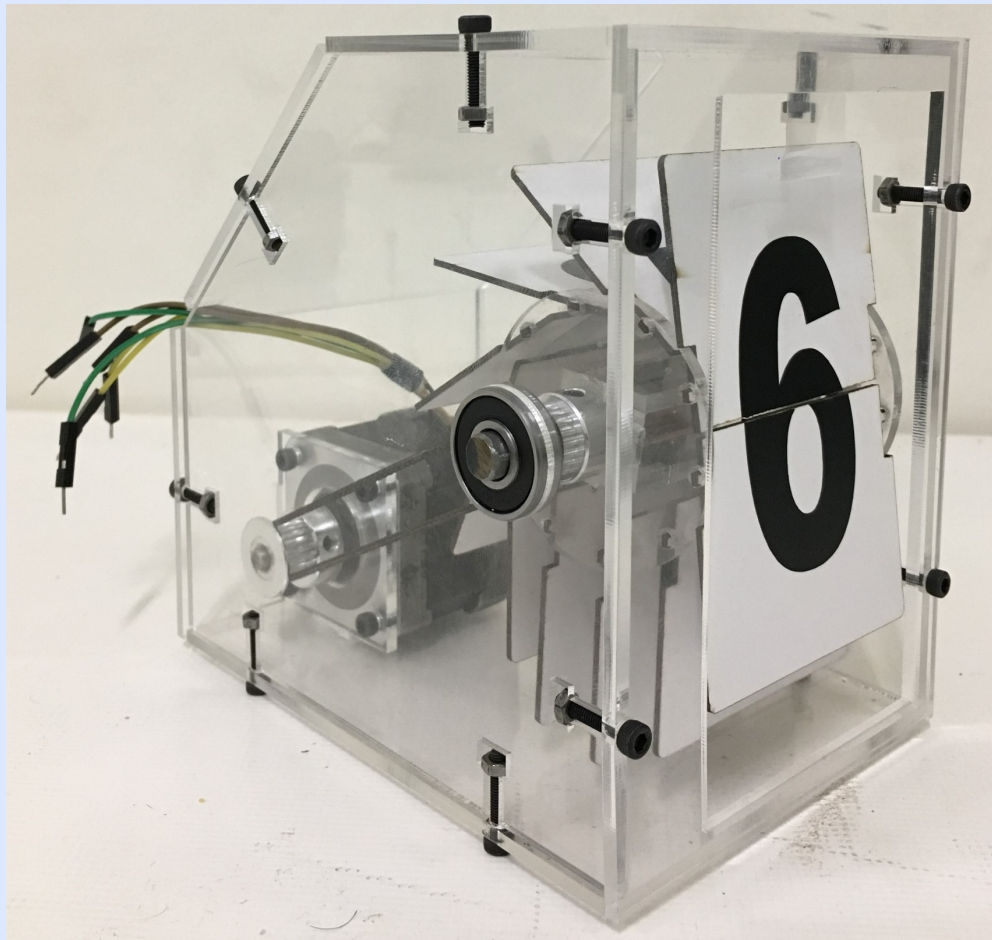


Figure 3) Experimental Split-Flap Prototype

An experimental split-flap prototype developed by Corridor of Comprehensive Knowledge for educational exploration.



Figure 4) The Goal that shook Ravenford.

Elias Vale turns Mason Reed's desperate cross into the title-winning goal, sending Ravenford Stadium and Seat 6 into celebration.



Football in the Heat

Humidity, Sweating, and Player Management

Abstract

A football match is not only a tactical contest. In hot conditions, the player's body becomes part of a larger environmental system: air temperature, humidity, sunlight, wind, sweat evaporation, hydration, and recovery all interact. This problem-based article uses three representative 2026 World Cup host-city climate scenarios (one from each host country) to estimate sweat loss, net fluid loss, dehydration percentage, and heat-index risk for a 75 kg player. The goal is not to forecast match-day weather, but to show how simple calculations can support coaching, medical, and player-management decisions.

Data note

The climate examples in this article are educational comparisons, not match-day weather forecasts. The host-city examples are connected to the official 2026 FIFA World Cup host-city structure [1]. The rounded climate values are based on public climate-normal or climate-summary sources for Canada, the United States, and Mexico [2]-[4]. The rounded heat-index values are estimated from air temperature and relative humidity using heat-index guidance from the National Oceanic and Atmospheric Administration (NOAA) [5]. The sweat-rate values are simplified educational assumptions chosen to represent increasing physiological load across the three scenarios; they are not measured values for a specific player, team, stadium, or match.

1) Tournament context: one tournament, several climates

The 2026 FIFA World Cup will be hosted across Canada, Mexico, and the United States, using 16 host cities [1]. This geographic spread matters because teams may encounter very different summer conditions: a milder coastal setting, a hot and humid setting, or a very hot inland setting. For coaches and medical staff, match preparation is therefore not limited to formation, tactics, and substitutions. It also includes heat management, hydration planning, training time, pacing, cooling breaks, and monitoring of player fatigue.

To keep the analysis focused, this article uses three representative host-city scenarios rather than a full catalogue of all host venues. Each scenario is connected to a real 2026 host venue and is used directly in the calculations.

2) Scientific introduction

When a player sprints, changes direction, presses, jumps, and collides with opponents, the body produces heat. Sweating is one of the main ways the body removes that heat, but sweat cools the body effectively only when it evaporates. In humid air, evaporation is more difficult, so a player may sweat heavily but still cool down less efficiently.

The heat index combines air temperature and relative humidity to estimate how hot the air feels to the human body. NOAA notes that heat-index values are calculated for shade; direct sunlight can make the perceived heat load even higher [5]. The CDC advises athletes to limit intense activity in hot conditions when possible, schedule activity during cooler parts of the day, pace activity, and drink more water than usual rather than waiting for thirst [6]. NIOSH also emphasizes water access, recovery time in cooler areas, rest breaks, and acclimatization when heat stress rises [7].

In sports physiology, water loss above about 2% of body mass is commonly treated as a meaningful hypohydration threshold, especially because performance impairment becomes more likely in warm or hot environments [8]. This article uses that threshold as an educational warning line, not as a medical diagnosis.



Figure 1) Representative host-city climate scenarios for the heat-stress model
The three illustrated cards compare Vancouver, Miami, and Monterrey using rounded temperature, relative humidity, and heat-index values.
The stadium and landscape visuals are symbolic, not exact views.

3) Problem setup

Suppose a 75 kg player is preparing for a 90-minute match. Including stoppage time, half-time re-warm-up, and high-pressure phases of play, the team medical staff estimates 100 minutes of effective physical load. The player drinks 0.90 L of fluid during the match. For a simple model, take the density of water as about 1 kg/L and use 2% body mass loss as an educational warning threshold.

The three scenarios in table 1 are not claims about exact match-day weather. They are rounded, representative climate examples connected to real 2026 host venues: Vancouver/BC Place in Canada, Miami/Hard Rock Stadium in the United States, and Monterrey/Estadio BBVA in Mexico. The temperature and humidity values are simplified from public climate-normal or climate-summary sources [2]-[4], while the heat-index values are rounded educational estimates based on NOAA heat-index guidance [5]. The sweat rates are model assumptions chosen to create a clear comparison across mild, hot-humid, and very hot conditions.

Table 1) Simplified heat, humidity, and sweat rate scenarios for selected 2026 host venues

Scn.	Representative host example	Climate type	AT	RH	SR	RHI
A	Vancouver / BC Place, Canada	Milder / coastal baseline	24 °C	60%	0.7 L/h	~25 °C
B	Miami / Hard Rock Stadium, United States	Hot and humid	32 °C	70%	1.4 L/h	~40 °C
C	Monterrey / Estadio BBVA, Mexico	Very hot	36 °C	55%	1.6 L/h	~46 °C

Scn. (Scenario), AT (Air Temperature), RH (Relative Humidity), SR (Sweat Rate), RHI (Rounded Heat-Index)

The role of the examples is not decorative: Scenario A supplies a lower-heat baseline, Scenario B highlights the additional burden of humidity on sweat evaporation, and Scenario C tests a very hot condition where air temperature itself becomes a dominant stressor.

4) Questions

- Convert the effective physical-load time from minutes to hours. Use: $\text{time in hours} = \text{minutes} / 60$.
- For each scenario, calculate sweat loss. Use: $\text{sweat loss} = \text{sweat rate} \times \text{time}$.
- Assuming the player drinks 0.90 L, calculate net fluid loss in each scenario. Use: $\text{net fluid loss} = \text{sweat loss} - \text{fluid intake}$.
- Calculate dehydration percentage in each scenario. Use: $\text{dehydration percentage} = (\text{net fluid loss} / \text{body mass}) \times 100$. Which scenario is closest to or above the 2% warning line?
- Compare the rounded heat-index values in the table. Why can the hot and humid scenario be more dangerous than air temperature alone suggests?
- In Scenario B, suppose two cooling breaks allow the player to drink an additional 0.40 L. Recalculate the net fluid loss and dehydration percentage.
- Based on the calculations, suggest three decisions a coach or medical team could make to reduce heat stress during a match.

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Figure 2) Player heat balance during match conditions

This schematic shows how direct sun and muscle heat production increase heat load, while sweating, evaporation, water intake, cooling breaks, and medical monitoring help manage heat stress.

5) Solution

a) Convert time to hours

The effective physical-load time is: $100 \text{ min}/60=1.67 \text{ h}$

So, the player is exposed to about 1.67 hours of effective physical load.

b) Sweat loss

Sweat loss is calculated as: $\text{Sweat loss} = \text{sweat rate} \times \text{time}$

In Scenario A, the estimated sweat loss is $0.7 \times 1.67 = 1.17 \text{ L}$.

In Scenario B, it rises to $1.4 \times 1.67 = 2.34 \text{ L}$.

In Scenario C, it reaches $1.6 \times 1.67 = 2.67 \text{ L}$.

This means that, under the very hot condition, the player may lose more than twice as much sweat as in the milder/coastal condition.

c) Net fluid loss after drinking 0.90 L

Net fluid loss is calculated as: $\text{Net fluid loss} = \text{sweat loss} - \text{fluid intake}$

After drinking 0.90 L, the player's net fluid loss would be 0.27 L in Scenario A, 1.44 L in Scenario B, and 1.77 L in Scenario C.

d) Dehydration percentage

Dehydration percentage is calculated as:

Dehydration percentage=(net fluid loss/body mass)×100

For a 75 kg player, this gives:

Scenario A: $(0.27 / 75) \times 100 = 0.36\%$

Scenario B: $(1.44 / 75) \times 100 = 1.92\%$

Scenario C: $(1.77 / 75) \times 100 = 2.36\%$

Scenario A stays far below the 2% warning line. Scenario B comes close, while Scenario C exceeds it. In a real match, risk also depends on acclimatization, clothing, exercise intensity, wind, sun exposure, and medical history.

e) Heat index and the role of humidity

The rounded heat-index values show why humidity matters. In Scenario A, 24 °C air temperature and 60% relative humidity give a rounded heat-index value of about 25 °C. In Scenario B, 32 °C and 70% relative humidity raise it to about 40 °C. In Scenario C, 36 °C and 55% relative humidity give a value of about 46 °C. Scenario B is especially useful because it shows that air temperature alone can be misleading. Although its air temperature is lower than Scenario C's, high relative humidity makes sweat evaporation less effective. When sweat stays on the skin instead of evaporating, the body loses a major cooling pathway. The player may feel hotter, fatigue sooner, and need a more careful hydration and recovery plan. The milder Scenario A is included mainly for comparison; heat-index guidance is most meaningful in warmer conditions.

f) Effect of cooling breaks in Scenario B

Total intake=0.90+0.40=1.30 L,

New net loss=2.34–1.30=1.04 L

New dehydration percentage= $(1.04/75) \times 100 = 1.39\%$

The extra fluid reduces the dehydration percentage from about 1.92% to about 1.39%. This does not eliminate heat stress, but it moves the player farther from the warning line and creates a chance for cooling and medical observation.

g) Coaching and medical decisions

- Schedule intense training or warm-ups during cooler times when possible.
- Use a pre-planned hydration and electrolyte strategy; players should not wait until they feel thirsty [6], [7].
- In hot and humid conditions, reduce repeated high-intensity pressing for vulnerable players and consider earlier substitutions.
- Use cooling breaks, shade, cold towels, misting, and short recovery routines when competition rules and match conditions allow.
- Monitor temperature, humidity, sunlight, wind, match time, and player response.

Table 2) Curriculum connections

Grade / year	Subject	Topic	Connection to the problem
Grades 8-10	Science	Homeostasis, body temperature, skin, sweating	Explains why sweat evaporation helps cool the body and why humidity interferes.
Grades 8-10	Mathematics	Ratios, percentages, unit conversion, table interpretation	Converts minutes to hours and calculates dehydration percentage.
Grade 10	Introductory physics/science	Heat energy, evaporation, environmental heat transfer	Analyzes why hot and humid air increases heat stress.
Grade 11	Biology	Human physiology, circulation, thermoregulation, water balance	Connects fluid loss to performance and physiological strain.
Grades 11-12	Physical education/health	Sport safety, heat illness prevention, hydration planning	Designs match-day hydration, rest, cooling, and substitution strategies.
Grades 11-12	Applied mathematics/statistics	Scenario modelling, comparison, decision-making	Compares climate scenarios and links calculations to coaching decisions.

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World Cup Carbon Footprint

Team Travel, Spectator Journeys, and the Mathematics of Routes

Abstract

A World Cup match is not only a sporting event; it is also a large movement of people, goods, energy, and services. In this problem-based article, students compare the carbon dioxide equivalent (CO₂e) emissions from team travel and spectator travel. They also learn why professional carbon accounting is not simply a matter of guessing: it combines recorded activity data, emission factors, direct meter readings, and, in some cases, continuous emissions monitoring equipment. The goal is not to make students pessimistic about sport, but to help them see how mathematics can support better planning, lower-impact travel choices, and more transparent sustainability decisions.

Data and modelling note. This article is designed for education. The tournament format and match geography are based on published FIFA information, but simplified route distances and emission factors are used for classroom modelling, not for official greenhouse gas reporting. A real event inventory would require verified travel data, fuel and electricity records, supplier data, ticketing information, hotel data, waste data, and documented assumptions.

1) Tournament context: a World Cup across three countries

The 2026 FIFA World Cup will feature 48 teams across Canada, Mexico, and the United States. The official format includes 12 groups of four teams, with the top two teams in each group and the eight best third-placed teams advancing to the round of 32 [1]. The official schedule places 104 fixtures across 16 host cities, from the opening match on 11 June to the final on 19 July [2]. Because the tournament is spread across a very large geographic area, travel becomes part of the event itself: teams move between host cities, fans travel from local neighbourhoods and distant countries, and host cities operate transport, security, electricity, food, media, and waste systems.

FIFA has also published a sustainability and human-rights strategy for the 2026 tournament, and previous FIFA sustainability reporting has treated greenhouse gas emissions as a major environmental topic [3], [4]. This makes the World Cup a strong classroom example: the same match schedule that fans read for excitement can also be read as a geography, mathematics, and environmental-systems problem.

2) How carbon emissions are measured in real projects

In everyday language, people often say that carbon emissions are “measured.” In practice, carbon accounting uses several levels of evidence. Some emissions can be measured directly with instruments; many others are estimated from activity data and emission factors. For example, spectator air travel is not usually measured by placing a sensor on every passenger. Instead, analysts estimate emissions from the number of passengers, travel distance, travel mode, and a published emission factor.

Emissions = Activity data × Emission factor

Activity data may be kilometres travelled, litres of fuel used, kilowatt-hours of electricity consumed, hotel nights, kilograms of waste, or tonnes of material. The emission factor converts each unit of activity into greenhouse gas emissions, often reported as carbon dioxide equivalent (CO₂e).

The Greenhouse Gas (GHG) Protocol framework commonly classifies emissions into Scope 1, Scope 2, and Scope 3. Scope 1 refers to direct emissions from sources owned or controlled by the reporting organization; Scope 2 refers to indirect emissions from purchased electricity, heat, steam, or cooling; Scope 3 includes other indirect emissions in the value chain, such as spectator travel, team travel by third-party carriers, purchased goods, accommodation, and waste services [5], [6]. Table 1 summarizes the main types of evidence and measurement tools used to estimate tournament carbon emissions.

Table 1) Evidence sources and measurement tools for estimating tournament carbon emissions

Evidence type	Examples in a major tournament	Typical instruments or data sources	Why it matters
Direct fuel or energy records	Stadium electricity, generators, fleet fuel	Electricity meters, submeters, fuel flow meters, fuel invoices	Good for venue operations and owned vehicles
Direct emissions monitoring	Large boilers, generators, or industrial stacks when applicable	Continuous Emission Monitoring System (CEMS), gas analyzers, stack flow measurement	Used when emissions from a stationary source must be continuously monitored
Activity-based travel estimates	Team flights, spectator flights, buses, trains, local transit	Ticketing data, travel surveys, origin-destination data, passenger-kilometres, emission factors	Essential for Scope 3 travel emissions
Material and waste records	Food, packaging, merchandise, construction, waste disposal	Weighbridges, waste manifests, procurement data, life-cycle emission factors	Connects event operations to supply chains

National reporting systems often use published conversion factors to estimate emissions from activity data, such as passenger-kilometres or litres of fuel [7]. A Continuous Emission Monitoring System (CEMS) is the total equipment needed to determine gas or particulate concentration or emission rate from a source using pollutant analyzers and calculations [8]. CEMS can be useful for some stationary sources, but it is not how analysts measure the carbon footprint of a fan flying to a match. For travel, the practical method is usually activity data multiplied by emission factors, with transparent assumptions and uncertainty notes.

3) Educational route categories for team travel

Instead of building the article around one national team, we use symbolic team positions and distance bands. This keeps the problem neutral and makes the mathematics more durable. The categories in table 2 are not official FIFA categories; they are an educational way to classify possible group-stage travel patterns by distance and logistical pressure. If the official match schedule changes, the exact team positions should be rechecked using the latest FIFA schedule [2].

Table 2) Simplified team-travel categories used in the educational model

Travel category	Educational definition	Representative code	Internal group-stage distance used in the model
A. Very low travel	Mostly one city or a very nearby region; low travel pressure	A1	700 km
B. Low travel	One main movement within a broad region	G2	1,550 km
C. Medium travel	Two movements or one longer internal route	L1	3,000 km
D. High travel	Movement between more distant regions; higher logistical pressure	B2	5,200 km

4) Problem set: team travel and spectator travel

Assume that each team delegation contains 55 people. For the educational model, use an emission factor of 0.15 kg CO₂e per passenger-kilometre for team air travel. This rounded teaching factor is inspired by conversion-factor methods, but it is not a route-specific or official reporting value [7].

Table 3) Representative route data used to calculate team-travel emissions

Representative	Route category	d	n	f
A1	Very low travel	700 km	55	0.15 kg CO ₂ e/person-km
G2	Low travel	1,550 km	55	0.15 kg CO ₂ e/person-km
L1	Medium travel	3,000 km	55	0.15 kg CO ₂ e/person-km
B2	High travel	5,200 km	55	0.15 kg CO ₂ e/person-km

d: Distance, n: Number of people, f: Emission factor

Questions

- Use $E = d \times n \times f$ to calculate the approximate internal group-stage travel emissions for each representative team route. In this formula, E is emissions, d is distance, n is number of people, and f is the emission factor.
- How many tonnes of CO₂e separate the lowest-travel and highest-travel representative routes?
- If the highest-travel route can be reduced by 20% through better logistics, how much emission is avoided?

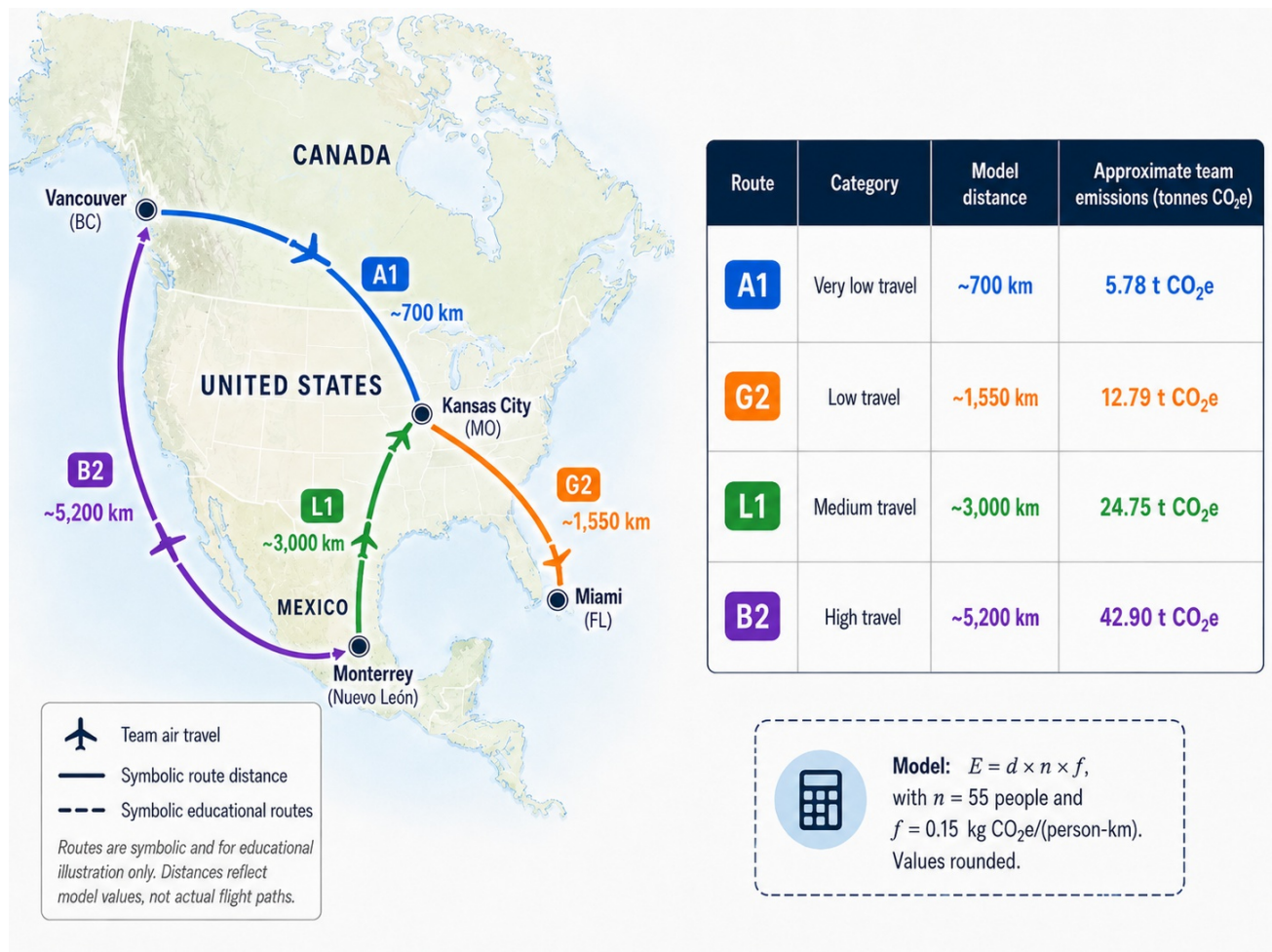


Figure 1) Educational route categories and approximate team-travel emissions

The map uses symbolic routes to compare how longer group-stage travel distances can increase CO₂e emissions; the routes are illustrative, not official team itineraries.

- d) Why should teams prepare several travel scenarios before the knockout stage begins?
- e) Now consider one match with 60,000 spectators. Use the spectator table below and $E_{\text{fans}} = N \times d \times f$ to calculate spectator travel emissions. Compare the result with team travel.
- f) Which parts of a real World Cup carbon footprint are directly measured, and which are normally estimated from activity data? Give two examples of each.
- g) Beyond team and spectator travel, what else should be included in a fuller carbon footprint of a tournament?

5) Spectator data for one model match

Assume one match has 60,000 spectators. The grouping below is a teaching model. In a real inventory, analysts would use ticketing data, travel surveys, transport-mode data, hotel information, and other evidence. The key lesson is that a smaller group of long-distance travellers can dominate the footprint.

Table 4) Representative spectator groups and travel assumptions for one model match

Spectator group	Share	N	d	f
Local	40%	24,000	40 km	0.06 kg CO ₂ e/person-km
Regional	30%	18,000	600 km	0.10 kg CO ₂ e/person-km
Intercity	20%	12,000	3,000 km	0.15 kg CO ₂ e/person-km
International	10%	6,000	14,000 km	0.15 kg CO ₂ e/person-km

N: Number, d: Round-trip distance, f: Emission factor

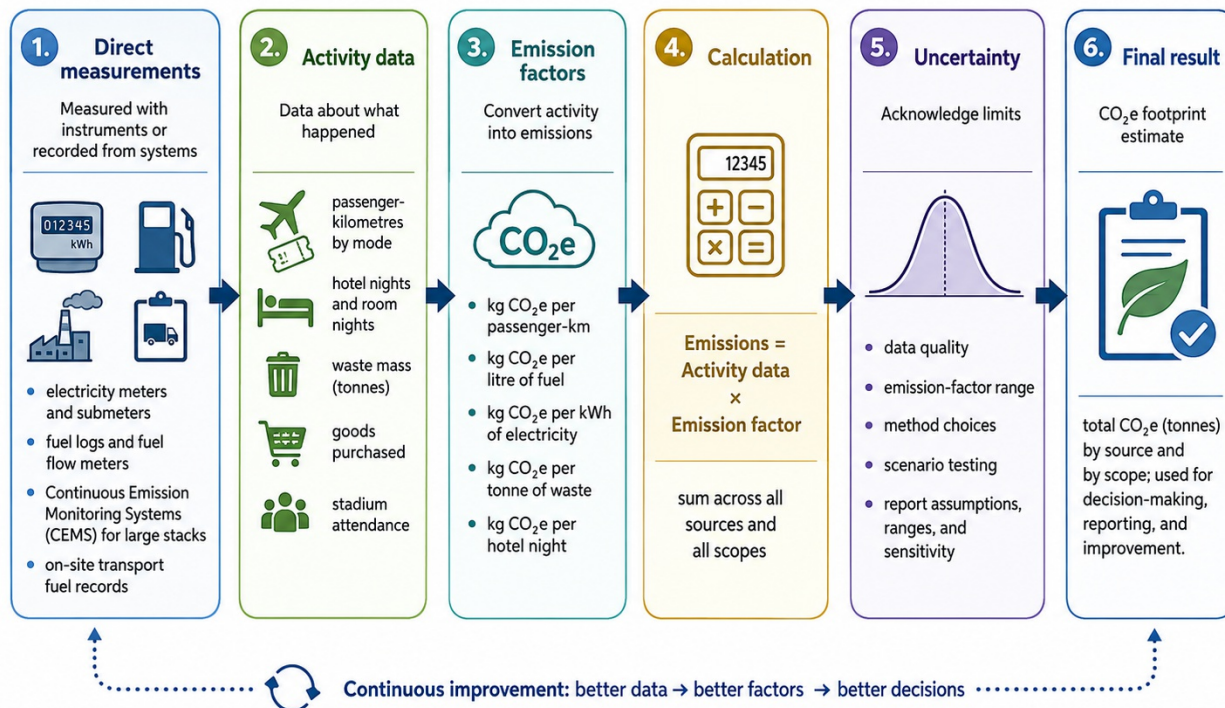


Figure 2. Simplified carbon-accounting workflow for a major sports event

The diagram shows how measured records, activity data, emission factors, calculations, and uncertainty notes combine to produce a CO₂e footprint estimate.

6) Worked solution

a) Approximate team-travel emissions ($E = d \times n \times f$)

Table 5) Calculated team-travel emissions for the representative routes

Representative	Distance	Approximate emissions	Emissions in tonnes
A1	700 km	5,775 kg CO ₂ e	5.78 tonnes CO ₂ e
G2	1,550 km	12,788 kg CO ₂ e	12.79 tonnes CO ₂ e
L1	3,000 km	24,750 kg CO ₂ e	24.75 tonnes CO ₂ e
B2	5,200 km	42,900 kg CO ₂ e	42.90 tonnes CO ₂ e

b) Difference between the lowest- and highest-travel routes

In this model, the highest-travel representative produces 42.90 tonnes CO₂e, while the very low-travel representative produces 5.78 tonnes CO₂e. The difference is 42.90–5.78=37.12 tonnes CO₂e. Using the unrounded kilogram values, the difference is 37,125 kg CO₂e, or 37.13 tonnes CO₂e. This is a large difference for team logistics, but it is still small compared with spectator travel at full-stadium scale.

c) Reducing the high-travel route by 20%

$$d_{\text{saved}} = 0.20 \times 5,200 = 1,040 \text{ km}$$

$$E_{\text{saved}} = 1,040 \times 55 \times 0.15 = 8,580 \text{ kg CO}_2\text{e} = 8.58 \text{ tonnes CO}_2\text{e}$$

This shows that route planning has a measurable effect. In reality, however, match fairness, broadcast schedules, stadium capacity, security, training facilities, and recovery time also shape tournament logistics.

d) Why the knockout stage creates uncertainty

In the 2026 format, the exact knockout destination depends on group ranking and the combination of third-placed teams that advance [1], [2]. Therefore, a team cannot prepare only one travel plan. It needs several scenarios: first-place route, second-place route, possible third-place route, and contingency plans for training, accommodation, medical recovery, and equipment movement. This is both a performance issue and an environmental planning issue.

e) Spectator travel emissions ($E_{\text{fans}} = N \times d \times f$)

Table 6) Calculated spectator-travel emissions for one model match

Group	Number	Distance	Emissions	Emissions in tonnes
Local	24,000	40 km	57,600 kg CO ₂ e	57.6 tonnes CO ₂ e
Regional	18,000	600 km	1,080,000 kg CO ₂ e	1,080.0 tonnes CO ₂ e
Intercity	12,000	3,000 km	5,400,000 kg CO ₂ e	5,400.0 tonnes CO ₂ e
International	6,000	14,000 km	12,600,000 kg CO ₂ e	12,600.0 tonnes CO ₂ e

The total spectator-travel estimate is 19,137.6 tonnes CO₂e. This is much larger than the 42.90 tonnes CO₂e of the highest-travel team route in the model. The international group is only 10% of spectators, but because the round-trip distance is very large, it contributes 12,600 tonnes CO₂e by itself.

f) Measured versus estimated emissions

Examples of directly measured data include electricity use from meters, fuel use from fuel records or flow meters, and emissions from some stationary sources monitored with a Continuous Emission Monitoring System. Examples of estimated emissions include spectator flights, hotel stays, purchased merchandise, and some supply-chain emissions. These are usually calculated from activity data and emission factors. A strong carbon footprint is therefore not just one number; it is a documented chain of evidence.

g) Beyond team and spectator travel

This problem focuses on team and spectator travel because travel is easy for students to model and can be very large. A fuller tournament carbon footprint would also include:

- stadium electricity for lighting, displays, cooling, ventilation, sound systems, and broadcasting,
- construction, renovation, or temporary conversion of stadiums and training fields;
- natural grass production and maintenance, irrigation, fertilizers, grow lights, and pitch-care equipment,
- hotels for teams, staff, media, officials, and spectators,
- food, packaging, waste management, and single-use materials,
- urban transport, security vehicles, buses, and operational fleets,
- fan merchandise, clothing, flags, signage, and promotional materials,
- media infrastructure, temporary offices, data systems, and broadcast compounds,
- fan festivals and side events,
- carbon-offset programs, with a critical question: are offsets additional, verified, durable, and not used as an excuse to avoid real reductions?

A useful final task for students is to propose three practical actions for a host city. For each action, they should state which emission source it reduces and why. Strong answers may include transit passes with tickets, low-emission shuttle fleets, clear fan travel guidance, renewable electricity procurement, food-waste reduction, reusable service systems, and transparent reporting of assumptions.

Table 7) Curriculum connections

Grade / level	Subject	Curriculum idea	Connection to the problem
Grades 7-9	Mathematics	Ratios, percentages, unit conversion, multi-step multiplication	Calculating emissions from people, distance, and emission factors
Grades 8-10	Science	Energy, resources, human impacts on ecosystems	Connecting major sports events with greenhouse gas emissions
Grades 9-11	Geography / Social Studies	Maps, distance, transport, city and region	Understanding how host-city geography shapes travel demand
Grades 10-12	Environmental Science	Carbon footprint, sustainability, transport, resource use	Comparing team travel, spectator travel, and wider event operations
Grades 10-12	Business / Management	Planning, constraints, scenarios, decision-making	Explaining why teams and host cities need multiple travel and operations scenarios
Grades 11-12	Technology / Engineering	Measurement, sensors, data systems, uncertainty	Distinguishing direct measurement from activity-based estimation

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Magnus Effect in Football

Abstract

A curving free kick is not magic. It is a combination of a player's technique, the ball's spin, the surrounding air, and the surface design of the ball. In this problem-based article, students use a two-stage model to study why a spinning soccer ball may seem to travel almost straight at first and then bend more clearly near the goal. The calculations connect geometry, force, acceleration, time, and sideways displacement. The article also links the physics of the Magnus effect to modern World Cup ball design, including seams, surface texture, and flight stability.

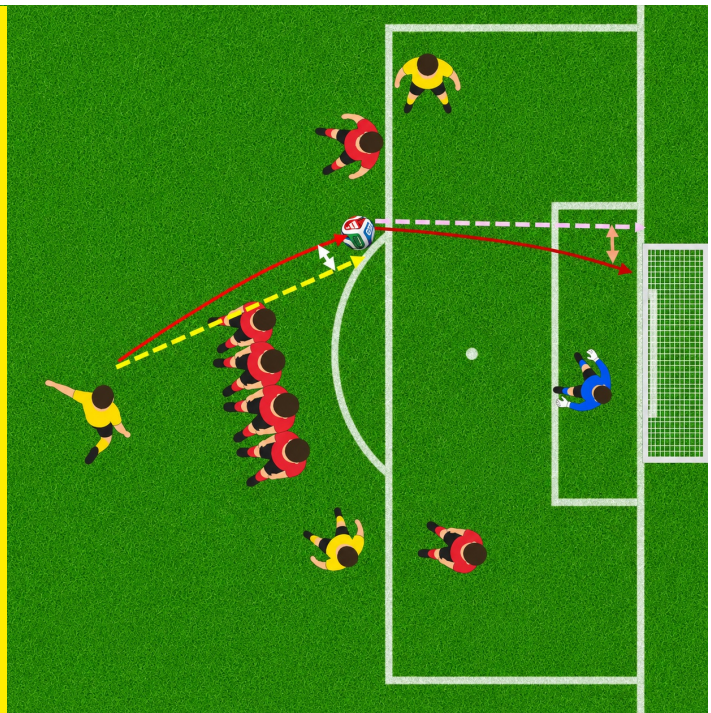
Data and modelling note. The numerical values in this article are not official measurements from a specific match. They are chosen to create an educational model that is close enough to real physics to be meaningful, while still remaining calculable for students. More advanced models would solve the equations of motion with drag, lift, spin decay, wind, and continuously changing aerodynamic coefficients. Here, we use a two-stage model so students can see why the bend of the ball may become more visible in the final part of its flight.

1) Context: modern balls and aerodynamics

The official match ball of the FIFA World Cup 26 is Trionda. FIFA describes the ball as having a four-panel construction, deeper seams intended to support in-flight stability, and connected-ball technology with a 500 Hz motion sensor chip that sends movement data to the Video Assistant Referee (VAR) system [1]. This matters for a lesson on free kicks because the path of the ball is not determined by the player's foot alone. Spin, seams, roughness, air flow, and surface design all influence the final motion of the ball. Aerodynamic studies of soccer balls also show that panel shape and surface grooves can affect drag, flow separation, and flight stability [2].

Figure 1) Educational trajectory diagram of a two-stage curving free kick

The red curve shows the modelled ball path, the yellow dashed line shows the early predicted path, the purple dashed line shows the forward distance toward the goal, the pink marker shows the late sideways displacement, and the small white arrows highlight where the curve becomes more noticeable. Because the early path appears nearly straight, the goalkeeper may predict the wrong final position before the bend becomes obvious.



2) Introduction

In a curving free kick, the player does more than kick the ball forward. The player also gives the ball spin. A spinning ball changes the air flow around itself and can experience a sideways aerodynamic force. This is commonly called the Magnus effect.

The National Aeronautics and Space Administration (NASA) explains the general lift equation as a way to represent aerodynamic force using air density, speed squared, a reference area, and an experimentally determined coefficient [3]. NASA also explains that a spinning ball can turn the surrounding flow of air and generate lift; the details are complex, but the core idea is that rotation changes the air flow around the ball [4].

For a soccer ball, the sideways-force coefficient is not a universal constant. It depends on speed, spin, surface roughness, seams, panel shape, and the state of the air flow. In trajectory-analysis research, lift coefficients for soccer balls have been extracted from measured flight paths, showing that the path itself can be used to study the sideways force on a spinning ball [5]. A separate study of the famous Roberto Carlos free kick showed that a spinning ball travelling over a long enough path can reveal a spiral-like trajectory; as speed decreases while spin remains important, the bend may become more visible later in flight [6].

Figure 2) Simplified airflow and force diagram for a spinning soccer ball

In this simplified top-view diagram, the yellow arrow shows the sideways Magnus force. The force is perpendicular to the ball's forward motion and depends on the spin direction.

Light orange arrow (v): direction of the ball's forward motion.

Red arrow (F_D): direction of the aerodynamic drag force.

Green circle with cross (S): spin axis/angular velocity vector, directed into the page.

Blue curved lines: airflow streamlines around the ball

Yellow arrow (F_M): direction of the Magnus force.



3) Problem statement

Suppose a player takes a free kick from 30 m away from the goal. At first, the ball seems to travel slightly outside the direct line to the goal. It passes the defensive wall and then bends back toward the goal. The goalkeeper sees only the early part of the path and must predict the future position of the ball very quickly. To model this, divide the flight into two 15 m stages.

Table 1) Data for the educational model

Parameter	Value	Use in the model
Mass of the ball, m	0.43 kg	Used in Newton's second law
Radius of the ball, R	0.11 m	Used to find cross-sectional area and spin parameter
Air density, ρ	1.20 kg/m ³	Used in the Magnus-force model
Free-kick distance	30 m	Total distance from kick to goal
Stage 1 distance and mean speed	15 m at 30 m/s	Early part of the flight
Stage 2 distance and mean speed	15 m at 22 m/s	Later, slower part of the flight
Effective sideways coefficient in Stage 1, C_{L_1}	0.06	Smaller visible bend
Effective sideways coefficient in Stage 2, C_{L_2}	0.14	More obvious late bend
Approximate spin rate, f	10 revolutions/s	Used to compute angular speed

In this model, the effective sideways coefficient is larger in Stage 2. This represents the idea that the ball has slowed down, the spin remains important, and the sideways effect becomes more visible to the goalkeeper. This is an educational simplification, not a full computational-fluid-dynamics simulation.

Formula guide for the problem

The formulas below are included so that students do not need to know every relationship in advance.

$$A = \pi R^2$$

A is the cross-sectional area of the ball facing the air flow, and R is the ball radius.

$$\omega = 2\pi f$$

This converts spin rate f , in revolutions per second, into angular speed ω , in radians per second.

$$S = \omega R / v$$

S is the spin parameter. It compares the surface speed caused by spin with the forward speed of the ball. If the forward speed v decreases while spin does not decrease as quickly, S increases.

$$F_M = 1/2 \rho v^2 A C_L$$

F_M is the simplified sideways Magnus force. ρ is air density, v is ball speed, A is cross-sectional area, and C_L is an effective sideways-force coefficient.

$$a = F_M/m$$

Newton's second law in sideways form converts sideways force into acceleration.

$$t = d/v$$

This estimates the time required to travel a stage of distance d at mean speed v .

$$y_1 = 1/2 a_1 t_1^2$$

This estimates Stage 1 sideways displacement, assuming zero initial sideways speed.

$$y_2 = v_{y_1} t_2 + 1/2 a_2 t_2^2$$

In Stage 2, the ball already has a sideways speed from Stage 1, so the Stage 2 displacement has two parts: continued sideways motion plus new sideways acceleration (v_{y_1} is the sideways speed gained during Stage 1.).

Questions

- Use $A = \pi R^2$ to calculate the cross-sectional area of the ball. In this formula, R is the radius of the ball and A is the area facing the air flow.
- Use $\omega = 2\pi f$ to calculate the angular speed of the ball. Then use $S = \omega R/v$ to calculate the spin parameter in Stage 1 and Stage 2. Explain why S increases when the forward speed decreases.
- Use $F_M = 1/2 \rho v^2 A C_L$ to calculate the sideways Magnus force in each stage. Then use $a = F_M/m$ to calculate the sideways acceleration in each stage.
- Use $t = d/v$ to find the time for each stage. Then calculate Stage 1 sideways displacement with $y_1 = 1/2 a_1 t_1^2$. For Stage 2, use $y_2 = v_{y_1} t_2 + 1/2 a_2 t_2^2$, where $v_{y_1} = a_1 t_1$ is the sideways speed gained during Stage 1.
- Use percentage = $100 \times y_2/(y_1 + y_2)$ to find what percentage of the total sideways displacement occurs in Stage 2. How does this help explain why a goalkeeper may be deceived?
- If the sideways coefficient stayed at 0.06 for the whole flight, how would the total sideways displacement change?
- In one paragraph, explain why surface design, seams, and roughness are not only visual design choices but can influence free-kick control.

4) Solution

a) Cross-sectional area of the ball

$$A = \pi R^2 = \pi(0.11)^2 \approx 0.038 \text{ m}^2$$

b) Spin parameter

The spin parameter compares the surface speed caused by rotation with the forward speed of the ball ($S = \omega R/v$). At 10 revolutions per second, the angular speed is:

$$\omega = 2\pi \times 10 \approx 62.8 \text{ rad/s}$$

$$S_1 = (62.8 \times 0.11)/30 \approx 0.23$$

$$S_2 = (62.8 \times 0.11)/22 \approx 0.31$$

The spin parameter increases in Stage 2 because the forward speed has decreased. This means the relative importance of spin is greater in the later part of the flight.

c) Sideways force and sideways acceleration

Using the simplified Magnus-force model, $F_M = 1/2\rho v^2 AC_L$, we have:

Stage 1:

$$F_1 = 1/2(1.20)(30)^2(0.038)(0.06) \approx 1.23 \text{ N}$$

$$a_1 = F_1 / m = 1.23/0.43 \approx 2.86 \text{ m/s}^2$$

Stage 2:

$$F_2 = 1/2(1.20)(22)^2(0.038)(0.14) \approx 1.55 \text{ N}$$

$$a_2 = F_2/m = 1.55/0.43 \approx 3.59 \text{ m/s}^2$$

d) Time and sideways displacement

$$t_1 = 15/30 = 0.50 \text{ s}$$

$$y_1 = 1/2 a_1 t_1^2 = 1/2(2.86)(0.50)^2 \approx 0.36 \text{ m}$$

At the end of Stage 1, the ball has gained sideways speed:

$$v_{y_1} = a_1 t_1 = 2.86 \times 0.50 \approx 1.43 \text{ m/s}$$

For Stage 2, $t_2 = 15/22 \approx 0.68 \text{ s}$. Therefore:

$$y_2 = v_{y_1} t_2 + 1/2 a_2 t_2^2 \approx (1.43)(0.68) + 1/2(3.59)(0.68)^2 \approx 1.81 \text{ m}$$

$$y_{\text{total}} = y_1 + y_2 \approx 0.36 + 1.81 = 2.17 \text{ m}$$

e) Why the bend can seem late

Stage 2 share = $1.81/2.17 \times 100 \approx 83\%$

About 83% of the sideways displacement occurs in the second half of the flight. The ball may look fairly direct at first, then bend sharply near the goal. The force is not sudden; its effect accumulates, making the sideways motion more visible later.

f) Comparison with a simpler constant-coefficient model

If the sideways coefficient stayed at 0.06, total displacement would be about 1.69 m. In the two-stage model, it is about 2.17 m. Hence, an extra half a metre of sideways displacement ($2.17 - 1.69 \approx 0.48 \text{ m}$) can be the difference between hitting the wall, missing the goal, or reaching the corner of the net.

g) Surface design and free-kick control

The surface of the ball, its seams, and its panel pattern can influence where air flow separates and how drag and sideways force develop. This is why modern World Cup ball design is about more than appearance. The surface must support predictable flight, control, and match technology [1], [2].

5) Educational conclusion

A curving free kick brings together athletic skill and fluid physics. The player must give the ball enough speed, enough spin, and the right direction. The goalkeeper must predict the ball's future position from a short early view of its path.

If most of the sideways displacement becomes visible in the second half of the flight, the goalkeeper's first prediction can be wrong. This is where mathematics, physics, and sport meet in a very visible way.

Table 2) Curriculum connections

Grade / level	Subject	Topic	Connection to the problem
Grades 9–10	Science and Mathematics	Speed, acceleration, force, ratio, and percentage	Calculate travel time, sideways acceleration, and the percentage of bend in each stage.
Grade 11 Physics	Dynamics and forces	Newton's second law and aerodynamic force	Convert Magnus force into sideways acceleration of the ball.
Grades 11–12 Physics	Two-dimensional motion	Motion components and projectile-style modelling	Separate forward motion from sideways displacement.
Grades 10–12 Mathematics	Modelling and functions	Two-stage models and scenario comparison	Compare a constant-coefficient model with a changing-coefficient model.
Physical Education / Sports Science	Skill and performance	Free-kick technique, spin, and goalkeeper decision-making	Connect physical technique with a mathematical model of the ball's path.
STEM / interdisciplinary project	Design and technology	Ball aerodynamics and surface design	Analyse how panels, seams, texture, and connected-ball technology relate to performance and officiating.

6) Extension question

This article used two average speeds and two effective sideways coefficients. If you wanted to make the model more realistic, what would you add? Consider continuously changing speed, gradual loss of spin, wind direction, humidity, altitude of the host city, panel design, surface texture, and the real contact angle of the kick. Which one of these factors do you think would most strongly affect goalkeeper deception? Explain your reasoning.

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Collective Visualization with HAMNAMA

Abstract

HAMNAMA is a design for turning a crowd of spectators into a human display. In this system, each seat, or each spectator, acts like one pixel in a large image. In the simplest version, a selected part of the spectator stands, or even the whole stand, is converted into a grid of image cells. Each spectator receives one assigned color according to their seat number. At the time announced by the program manager or leader, the spectator shows the placard that matches that color. Through the combination of thousands of individual actions, a large image, message, symbol, or face appears in the stadium. This article introduces the development of the HAMNAMA idea and its simple and advanced versions.

1) Introduction

A stadium is not only a place for watching a match. In many major events, spectators become part of the scene through flags, placards, human waves, chants, and coordinated movements. However, turning a large crowd into a precise, coordinated, and controllable image requires a clear, simple, and practical mechanism.

The idea of HAMNAMA begins here. If each spectator can show a specific color or state at a specific time, thousands of spectators can together create an image, message, symbol, or visual pattern. In HAMNAMA, part of the stands is treated as an image grid. Each seat is one cell in this grid, and each spectator acts as a human pixel.

This logic is inspired by digital displays. In a digital image, one pixel alone has little meaning. But when many pixels are placed next to each other, the complete image appears. HAMNAMA transfers this principle to the stadium. For example, if one stadium section has 100 columns and 50 rows, it can become a human grid of 5,000 pixels. Based on the image to be displayed, a visual value, that is, a specific color, is assigned to each seat. This value may be black, white, a shade of gray, or one of the defined colors. At the proper time, and in coordination with other spectators, the spectator displays the assigned color by raising the placard with that color.

As a result, what looks from nearby like a simple color held by one spectator becomes, from a distance, part of a large and coordinated image.

The basic idea of coordinating spectators to raise placards matching the colors assigned to them at the right time is not new. It has been used in stadiums for many years. The innovation in HAMNAMA lies in two areas: new methods for quickly informing each spectator of the color they must show, and suitable placards that allow rapid color changes. Together, these two features can produce very large and artistic images in a short time. Once spectators become familiar with HAMNAMA, it is reasonable to imagine large stadium animations created by the spectators themselves.

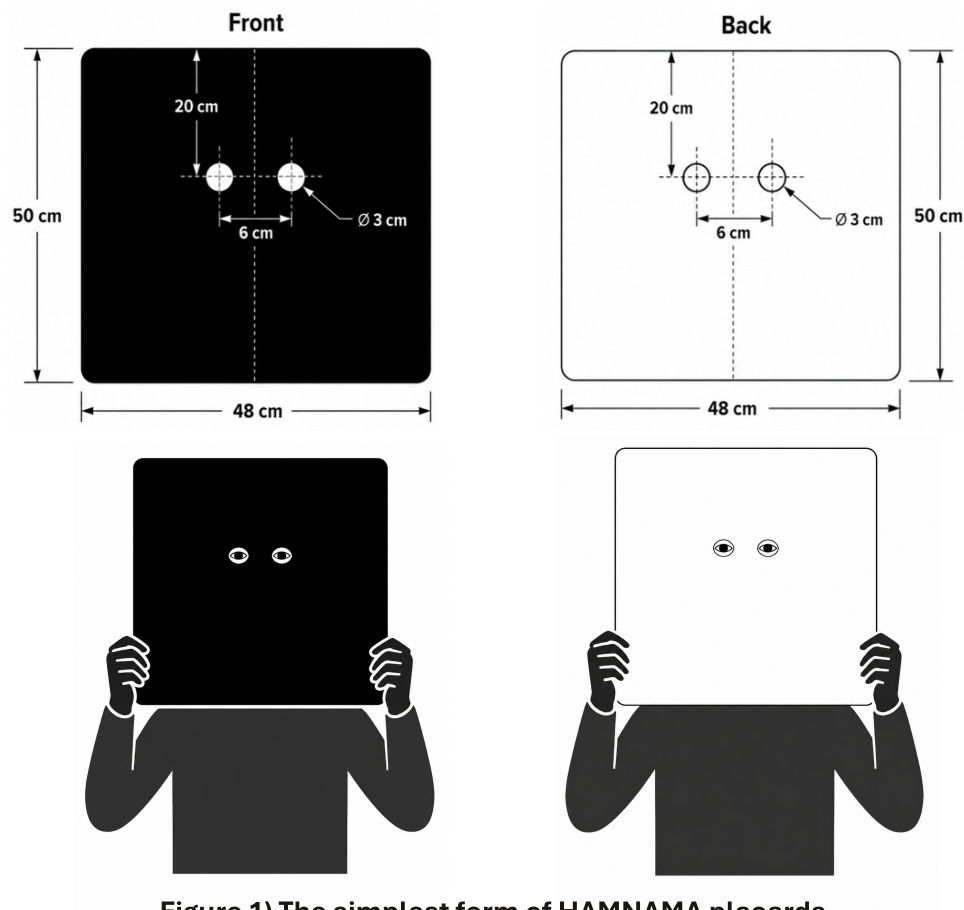


Figure 1) The simplest form of HAMNAMA placards

This article explains, step by step, the two specific features of HAMNAMA: the design of suitable placards that can change color quickly, and the methods for informing each spectator which color to show.

2) Design of HAMNAMA placards and the mechanism for rapid color change

One part of HAMNAMA concerns the physical tool used to display color. This is the object that the spectator raises at the announced time to show the color assigned to their seat. This tool must meet several basic needs. It must show the color clearly from a long distance. It must be easy for the spectator to use. It should disturb the spectator's view as little as possible. If needed, it should also allow the spectator to change color quickly. In the simplest form, a double-sided placard can be used. The proposed size for each placard is about 48 centimeters wide and 50 centimeters high. The placard includes two viewing holes, each about 3 centimeters in diameter. The center of each hole is about 20 centimeters from the upper edge of the sheet. The two holes are symmetrical around the vertical centerline of the sheet, and the center-to-center distance between them is about 6 centimeters. These holes allow the spectator to continue seeing the field or the coordination signals while holding the placard in front of the face.

Each simple placard can show two colors, because its two sides can have different colors. For example, if one side is white and the other side is black, the same placard is enough for a two-color display. If four colors are defined for a HAMNAMA design, two double-sided placards are needed.

This method is simple and low-cost to produce. However, it has an important practical limitation. Every time a spectator must show a new color, they may need to choose the correct placard from several placards or find the correct side of a placard. This process can be slow and prone to error, especially in multi-stage or fast displays.

To reduce decision time and increase the speed of color change, a simple mechanism called the “flipbook technique” can be used. In this method, the placard is designed like an opening notebook or folder. When fully open, the cover has a total size of about 48 centimeters wide and 50 centimeters high. The internal pages are each about 24 centimeters wide and 50 centimeters high. They are attached around the central axis of the cover and can turn left or right like pages of a notebook. This central axis is the line that connects the two halves of the cover.

Each page, including the cover, has one viewing hole with a diameter of about 3 centimeters. The center of this hole is about 20 centimeters from the upper edge of the page and about 3 centimeters from the turning axis. With this arrangement, when a page lies over one half of the cover, its hole aligns with the hole on that half of the cover. The spectator can therefore still see through the placard.

The key principle is that two adjacent surfaces must have the same color. In other words, whenever a page lies over the inside of the cover or over another page, the two surfaces visible from the front must together form one single color. Therefore, the color order of the pages must be planned so that every flipped position creates a unified front surface.

The simplest example is a two-color placard with only one moving page. Suppose one side of this moving page is white and the other side is black. These are the only two colors that the spectator must show. In this case, the half of the inside cover next to the black side of the moving page is also black. The half next to the white side is also white. When the page is turned to one side, the two visible surfaces create a black display. When the same page is turned to the other side, the two visible surfaces create a white display. In this way, the spectator can switch from black to white, or from white to black, with only one simple page-turning motion.

This method can also be expanded to include more colors. For example, Figure 3 shows how green can be added to the white and black colors in a HAMNAMA placard.

By adding pages and carefully arranging the color order, the spectator no longer needs to choose from several separate placards. They only need to flip the pages until the two adjacent surfaces with the required color face outward.

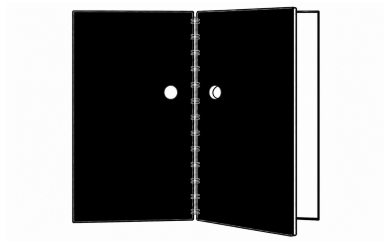
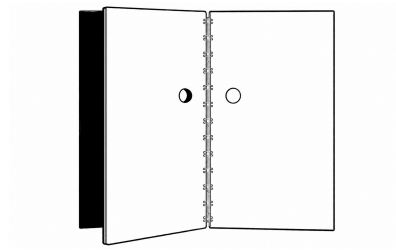
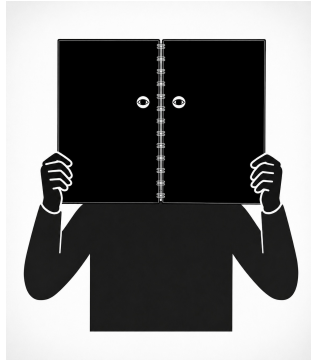
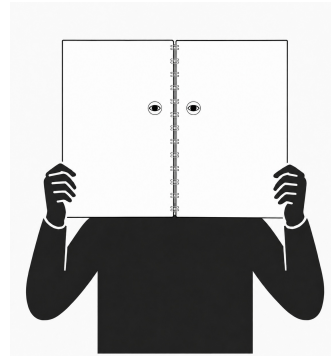


Figure 2) Two-color flipbook form of HAMNAMA placards

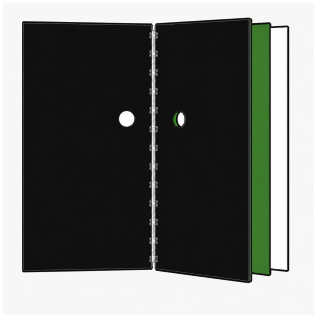
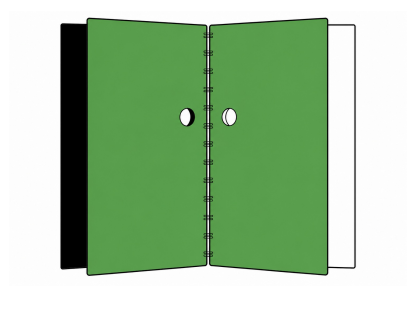
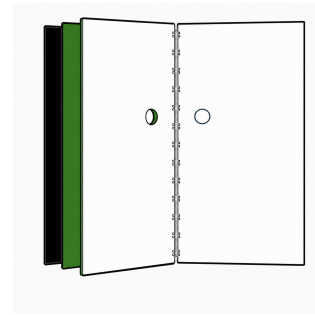
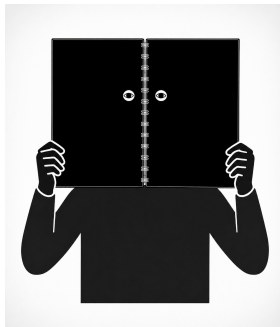
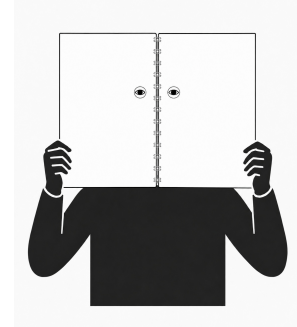


Figure 3) Three-color flipbook form of HAMNAMA placards

This mechanism increases the speed of color change, reduces the chance of choosing the wrong color, and makes multi-frame or faster HAMNAMA displays more practical. Overall, the design of HAMNAMA placards must balance several needs: clear color visibility from a distance, simple construction, easy use, preservation of the spectator's view, and rapid color change. A double-sided placard is the simplest solution. For more dynamic displays, however, the flipbook technique can provide a low-cost, mechanical, and easy-to-understand mechanism that greatly improves the system. For placards that change color by page turning, an elastic strap attached to the back of the placard can hold it steadily on the face like a mask. This allows the spectator to change colors very quickly and can even make large moving images possible in stadiums.



Figure 4) Hands-free HAMNAMA placard concept

This conceptual illustration shows the HAMNAMA placard in front of the spectator's face. Dimensions, binding, and attachment details are schematic. This is a conceptual illustration. Any hands-free version would require safety testing and venue approval.

3) Methods for informing spectators of their colors

In a simple HAMNAMA implementation, before each stadium display, the intended image or message is converted into an image grid. In a proper implementation, the number of available colors and the physical form of the stadium are especially important in this conversion.

Each cell of the grid is assigned to a specific seat or location in the stadium. Then a display value is assigned to each seat. This value may be one of the defined colors, such as white, black, several shades of gray, or a set of colors such as red, blue, yellow, green, white, and black. Therefore, in each event, the number and type of colors are determined in advance according to the image design, the practical resources, and the type of placards.

After this step, the main issue is how to deliver the color information to the spectator in the simplest, most reliable, and clearest way. Several levels of information delivery can be used.

3-1) Information delivery through the ticket

The simplest and most static form of HAMNAMA is to print each spectator’s color or display code directly on their ticket. At the display moment, announced by a leader, loudspeaker, countdown, stadium screen, drum, spotlight, or another coordination signal, the spectator already knows which color to show and displays the placard with that color. More than one HAMNAMA display can also be planned for a single match. In that case, the ticket can list the instruction for each display separately. For example, the spectator whose ticket is shown in Figure 5 knows that they will participate in three HAMNAMA moments during the event. In the first and third moments, when the display is announced, they must show the red placard. In the second moment, they must show the blue placard. The image that will be created through their participation and the participation of other spectators is also shown on the ticket.

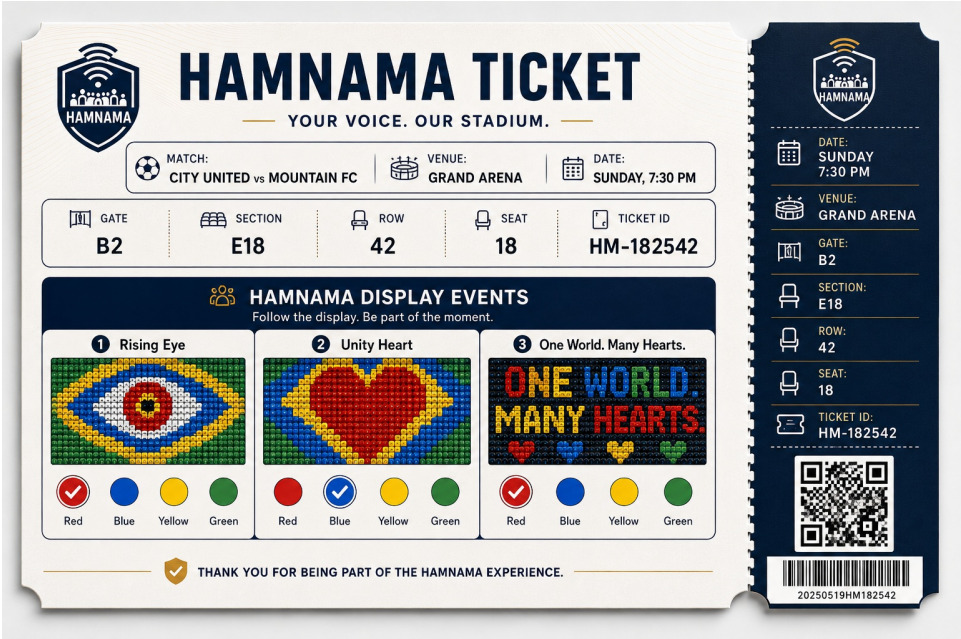


Figure 5) Informing each spectator of their placard color through the ticket

The advantage of this method is its simplicity and low cost. The spectator does not need a phone, internet access, or a website login. Its main limitation is that the information printed on the ticket is fixed. Therefore, this method is more suitable for one static image or a very small number of predefined frames. If the image needs to change several times during the match, the ticket alone is not flexible enough, unless several timed instructions are printed on it. This method also cannot create images in response to live events that happen on the field.

3-2) Information delivery through the HAMNAMA website

A more flexible method is to use a HAMNAMA website or web app. In this model, the spectator enters the website with a phone, selects the event, and enters their seat number. The system then shows the color or display instruction for that seat.

The website may give only one simple instruction, such as “Show white in Frame 1” or “Your color in this display is Gray 2.” It can also provide more information, including:

- the event name,
- a short explanation of the design,
- the timing of the frames,
- the color for each frame;
- instructions for using the placard or mask,
- safety and operational messages,
- the spectator’s approximate position in the complete image.

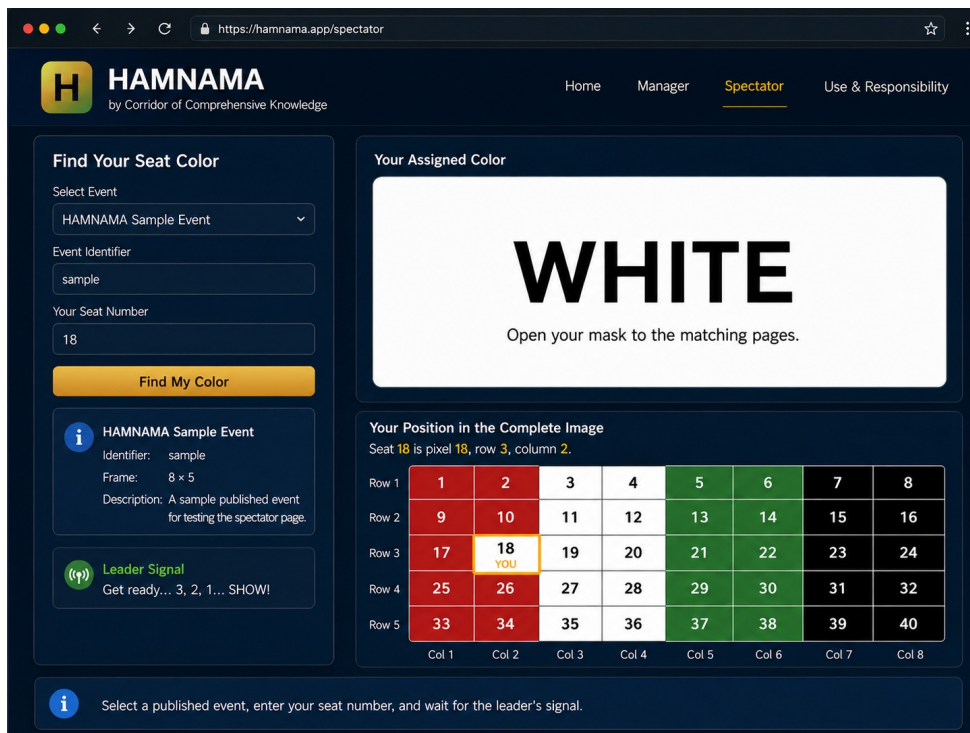


Figure 6) The HAMNAMA information website

The main advantage of the website is that the information can be updated. If the organizer decides to adjust the design, change the display time, or add new frames, the information can be changed in the system. At the same time, the spectator only needs to enter their seat number to receive the exact instruction assigned to them. This method is well suited to early versions of HAMNAMA. It remains relatively simple, does not require special equipment, and provides more flexibility than the ticket method.

3-3) Information delivery through an application and data packages

At a more advanced stage, a dedicated HAMNAMA application can be used. In this case, the spectator enters their seat number in the app. The application receives data from the event management center and automatically displays the color or instruction assigned to that seat. In this model, the system manager can publish data packages for different images or frames. Each package defines which color each seat must show at each moment. The spectator's application extracts only the part related to that seat and shows it to the user. This method is more suitable for multiple frames, rapid image changes, or even collective animations.

The app can also provide a countdown, sound alert, vibration, or visual guidance. For example, a few seconds before the frame changes, the phone can warn the spectator and then show the new color. This reduces human error and improves collective coordination. In an app-based HAMNAMA system, where permitted and with approved secure holders, each spectator can mount their phone on the back of the seat in front of them. In this way, the phone screen remains in front of their eyes, and they can immediately see which color they must show.

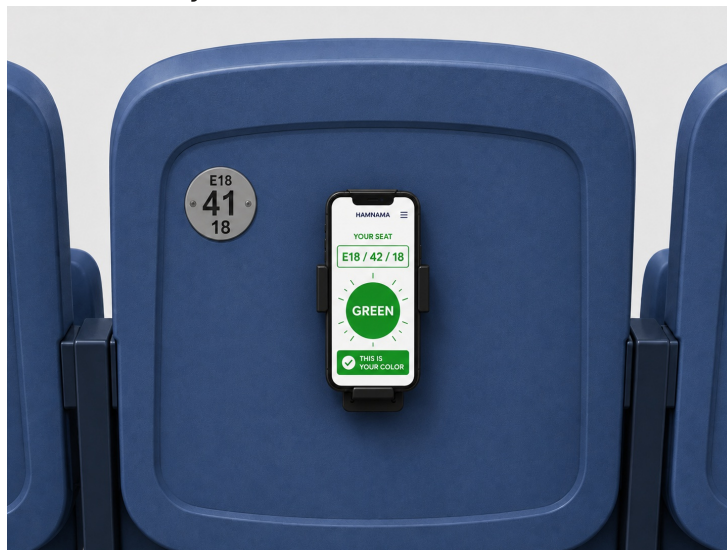


Figure 7) Information delivery through the application

The mounted phone displays the assigned color for the spectator seated in the row behind this seat. The seat number shown on the phone identifies the user's seat, while the number on the seat back identifies the seat on which the phone is mounted.

3-4) Information delivery through smart equipment, IoT, RFID, or similar systems

At a more advanced level, part of the information process can be separated from the spectator's phone or decision-making and transferred to smart equipment. In this model, an electronic component is installed on the seat, placard, wristband, card, mask, or another object carried by the spectator. This component may include a seat identifier, wireless receiver, RFID module, Bluetooth connection, Wi-Fi, local network connection, or any other suitable technology.

In this method, the event management center sends color commands to the equipment. Each device receives the color assigned to its own seat or spectator according to its identifier. Then an LED light, small display, or color indicator on the device turns on and tells the spectator which color to show with the placard or mask. In some versions, the device itself may directly display the required light or color.

This model is very powerful for coordination, because it gives more control to the central management system. For fast, multi-stage, or highly precise performances, such a system can reduce error. However, compared with the ticket or website methods, it requires more cost, equipment, technical support, maintenance, safety testing, battery management, network communication, and operational coordination.

The choice of information method in HAMNAMA depends on the purpose of the performance, the budget, stadium capacity, number of frames, number of colors, expected level of participation, and complexity of the design. In the simplest case, the ticket and a display-time announcement are enough. In a more flexible case, the website or web app can provide exact information for each seat. In more advanced versions, an application, data packages, the Internet of Things, RFID, or smart equipment can turn HAMNAMA into a coordinated and dynamic system.

Spectators' familiarity with HAMNAMA and its use can increase collective participation and the joy of creating beautiful moments together. HAMNAMA, by its nature, can greatly expand what is possible in a stadium. For example, imagine a very important national match in which all 70,000 spectators in the stadium volunteer to participate in HAMNAMA images. Also suppose that the system manager can receive authorized video footage of the match and convert selected frames into HAMNAMA images. The manager selects five frames of the national team goalkeeper making a long dive to stop a very difficult shot. By sending these frames to the spectators at intervals, the spectators reconstruct that moment across the stands.

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**“I will write of my life as a footballer as if it were
a love story, for who shall say that it is not?”**

Ferenc Puskás

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