

Analyzing the beautiful game with simulation

Modeling and simulation reveal how sensor strategies, stadium acoustics, and ball design influence the outcomes of the 2026 FIFA World Cup®.

Ed Fontes

What do a bending free kick, a data-driven substitution, and the roar of a packed stadium have in common? All rely on physical phenomena that can be explored through modern modeling and simulation, offering new insights into the science behind the 2026 FIFA World Cup®.

In minute 98 of the U.S. team's home-opening World Cup match this year, Gio Reyna shot the ball with the outside of his foot to score a goal that solidified the U.S.'s 4:1 upset over Paraguay. While Reyna used a delicate touch to create the late-bending, deceptive arc of this particular trivela, it was players like Nelinho, Éder, and Roberto Carlos who first elevated the „power trivela“ to an art form by combining this finesse with a more aggressive run-up and explosive strike. Whether missile-like or feather-light, the trivela owes its signature curved trajectory to the Magnus effect. While factors like how the player strikes the ball of course make a difference in the trajectory, the design of the official match ball also plays a big role in how these shots behave.

The 2026 Adidas Trionda® ball

At high speeds like those induced by a power trivela, the boundary layer around a football transitions to turbulent flow, making the separation points on the two sides of a spinning ball more symmetric. Since the Magnus effect relies on asymmetry in the flow, the influence of spin is reduced in this regime, and the ball travels almost in

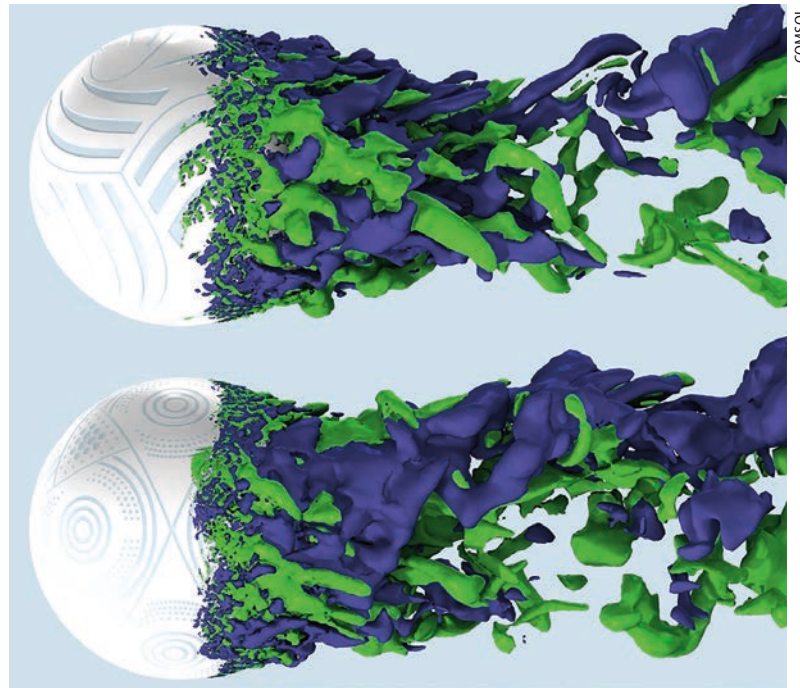


Fig. 1 The wakes of the Trionda (top) and the Fussballliebe (bottom) show similarly early detachment behavior.

a straight line, despite the spin. As the ball slows down, the Reynolds number decreases and the boundary layer transitions toward laminar flow. The separation points shift, the asymmetry increases, and the ball begins to curve more strongly.

For balls like the Adidas Jabulani®, the highly controversial match ball of the 2010 World Cup, this transition, or drag crisis, occurs at relatively high speeds – leading to late and sharp deviations in the trajectory that make shots extremely difficult for goalkeepers to predict. Later match balls, like the Adidas Fussballliebe® used for the Euro in 2024, were designed to maintain a turbulent boundary layer even at lower speeds, which shifts the low

drag region further into the low speed regime. As a result, these balls do not decelerate as quickly as the Jabulani. According to Harry Kane, the Fussballliebe “stays hit” [1]. Instead, the latest match balls exhibit less dramatic late movement and more predictable trajectories. Wind tunnel experiments showed that the official match ball of the 2026 World Cup, the Trionda, followed this trend, retaining turbulent flow down to very low speeds [2].

In large eddy simulations (LES) of the wakes of the Trionda and the Fussballliebe, the boundary separation line can be identified relatively early downstream of the vertical equator for both match balls (Fig. 1).

The computed drag coefficient at 20 m/s is approximately 0.17, in good agreement with experimental data [2]. This is slightly lower than the value computed for the Fussballliebe, 0.19.

According to FIFA's Technical Study Group, the 2026 World Cup saw 16 % of all goals scored kicked from outside the penalty area, up from 8 % in the 2022 World Cup (although the number of shots from outside the penalty box remained the same). Similarly, at Euro 2024, a record 16.2 % of all goals came from such shots. The results of our Computational Fluid Dynamics (CFD) simulations help explain this recent increase in long-range goals: Both the Fussballliebe and the Trionda showed a stable boundary layer and relatively low drag at moderate speeds, yielding more predictable flight behavior and longer-lasting velocity. In practical terms, this means that players could shoot both tournaments' match balls with greater power and accuracy from outside the box.

Friction and the trivela

The most recent tournament match balls also feature a noticeably rougher surface texture than that of traditional 32-panel balls, making it feel easier to strike them cleanly. But is this only a psychological effect? According to a modeling and experimental investigation by Ishii et al. on curved shots taken with the inside of the foot, the friction between the shoe upper and the ball has only a limited effect on the ball velocity and spin [3]. To investigate the effect of friction, we used the new explicit dynamics functionality in COMSOL Multiphysics® to set up our own model of a power trivela taken with the Trionda. For the boot, we modeled the Adidas® F50 Elite Laceless worn by many top players for this year's World Cup, including Lamine Yamal. This

boot provides excellent contact between the ball and the foot, not only for a pure instep shot but also for a power trivela.

While the ball in the background of the frames in Fig. 2, with high friction, clearly rotates, the frictionless trajectory seen in the foreground is much more lateral and shows essentially no curl. Without friction, the ball slips across the foot and very little spin is generated. The exit velocity also decreases significantly, from about 34 m/s in the high-friction case to approximately 24 m/s without friction.

These simulations show that, unlike with curved shots taken with the inside of the foot [3], in the trivela, the off-center, slicing impact makes friction a key factor in generating both spin and speed. Friction becomes even more important in a real game situation, where the ball is often already moving and strikes are not perfect.

Tracking performance

In thinking back to some of the most memorable moments from the 2026 World Cup, it's clear that

the impact of imperfection on real game situations is not limited to the behavior of the ball itself. In the beautiful game, coaching and refereeing are two imperfect sciences that have long fueled fans' ardor ... and antipathy. At this year's cup, new motion sensor technology embedded in the Trionda and in the vests that players wore under their jerseys changed the game for coaches and VAR staff. Decisions informed by real-time tracking and analysis played a decisive role in match outcomes.

During Sweden's 5:1 group stage thrashing of Tunisia, for example, a tip-of-the-toe touch made by a teammate between Mattias Svanberg's shot on goal and the free kick that served it to him was detected by the sensors inside the ball. Because the sensors, designed to detect even miniscule changes acceleration and angular velocity, could determine the exact moment of contact, the VAR team was able to establish that Svanberg was no longer in an offside position when his teammate touched the ball. The goal – which was initially disallowed – was therefore allowed to stand.

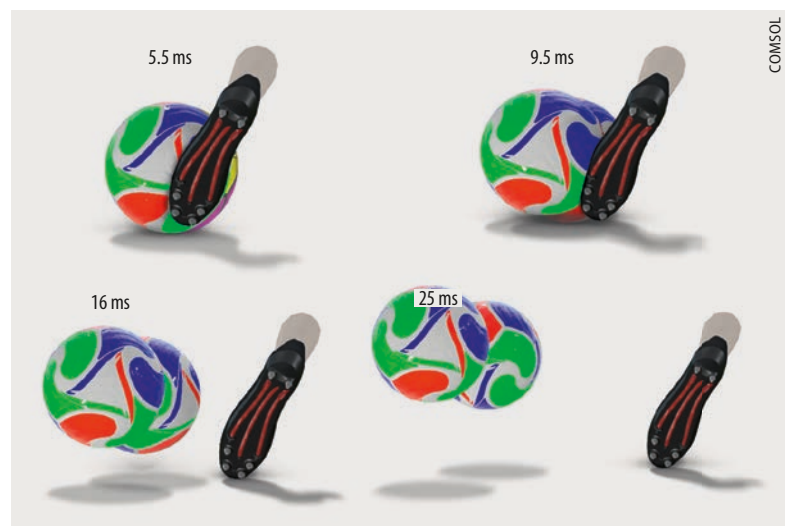


Fig. 2 The figure shows the trajectory of a trivela at 5.5, 9.5, 16, and 25 ms after impact for two simulations, one with a friction coefficient of 0.5 (background in all frames) and one with a friction coefficient of 0 (foreground).



Fig. 3 The “user interface” displays data from the vest of the player “John Doe.” The heat map reveals that the player is an attacking central midfielder, since there are few defensive high-speed sprints. The heat map almost always shows the attacking direction from left to right.

Because Svanberg had come off the bench mere seconds before the play, the goal was argued by some to be the result of a coaching coup for the Swedish side. Armed with data extracted from the players’ vests, coaches in the 2026 World Cup were able to make more strategic decisions about substitutions and other aspects of gameplay than ever before. Thus, during the game, the coaching staff was able to view in real time the data transmitted by a player’s vest (for a fictional player see **Fig. 3**). If the player was, for example, taking fewer sprints with lower acceleration and showing other signs of fatigue, the coach might decide to substitute him.

After the game, the coaches might use this heat map to analyze how the player moved across the pitch and make tactical adjustments. For example, if the heat map showed good possession statistics and a high number of offensively successful crosses from one side of the pitch (“field”) for a central midfielder, the coaches might decide

that the player should prioritize attacks on this side while remaining more central when defending.

The enabling technology of the sensors in the ball and player vests, including MEMS accelerometers, gyroscopes, magnetometers, and RF communication systems, can

all be analyzed and optimized using modeling and simulation. For example, the 500-Hz inertial measurement unit (IMU) embedded in the Trionda contains MEMS sensors that measure the motion of the ball [4]. COMSOL Multiphysics is widely used for modeling and designing these types of MEMS and related devices, from the mechanical behavior of microscopic sensing structures to their interaction with electromagnetic fields and surrounding electronics.

Stadium acoustics

While sensor technology has transformed the way fans experience the game, nothing compares to watching football live in a stadium, where the roar of the crowd rattles your seat and reverberates through your chest. To ensure that fans can hear public-address announcements loud and clear over this wall of sound, FIFA imposes strict audio requirements for stadiums, including a minimum Speech Transmission Index (STI) of 0.55 in a full stadium, a maximum reverberation time of 4 s over the frequency range from 125 to 4000 Hz, and a maxi-



Fig. 4 A sound-pressure-level map reveals the acoustic field in a plane above the seating area and below two loudspeakers.

mum sound-field non-uniformity of ± 3 dB in the stands.

To meet these requirements, a completely new sound system was installed in Mexico City's iconic Estadio Azteca, host of five World Cup matches this summer. In anticipation of how the new system would sound to fans in the stadium, the COMSOL team simulated the acoustic wave propagation from one of the system's speaker arrays.

The team used built-in tools in COMSOL Multiphysics® to construct the model geometry from photographs and published loudspeaker specifications. Using multiple modeling approaches allowed the team to generate an accurate picture of the quality of the sound at the Azteca. In the low-frequency regime, where wave phenomena such as diffraction play an important role, the acoustic field was modeled using a wave-based method in the time domain. As the analyzed frequency increases, the computational cost also increases, so representing high-frequency sound as rays is often more efficient. To do this, the team first computed the radiation pattern of a simplified loudspeaker cluster using the boundary element method. This radiation pattern was then used as the source definition in a ray acoustics model to estimate the sound pressure field generated by a single loudspeaker cluster (Fig. 4).

The impulse response, reverberation time, and speech transmission index could also be computed using this model. And to estimate the full acoustic coverage in Estadio Azteca, all of the stadium's loudspeaker clusters could be placed throughout the model.

While no one from the COMSOL team was fortunate enough to experience the "sound of the giant" in person and compare it with the simulation results, TV viewers at home reported that the PA system was used to full, chill-inducing effect when announcing Memo Ochoa's historic substitution in his sixth World Cup:

Loudspeaker announcer: "Cambio por México. Entra con el número trece... Guillermo..."

*Crowd: "...¡OCHOA!"
"Memo..."
"...¡OCHOA!"*

And the crowd went wild.

For the love of the game (only!)

Although the models presented here are based on state-of-the-art simulation methods, they are intended for illustration. Comprehensive scientific studies would require a more systematic investigation of parameters and validation against experimental measurements.

These simulations were performed independently and are not associated with FIFA, Adidas, or Estadio Azteca.

For more examples of simulation in football, see our posts on the COMSOL Blog: comsol.com/blog.

*

Adidas, Fussballliebe, and Trionda are registered trademarks of adidas AG. Jabulani is a registered trademark of adidas International Marketing B.V. FIFA World Cup is a registered trademark of the Federation Internationale de Football Association. COMSOL AB and its subsidiaries and products are not affiliated with, endorsed by, sponsored by, or supported by any of the foregoing trademark owners.

References

- [1] C. Davis, The New York Times, 16. Juni 2024; <https://tinyurl.com/yrdwxbnd>
- [2] J. E. Goff et al., Appl. Sciences **16**, 2808 (2026)
- [3] H. Ishii, Y. Sakurai, and T. Maruyama, Sci. Rep. **4**, 6067 (2014)
- [4] RootedintheGame, The technology inside the Adidas Trionda 2026 FIFA World Cup ball, <https://www.youtube.com/shorts/qeSY-4HX4Uc>

Contact

Ed Fontes,
VP of Product Development,
COMSOL AB;

Dr. Phillip Oberdorfer
Comsol Multiphysics GmbH
Robert-Gernhardt-Platz 1
37073 Göttingen
Tel: +49 (0) 551 99721 0
E-Mail: info@comsol.de
Website: www.comsol.de

Loooooong Coherence

Ultra-stable clock laser systems



toptica.com/fidelity

