RT Racing: Perception-Oriented Hybrid Reflection Switching for a Real-Time Racing Game

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Abstract.* *Introduction: *Real-time Ray Tracing (RT) improves reflection fidelity in digital games, but its computational cost remains challenging for interactive applications. In fast-paced racing games, motion, camera displacement, and player focus may reduce the perceptual relevance of high-precision reflections in peripheral or transient regions.* ***Objective:*** *This paper presents RT Racing, an Unreal Engine 5 prototype for investigating perception-oriented hybrid reflection switching in a real-time racing game.* ***Methodology:*** *The prototype supports four configurations: full Ray Tracing, Screen Space Reflections (SSR), a hybrid reflection mode, and a low-quality baseline. We combine spatial analysis of rendering complexity using Unreal Engine diagnostic view modes with a user evaluation involving 15 participants, who assessed visual fidelity, reflections, lighting, perceived stability, and gameplay-related aspects.* ***Results:*** *The hybrid mode achieved perceptual scores close to RT Full and SSR, while the low-quality baseline received consistently lower evaluations. Observations suggest that dynamic lighting, reflective surfaces, environmental diversity, and performance feedback supported engagement, whereas interface legibility, lap feedback, vehicle physics, and NPC recovery remained limitations. The results provide preliminary evidence that perception-oriented hybrid reflection strategies can help balance visual quality and rendering cost in racing games.*
Keywords *Ray Tracing, Screen Space Reflections, Hybrid Reflection Switching, User Perception, Perceived Performance, Real-Time Rendering, Racing Game*

1. Introduction

Real-time Ray Tracing (RT) has substantially improved the visual fidelity of reflections and lighting in digital games. However, its computational cost remains a major challenge for interactive applications, especially when scenes include dynamic objects, reflective materials, dense geometry, and frequent camera movement [Whitted 1980, Kajiya 1986, Parker et al. 2010, Haines and Akenine-Möller 2021]. To maintain acceptable frame rates, modern game engines often combine rasterization, Screen Space Reflections (SSR), denoising, acceleration structures, and selective RT effects within hybrid rendering pipelines [Barré-Brisebois et al. 2019, Marrs et al. 2021, Tan et al. 2022].

Although hybrid rendering is widely adopted, deciding when and where to use expensive RT effects is still a relevant problem in game graphics. Many solutions rely on static quality presets or manually tuned parameters, with limited consideration of the gameplay context and of what the player is likely to perceive during interaction. This is particularly relevant in fast-paced racing games, where camera displacement, motion blur, and the player's focus on the road may reduce the perceptual importance of high-precision reflections in peripheral or transient regions of the image.

This paper presents RT Racing, an Unreal Engine 5 prototype for investigating perception-oriented hybrid reflection switching in a real-time racing game. The prototype compares four visual configurations: RT Full, SSR, Hybrid, and Low Quality. The study combines spatial analysis of rendering complexity, supported by Unreal Engine diagnostic viewmodes, with a user evaluation involving 15 participants. The evaluation focuses on perceived visual fidelity, reflections, lighting, stability, and gameplay-related aspects, complemented by qualitative observations collected during the test sessions.

The contribution of this paper is not a new RT algorithm, but an exploratory computational evaluation of hybrid reflection switching in a playable racing prototype. More specifically, this paper contributes: (i) a controlled prototype that supports switching among reflection configurations; (ii) a macro-spatial inspection strategy for identifying visually demanding regions of the track; (iii) a perception-oriented evaluation protocol based on user ratings and observer notes; and (iv) preliminary evidence on how a Hybrid mode compares perceptually against RT Full, SSR, and Low Quality configurations.

The study is guided by three research questions:

- **RQ1:** How can rendering diagnostic viewmodes support the identification of visually demanding regions in a real-time racing scenario?
- **RQ2:** How do users perceive the visual quality of RT Full, SSR, Hybrid, and Low Quality rendering configurations?
- **RQ3:** Can the Hybrid mode provide a perceptually competitive alternative to higher-quality reflection configurations while preserving an acceptable gameplay experience?

2. Related Work

This work is related to hybrid rendering for real-time reflections, perception-aware rendering, and performance-oriented graphics adaptation in games.

2.1. Hybrid Rendering for Real-Time Reflections

Screen Space Reflections (SSR) are widely used in games because they provide reflections at relatively low cost by reusing information already available in screen space, such as depth and normal buffers [Clemenz and Weydemann 2021]. However, SSR cannot reflect objects outside the camera view, occluded geometry, or elements located behind the observer, which may lead to missing reflections and border artifacts [Macedo and Rodrigues 2018, Macedo et al. 2018, Clemenz and Weydemann 2021]. Hybrid rendering pipelines address these limitations by combining rasterization and selective RT. In such pipelines, rasterization is typically used for primary visibility, while RT is invoked for secondary effects such as accurate reflections, refractions, or global illumination [Barré-Brisebois et al. 2019, Marrs et al. 2021, Tan et al. 2022]. Previous approaches also explored failure masks and heuristics to restrict RT computation to image regions or reflective surfaces where screen-space methods are insufficient [Andrade et al. 2014, Macedo and Rodrigues 2018]. In contrast to static quality presets, our work investigates hybrid reflection switching in a playable racing prototype, considering both spatial rendering complexity and user perception.

2.2. Perception-Aware Rendering

Perception-aware rendering techniques exploit limitations of the human visual system to reduce rendering cost while preserving perceived quality. Foveated rendering is motivated by the fact that visual acuity is higher near the fovea and decreases toward peripheral vision [Guenter et al. 2012, Koskela et al. 2019]. This effect may be particularly relevant to fast-paced racing games, where motion blur, camera displacement, and the player's focus on the road can reduce the perceptual relevance of high-precision reflections in peripheral or transient regions. Prior work showed that users perceive less peripheral degradation at higher movement speeds [Lisboa et al. 2023]. While that study does not address hybrid reflections, its findings are relevant to our hypothesis that visual differences between SSR and ray-traced reflections may be less noticeable during high-speed gameplay. Rather than relying on eye tracking, the present work uses a flat-screen racing scenario as a controlled context to evaluate whether a hybrid reflection mode can remain perceptually competitive when compared with RT Full and SSR.

2.3. Performance-Oriented Graphics Adaptation

Real-time RT remains computationally expensive in dynamic scenes due to ray traversal, denoising, and acceleration-structure updates, such as BVH, TLAS, and BLAS management [Marrs et al. 2021]. Modern engines therefore provide mechanisms to control rendering cost, including Level of Detail (LOD), Hierarchical LOD, far-field representations, and ray-tracing-specific budget parameters [Zhang 2024]. These mechanisms show that high-fidelity rendering in games depends not only on the rendering technique itself, but also on when and where each technique is applied. RT Racing follows this direction by combining Unreal Engine diagnostic viewmodes, spatial inspection of the track, and user-perception data to study hybrid reflection switching.

3. Methodology

The test environment is a closed arcade-style racing circuit developed in Unreal Engine 5. The prototype was designed as a controlled scenario for studying reflection quality and perceived rendering stability under fast camera movement. The methodology combines three layers: (i) spatial inspection of rendering stress through Unreal Engine diagnostic viewmodes; (ii) runtime comparison of four rendering configurations; and (iii) a preliminary user-perception study.

The RT Racing prototype is set on a cyberpunk-inspired highway at sunset, where ray tracing is most needed in visually demanding sections of the track. On one side, a large body of calm water acts as a near-perfect mirror, requiring accurate rendering of sharp reflections, sunlight, and sky color transitions. On the other, modern glass-and-concrete buildings create complex reflective and shadowed regions as evening light passes between structures. Additional stress comes from the player car's glossy bodywork, which reflects the surrounding scene, while the asphalt exhibits broader, rougher specular responses. These areas were intentionally designed to concentrate the highest reflection and lighting demands along the circuit. Figure 1 presents representative views of the RT Racing game: (a) a daytime urban section with high motion, dense geometry, and increased shader complexity; (b) a nighttime area with heavy foliage and semi-transparent elements that intensify overdraw; and (c) a sunset segment where reflections on wet asphalt and water challenge screen-space techniques.

3.1. Prototype and Rendering Configurations

The prototype exposes four rendering configurations to the evaluator: RT Full, SSR, Hybrid (RT + SSR), and Low Quality. RT Full works as a high-fidelity visual reference; SSR works as a screen-space baseline; Hybrid represents the perception-oriented compromise under investigation; and Low Quality serves as a degraded lower-bound reference. Table 1 summarizes their role in the study.

In this study, the Hybrid condition is an engine-level rendering configuration, not a newly proposed switching algorithm. It combines RT and SSR behavior through Unreal Engine settings, while the paper focuses on its spatial inspection and perceptual evaluation within a playable racing prototype.

Table 1. Rendering configurations evaluated in the playable prototype.

Condition	Role	Expected behavior
RT Full	High-fidelity reference.	Emphasizes physically plausible reflections and material response at higher rendering cost.
SSR	Screen-space baseline.	Cheaper and visually acceptable when reflected information is available in screen space, but limited by occlusion and off-screen content.
Hybrid	Proposed compromise.	Aims to preserve relevant visual cues while avoiding unnecessary use of full RT in less critical regions.
Low Quality	Degraded baseline.	Helps verify whether participants can distinguish a clearly reduced visual preset.

3.2. Spatial Rendering Inspection

The 3D RT Racing scenario was inspected from a top-view perspective using Unreal Engine diagnostic viewmodes. The analysis considered five rendering stress variables: geometric density, dynamic-object impact on acceleration structures, reflective-surface distribution, lighting complexity, and camera motion under high-speed conditions. These variables guided the identification of visually demanding regions, such as reflective buildings, water surfaces, dense geometry, and dynamic vehicles, where hybrid reflection switching would be most relevant. To visually document the observation zones and compare rendering configurations, we use a 3×3 panel of representative prototype captures.

Figure 2 shows top-view captures of the circuit used to inspect rendering complexity, relevant to hybrid reflection switching.

The diagnostic panel summarizes the main rendering stress factors observed in the prototype. The Lit view (a) serves as the subjective visual reference, while the UV density (b) and texture-scale (g) views reveal possible memory and bandwidth pressure. Light complexity (c) and shader complexity (d) expose shading hotspots that may reduce the budget available for reflections. The roughness buffer (e) identifies surfaces where reflection quality is visually relevant and potentially costly, especially under intermediate roughness. Quad overdraw (f) highlights dense or semi-transparent geometry that may increase GPU load. Reflection (h) and depth (i) views indicate where SSR or hybrid reconstruction may fail due to missing screen-space information, occlusion, or unstable depth cues. Together, these views guided the selection of circuit regions where hybrid reflection switching is most meaningful. Table 2 summarizes the diagnostic role of each viewmode in the spatial inspection.

Table 2. Diagnostic viewmodes used in the spatial inspection.

Viewmode	What it reveals	Use in this study
Lit	Final rendered appearance.	Subjective visual reference for the scene.
Mesh UV Density	Texel distribution and possible memory waste.	Identifies assets that may consume unnecessary VRAM.
Light Complexity	Overlapping light volumes and shading cost.	Locates lighting hotspots that can reduce the budget for reflections.
Shader Complexity	Per-pixel material instruction cost.	Highlights expensive materials combined with RT/SSR.
Roughness Buffer	Reflective and diffuse material regions.	Identifies surfaces where reflection quality is more visually relevant.
Quad Overdraw	Overlapping geometry and transparency.	Detects regions that may stress rasterization and traversal.
Texture Scales	Texture scale and sampling consistency.	Supports memory and bandwidth inspection.
Reflections	Distribution of reflection methods.	Detects overlap or redundancy among reflection techniques.

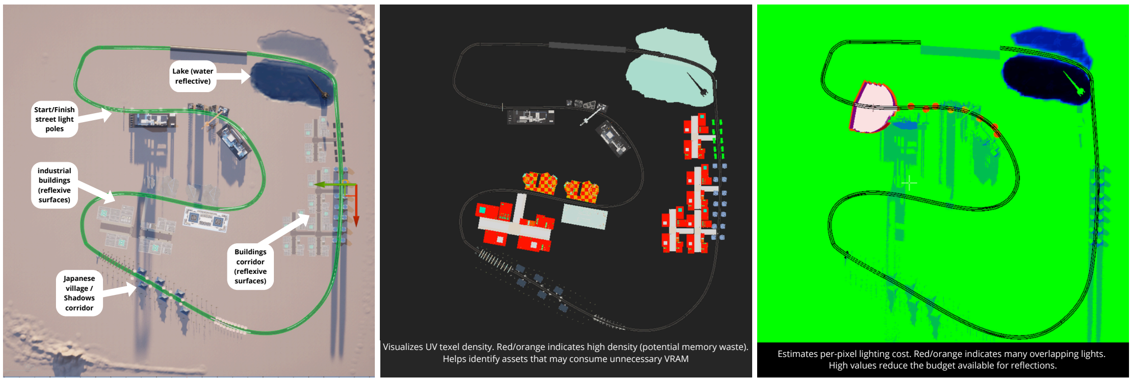
3.3. User Evaluation Protocol

The study was designed as a preliminary within-subject evaluation with 15 experienced players and does not support broad statistical claims. Each participant interacted with the playable prototype and evaluated the available rendering modes using the same questionnaire structure. The sample included 12 male and 3 female participants; 12 were between 18 and 34 years old, and all reported high previous experience with digital games. Although this profile limits generalization, experienced players were considered suitable for this exploratory study because of their familiarity with rendering artifacts and frame-rate variations.

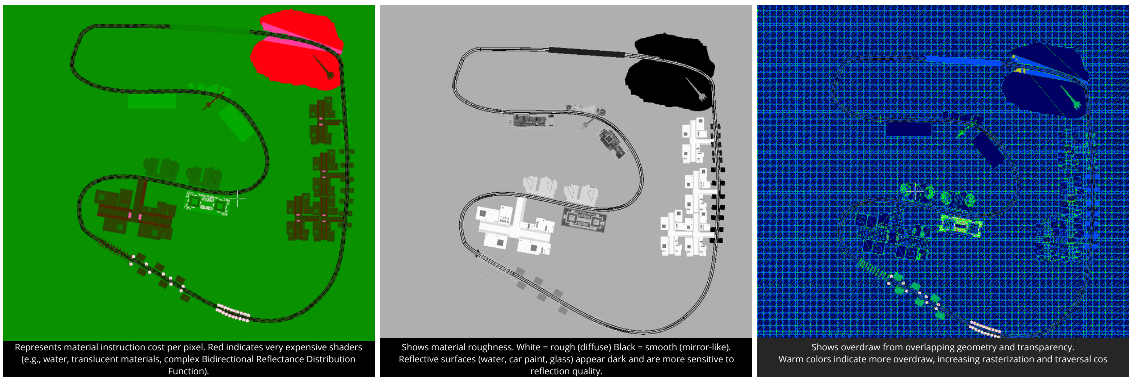
The questionnaire contained general gameplay items and rendering-specific items. General items covered menu navigation, autonomy, HUD clarity, challenge level, comfort, vehicle response, perceived speed variation, and overall satisfaction. The rendering-specific block was repeated for RT Full, SSR, Hybrid, and Low Quality, covering motion sharpness, reflection realism, rear-view mirror reflections, complete scene reflections, vehicle paint/metal, wheel reflections at high speed, fast-motion stability, lighting realism, NPC behavior, day–night transition, gameplay image sharpness, and perceived FPS performance. The questionnaire used a five-point emoji scale. For analysis, responses were mapped to an ordinal numerical scale from 1 to 5, where 1 indicates a very negative rating and 5 a very positive rating. We report means, medians, standard deviations, and the percentage of positive ratings (scores 4 and 5). Because the data are ordinal and the sample is small, these statistics are used descriptively and do not support strong claims of perceptual equivalence among rendering modes. The current spreadsheet contains perception ratings rather than raw engine telemetry; therefore, performance-related findings refer to perceived FPS satisfaction, not measured GPU time, frame time, or VRAM usage.

(a) Circuit overview **(b) Mid-track zone** **(c) Critical section**

Figure 1. Representative views of the RT Racing prototype showing regions with distinct rendering demands.



(a) Lit (Default Mode) (b) Mesh UV Density (Optimization Viewmodes) (c) Light Complexity (Optimization Viewmodes)



(d) Shader Complexity (Optimization Viewmodes) (e) Roughness (Buffer Visualization) (f) Quad Overdraw (Optimization Viewmodes)

(g) Material Texture Scales (Optimization Viewmodes) (h) Reflections Mode (i) Scene Depth (Buffer Visualization)

Figure 2. RT Racing top views in Unreal Engine Viewmodes.

4. Results and Discussion

This section summarizes subjective results from the playable RT Racing prototype, presented as descriptive trends from a within-subject evaluation. The goal is to assess whether Hybrid is perceptually competitive, not to claim objective GPU-cost reduction. Objective telemetry is left for future work.

4.1. Gameplay Perception

Before comparing rendering modes, we evaluated gameplay perception. The strongest results were HUD clarity (mean 4.47; 93.3% positive ratings), menu navigation (mean 4.13; 80.0%), and overall satisfaction (mean 3.87; 66.7%). The weakest dimensions were challenge balance (mean 3.13), perceived speed variation (mean 3.27), long-session comfort (mean 3.40), and vehicle response realism (mean 3.40). These results indicate that some issues observed during the test sessions were related not only to rendering, but also to vehicle physics, race feedback, difficulty balance, and speed sensation.

4.2. Perceptual Comparison of Rendering Modes

Table 3 summarizes the ratings aggregated over the 12 rendering-specific questions applied to each mode. RT Full obtained the highest overall mean (3.83), followed by Hybrid (3.69) and SSR (3.68). Low Quality obtained the lowest overall mean (3.03). The same tendency appears in the positive-rating percentage: RT Full reached 66.1%, Hybrid 62.8%, SSR 60.0%, and Low Quality 35.6%.

Table 3. Aggregated ratings by rendering mode. Scores range from 1 to 5.

Mode	Mean	Median	SD	Positive (%)	Negative (%)
RT Full	3.83	4.00	1.16	66.1	13.9
SSR	3.68	4.00	1.07	60.0	12.2
Hybrid	3.69	4.00	1.14	62.8	18.9
Low Quality	3.03	3.00	1.28	35.6	40.6

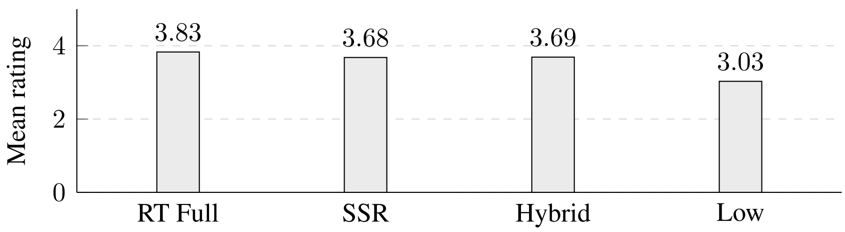


Figure 3. Mean perceptual rating by rendering mode.

The participant-level comparison provides an additional safeguard against overinterpreting item-level averages. Hybrid was higher than SSR for 5 participants, equal for 5, and lower for 5. Compared with RT Full, Hybrid was higher for 5 participants, equal for 4, and lower for 6. Compared with Low Quality, Hybrid was higher for all 15 participants. The mean participant-level difference was -0.14 for Hybrid minus RT Full, $+0.02$ for Hybrid minus SSR, and $+0.67$ for Hybrid minus Low Quality. Thus, the results do not show that Hybrid is indistinguishable from RT Full; rather, they show that Hybrid remained in a similar positive range and was clearly above the degraded baseline.

4.3. Criterion-Level Analysis

Table 4 details the mean ratings by criterion and rendering mode. RT Full was more clearly favored in reflection-centric items such as rear-view mirror reflections, vehicle paint/metal realism, and reflection realism. Hybrid remained competitive in image stability, gameplay image sharpness, perceived FPS, and reflection realism. Low Quality was consistently weaker, especially for reflection realism, complete scene reflections, vehicle paint/metal realism, and lighting realism.

Table 4. Mean ratings by criterion and rendering mode.

Criterion	RT	SSR	Hybrid	Low
Motion sharpness	4.07	4.07	3.93	3.47
Reflection realism	4.13	3.53	3.93	2.47
Rear-view mirror reflections	4.27	3.67	3.93	2.47
Complete scene reflections	3.80	3.73	3.60	2.40
Car paint/metal realism	4.20	4.00	3.93	2.67
Wheel reflections at speed	4.00	3.73	3.67	2.80
Fast-motion stability	3.80	4.00	3.93	3.93
Lighting realism	3.53	3.40	3.27	2.27
NPC vehicle behavior	2.73	2.60	2.60	2.53
Day–night transition	3.27	3.13	3.33	2.87
Gameplay image sharpness	4.00	3.87	3.87	3.87
Perceived FPS performance	4.20	4.40	4.33	4.27

All participants positively rated the statement that the differences among rendering modes were clear (mean 4.47; median 4.00). This prevents an overly strong interpretation of the findings: users noticed differences among modes, but the Hybrid mode was still perceived as acceptable and remained close to RT Full and SSR in several criteria. The discomfort item produced a mean of 2.40 and a median of 2.00; qualitative notes suggest that discomfort was more associated with brightness, abrupt lighting changes, HUD contrast, and vehicle-physics behavior than with reflection mode alone.

4.4. Qualitative Observations and Design Implications

The applicator's observations reinforce the questionnaire results. Participants repeatedly praised the visual fidelity of the prototype, the diversity and scale of the environment, reflective surfaces, the rear-view mirror, lighting effects, and the day–night cycle. They also frequently perceived differences among rendering modes, supporting the need for careful transition policies rather than abrupt quality changes. Table 5 summarizes the recurring qualitative themes identified in the applicator's observations.

For the hybrid reflection policy, these findings suggest a cautious design direction. Hybrid should not be presented as perceptually identical to RT Full, but as a promising perception-aware compromise. In high-speed or visually complex regions, the Hybrid mode can be prioritized when it remains perceptually close to RT Full from the player's perspective, provided that future telemetry confirms a meaningful performance benefit. RT Full should be preserved for zones where reflections are central to the experience, such as reflective tunnels, water surfaces, slow-speed segments, or close-up vehicle inspection. SSR can remain useful in regions where image stability and perceived performance are more important than mirror-like physical accuracy.

Table 5. Recurring qualitative themes extracted from the observations.

Theme	Mentions	Implication
Visual fidelity and scenario quality	15/15	Art direction, realism, reflections, and environment scale were strong aspects.
Rendering-mode differences	12/15	Users often noticed mode changes, so transitions should be carefully controlled.
Interface/HUD readability	12/15	Timer, warnings, button contrast, lap feedback, and race-state communication should be improved.
Lighting and day–night transition	13/15	Brightness, glare, emissive lights, and night transitions require calibration.
Vehicle physics and speed sensation	7/15	Suspension, traction, inertia, curbs, and speed feedback may confound rendering perception.
NPC behavior and race continuity	6/15	NPC recovery/respawn is needed to preserve competition.
Affective engagement	8/15	Credits, developer-as-pilot presentation, Easter eggs, and surprise elements supported engagement.

4.5. Limitations

This study has limitations. The small and relatively homogeneous sample limits generalization. The ordinal emoji scale supports descriptive trends, but numerical averages should not be interpreted as interval-scale measurements. Since no raw telemetry was collected, performance findings refer to perceived FPS satisfaction rather than measured frame time or VRAM usage. Rendering judgments may also be affected by gameplay and interface factors, including vehicle physics, NPC behavior, HUD readability, and lighting comfort. Finally, without eye tracking, the assumption that high-speed racing shifts attention toward central screen regions remains a design hypothesis rather than directly measured gaze evidence.

5. Conclusion and Future Work

This paper presented RT Racing, a racing-game prototype designed to investigate perception-oriented switching between SSR, RT Full, and Hybrid reflection modes. The work combines spatial inspection through Unreal Engine viewmodes with a user-perception study involving 15 participants. The results suggest that Hybrid is a viable candidate for adaptive reflection switching: it achieved a median rating equal to RT Full and SSR, remained close to them in several criteria related to reflection quality, image sharpness, and perceived performance, and outperformed Low Quality in participant-level comparisons. The study also shows that the main weaknesses of the current prototype are not restricted to rendering. Participants identified issues related to HUD readability, finish-line feedback, lap counting, NPC recovery, vehicle physics, lighting intensity, and perceived speed. These findings indicate which gameplay and interface factors must be stabilized before conducting a larger controlled experiment focused exclusively on rendering perception. Overall, the study highlights the value of evaluating rendering adaptation within playable game contexts, where visual quality, player perception, and gameplay feedback interact with the underlying graphics pipeline. Finally, this study focuses on subjective player experience; future perceptual studies are planned to expand the sample and integrate objective measures such as FPS, frame time, VRAM usage, stuttering, input lag, eye tracking, and map-region metadata.

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