Detonation is a highly efficient mode of pressure gain combustion (PGC) that exploits a rise in stagnation pressure to achieve high thermodynamic efficiencies and thrust capabilities. It has been a challenge to integrate detonation combustion into power generation and combustion applications due to the unstable and unsteady nature of detonations. The critical flow field conditions that drive the onset of a detonation require further investigation. One of the fundamental mechanisms for detonation initiation is turbulence driven deflagration to detonation transition (TDDT). The present research experimentally explores the propagation dynamics of fast, deflagrated hydrogen-air flames interacting with highly turbulent reactants. Fast flames produce extremely high turbulent flame speeds values, increased levels of compressibility and develop a runaway mechanism that leads to TDDT. The flame structural dynamics and reacting flow field are characterized using advanced optical diagnostics including simultaneous high-speed particle image velocimetry, chemiluminescence, and schlieren. These techniques enable the detailed classification of flame propagation modes at various flame acceleration regimes. The study further examines a turbulent, fast flame at the boundary of transitioning to quasi-detonation in order to characterize the evolution of flame-compressibility dynamics approaching critical TDDT conditions. The local measured turbulent flame speed is found to be greater than the Chapman-Jouguet deflagration flame speed, which classifies the flame in the spontaneous transition regime within the deflagration-to-detonation transition runaway process.